Tidal Energy, Underwater Noise & Marine Mammals

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“The Drifting Ear”
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DECLARATION

I Caroline Carter confirm that this thesis has been completed by myself, that it has not been accepted in any previous application for a degree, that any joint work has been clearly indicated and all quotations have been distinguished by quotation marks and the sources of information specifically acknowledged.

2013
SUMMARY

- Sourcing energy from renewable sources is currently a key theme in modern society. Consequently, the pace of development of these emerging technologies is likely to increase in the near future, particularly in marine renewables. However, the environmental and ecological impact of many of these new developments in the marine environment is largely unknown.

- My thesis has focused on one unknown area of interaction; the potential effect of tidal-stream devices on marine mammals. Collision risk is often cited as a key concern. Therefore, my premise was - for marine mammals to avoid a collision with a marine renewable device (assuming they are on a collision course) they must first detect the device.

- It is well understood that marine mammals use sound and hearing as their primary sense for communication, foraging, navigation and predator avoidance, so it is highly likely that the primary cue for device detection will be acoustic.

- However, it is not known how operational marine renewable devices might modify the acoustic landscape in these areas, or whether they will be audible to marine mammals in time to alert them to the presence of devices. It has been suggested that the high level of natural and anthropogenic background noise in tidal-stream areas may mask (drown out) the signal of the tidal devices.

- The acoustic characteristics of underwater noise in shallow coastal waters are currently not well known. My thesis adds data to this knowledge gap by measuring and mapping underwater noise levels in tidal-stream areas.

- My thesis hypotheses were that:
  1) Tidal stream areas are loud environments.
  2) The acoustic output of tidal devices may therefore be masked by the environment and thus not easily detected acoustically.

- Consequently, my research questions for this thesis were as follows:
  1) What are the noise levels in areas suitable for tidal energy extraction and how varied is the underwater noise field?
  2) How does this compare to better quantified deep-water sound levels?
  3) What effect does the tidal flow have on the background noise?
4) What is the likely acoustic output from tidal-stream devices?
5) Is it the case that when the turbines turn at their optimum revolutions per minute, the background noise in the area is at its noisiest?
6) Over what range might the signal of tidal devices be greater than the background noise?

- Currently there are no standardised methods for measuring and reporting underwater noise. The drifting hydrophone methodology described here was therefore tailored for the challenging tidal-stream environment, and the methods described here represent a relatively low-cost method of acquiring underwater acoustic data.

- Underwater background noise levels were measured and mapped for three tidal-stream case study sites, all of which are of interest to tidal-energy developers. These were: 1) the Fall of Warness in Orkney (59° 8’N 02° 49’W), the location of the European Marine Energy Centre (EMEC) tidal-stream test facility, 2) Kyle Rhea (57° 14’N 05° 39’W) a narrow strait between the Isle of Skye and the mainland coast of western Scotland and 3) the Sound of Islay (55° 50’N 06° 06’W), a strait between the islands of Islay and Jura on the west coast of Scotland.

- The background noise-maps presented here all highlight a spatial heterogeneity in sound levels. The broadband noise levels determined have a mean value of 114 dB re 1 µPa (with a variability of approximately ± 20-30 dB).

- The frequency range of underwater background noise or signal is biologically relevant because it is the particular frequencies of the signal or noise that will determine whether the sound is audible to marine life. It is therefore important to understand the frequency characteristics of the background noise as well as the levels. Therefore, frequency spectra from each of the case study locations are presented. Frequency spectra plots were generated for frequencies up to 48 kHz from a subsample of the acoustic sound files that were used to generate the background noise-maps. The comparison of the frequency spectra suggests that there is a large within site variability even within the relatively short time frame of the surveys.
• The broadband sound pressure levels suggest that these case study tidal stream areas were loud environments when compared to the deep water environment. In addition, the average frequency spectral levels were plotted against the commonly used deep water curves (Wenz curves) and were found to tend towards the upper levels of the Wenz curves or higher. Also, the frequency spectral profiles all tended towards a flatter profile than the Wenz curves, with higher levels in frequencies above 10 kHz.

• Information detailing the acoustic characteristics of tidal turbines is scarce. So, to consider the acoustic output of tidal devices, data were reviewed from publicly available reports and from commercial data (with developers’ permission). There is a huge diversity in device types (see www.emec.org.uk) and most are at the testing stage with few at full-scale development. The diversity in device types and designs may mean that each device could have a characteristic acoustic output.

• In general, tidal stream device acoustic output includes both a tonal and broadband signal. Estimated source levels from measurements of tidal-stream devices range from 125 to 174 dB re 1 µPa @ 1 m. Based on the data from these examples, tidal-stream device acoustic output is dominated by low frequency energy.

• Marine mammals’ primary sense is hearing; sound is used for communication, navigation, prey detection and obstacle avoidance. Hence the consideration of how audible these devices may be in tidal-stream locations is of relevance. However, the marine mammal response to sound is highly variable and dependent on context, and therefore is difficult to predict.

• The hearing abilities of a selection of marine mammal species were considered and compared to background noise levels measured in the case study areas. The minimum, average and maximum third octave levels were plotted with generalised audiograms. This highlighted a raised spectral profile in the higher frequencies, within the similar frequency range as the marine mammals’ peak hearing band. This suggests that in these tidal-stream case study areas, it will be the background noise levels that will limit device detection rather than species hearing ability.

• To compare background noise and potential tidal-stream device output and therefore estimate the range a device may be detectable to the few marine mammals selected as example species, a basic geometric spreading transmission
loss model was used. A generic model was used in this case because of the limited data available to be included in a more complex model and the intention was to explore the scenario.

- For this study I have assumed that the signal from the tidal-stream device is audible where the broadband received level is greater than the broadband background noise levels in the area. Using these criteria, the model suggests that the range of device audibility varied from inaudible to audible out to a distance of 1.2 km.

- The signal-to-noise maps presented non-symmetrical acoustic ‘zones of influence’ due to the ‘patchiness’ of the background noise levels. These patterns are likely to be further complicated by any directionality of the device sound signatures, and due to any variability in the propagation loss characteristics because of site specific parameters.

- Lessons learnt and conclusions from this study:
  1. Drifting hydrophone methodology is suited to the challenge of tidal-stream locations and enables a greater spatial area to be covered during a survey and is therefore ideal for pre and post deployment surveys and monitoring surveys. This method however only provides snapshot data for the survey, unless repeatedly deployed in one area, which would generate vast quantities of data. Using the analysis methods employed in this study this would be time consuming, therefore an automated method of analysis would be necessary.

  2. It is a challenge to operate the drifters in worsening weather conditions, and certainly would not be practicable above Beaufort Force 5.

  3. The direction of tidal flow (flood or ebb) or tidal cycle (springs or neaps) are not necessarily the parameters of relevance in the measurement of background noise levels in tidal-stream areas. The relevant parameters that have more influence in background noise levels in these areas are the location plus the weather and local anthropogenic activity and then the tidal-flow speed (to a lesser extent).

  4. The variability of the acoustic noise-field and the main contributors as detailed in this thesis, are consistent with existing knowledge, but this thesis has shown that the spatial background noise-field in these tidal-stream areas is very patchy,
and that the levels tend to be higher than the upper Wenz curve suggesting these areas are already noisy environments.

5. During higher tidal flow-speeds, noise levels in the higher frequencies (1 kHz and above) are elevated, probably due to sediment transport leading to a flatter spectral profile than is observed in the deep water/low tidal-speed Wenz curves.

6. These patterns were consistent across all three areas in the west and north of Scotland and it would be rewarding to look elsewhere to establish how general these findings are.

7. Based on the data presented here, it is unlikely that the operational noise from tidal-stream devices will be a hazardous noise for marine mammals, or that they will present an acoustic barrier, rather that it is conceivable that tidal-devices may not be audible in all circumstances for marine mammals to detect them at distance against the background-noise environment using passive hearing alone.

- **Recommendations for further research**

  1. To further investigate the relationship between tidal flow speed and measured noise levels. Other drivers should be considered as well as depth and distance to shore, such as weather, vessel activity, sea bed type and sea bed slope.

  2. To further investigate the causes of the patchy noise maps, and attempt to correlate parameters in a more detailed methodology. Suggestions include, the use of weather stations coincident with the survey runs of drifting hydrophones, the use of current meters, to better define the flow speed within which the drifter is travelling, the use of a drop down video to gain better detail on the sea bed composition and if available better resolution sea bed type spatial information.

  3. To investigate the temporal stability of the discrete noise patches, to run drifters over multiple days and compare the spatial data. In this study, only the Sound of Islay work was conducted over multiple days.

  4. These data were acquired during the day for operational reasons. The drifters had to be tracked visually to be retrieved at the end of the run. It would be interesting to collect data at night to assess what difference there might be. This would require a new method of deploying the drifters and then tracking.
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To my children - Ben and Tierney Carter – thank you 😊

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## GLOSSARY OF TERMINOLOGY

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<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>A measure of the intensity of the sound signal i.e. how loud it is.</td>
</tr>
<tr>
<td>Audiogram</td>
<td>A graph showing the auditory threshold (the minimum sound level that can be perceived in the absence of other sound sources). The auditory threshold varies by frequency.</td>
</tr>
<tr>
<td>Broadband</td>
<td>Describes sound over a wide range of frequencies.</td>
</tr>
<tr>
<td>Decibel</td>
<td>The decibel is a relative unit representing a logarithmic scale for sound intensity. Quantities described in decibels (dB) are usually referred to as ‘levels’. The logarithmic scale is used because it is a convenient method of expressing the wide range of underwater sound pressures (for example from 0.0000001 Pa in the quiet deep sea to the 10000000 Pa of an explosive blast (Nedwell &amp; Howell, 2004)).</td>
</tr>
<tr>
<td>Fourier transformation</td>
<td>A mathematical transformation called a Fourier transformation can be performed to compute the frequency content (spectra) of the sound measured. Frequency spectra are represented by a graph of frequency versus sound level.</td>
</tr>
<tr>
<td>Frequency</td>
<td>Is the rate of oscillation, i.e. the number of cycles per second and is measured in Hertz (1 Hz = 1 cycle/sec).</td>
</tr>
<tr>
<td>Narrowband</td>
<td>Describes sound contained in a narrow band of frequencies.</td>
</tr>
<tr>
<td>Octave bands</td>
<td>A series of adjacent bands that are one octave wide. From one octave to another there is a doubling of frequency.</td>
</tr>
<tr>
<td>Power spectrum density</td>
<td>Describes how the power of the signal is distributed with frequency (dB re 1µPa^2/Hz).</td>
</tr>
<tr>
<td>Sound</td>
<td>A mechanical wave that is transmitted through the medium, in this case, water. The wave is an oscillation of water particles and travels through the water as a longitudinal wave comprised of a series of compressions and rarefactions. These compressions and rarefactions are detected by the receiver (ear or hydrophone) as a fluctuation of pressure.</td>
</tr>
<tr>
<td>Sound pressure</td>
<td>Underwater acoustic pressure is the deviation from the ambient hydrostatic pressure caused by the sound wave (the force per area) Measured in micropascals (µPa).</td>
</tr>
<tr>
<td>Sound pressure level (SPL)</td>
<td>Is a logarithmic measure of the effective sound pressure, relative to a reference pressure (in air this is 20µPa; in water 1µPa).</td>
</tr>
<tr>
<td>Source level</td>
<td>An effective level of sound calculated for a point source. Usually determined from measurements made at distance from the source and back propagated to a nominal 1m distance (dB re 1µPa referred to 1m).</td>
</tr>
<tr>
<td>Third Octave bands</td>
<td>Each Octave band is split into three adjacent bands logarithmically.</td>
</tr>
<tr>
<td>Tone</td>
<td>Is sound where the energy is confined to a particular frequency.</td>
</tr>
<tr>
<td>Transmission (or propagation) loss</td>
<td>As sound travels away from source, the intensity of the sound diminishes with distance.</td>
</tr>
<tr>
<td>Wavelength</td>
<td>Is the length of the sound wave’s oscillation i.e. the distance between one particular point in the wave and the next time it is repeated (e.g. the peak).</td>
</tr>
</tbody>
</table>
CHAPTER ONE – GENERAL INTRODUCTION

1.1 PREAMBLE

My thesis has evolved from current interest in marine renewables and how they might interact with their environment and may therefore be of interest to researchers, marine renewable developers and their consultants and to marine development regulators. In this general introduction, I will describe my motivation behind the choice to study underwater sound in tidal-stream areas that are suitable for energy extraction, by considering the status of the renewable industry and what is unknown with regard to the effect renewable development may have on the natural environment. I will explain why tidal-stream devices and marine mammals were the focus of this study and I will highlight where this thesis contributes new information. I also introduce underwater acoustic concepts used for this study and I will then conclude the section by detailing the structure of the thesis chapters that follow.

1.2 THESIS MOTIVATION

Sourcing energy from renewable sources is currently a key theme in modern society. Consequently, the pace of development of these emerging technologies is likely to increase in the near future. However, the environmental and ecological impact of many of these new developments in the marine environment is largely unknown (Boehlert & Gill, 2010). This degree of uncertainty is due to a combination of the novelty of these new machines, the lack of relevant environmental data in the shallow coastal locations suitable for energy extraction, and the unknown marine mammal behavioural response to the presence of these devices.

My thesis focused on one unknown area of interaction: the potential effect of tidal-stream devices on marine mammals. Two commonly cited concerns with respect to marine renewable devices are collision risk and noise impact (Inger et al, 2009). Currently, there is very little information available to quantify collision risk, especially when marine mammal behavioural reactions to anthropogenic stimuli are variable and may depend on context (Thompson et al, 2010a). At the commencement of this thesis, there were few energy extraction devices in the water and also it was not well known which animals were present in the various tidal-stream locations, so it was not clear how much of a collision risk there might actually be. Now, three years on, research in the
area of environmental effect is growing rapidly, stimulated by the pace of development and the requirement for an understanding of impact for device consenting purposes. However, it is still not well known what the collision risk may be for marine animals.

I decided to focus on what was possible to quantify in an area of so many unknowns. My premise was, for a marine mammal to avoid a collision with a marine renewable device (assuming it was on a collision course) it must first detect the device. This thesis does not consider the collision probability, it is possible that some animals in the area would not be on a collision course simply because they were not in the same space as the tidal device.

Marine mammals are well adapted to their environment with excellent vision and hearing capabilities, but the operating range of vision is limited by the transmission of light underwater. Oceanic water is very clear, and light can travel up to approximately 90 m in these waters (Stewart, 2008). Coastal waters are much less clear mainly due to terrestrial input (run off from the land). Very little light penetrates more than a few metres in these waters (Stewart, 2008; Apel, 1988). Conversely, sound can travel through the water extremely well (Apel, 1988). It is well understood that marine mammals use sound and hearing as their primary sense for communication, foraging, navigation and avoidance of predators (Dolman & Simmonds, 2010) so it is highly likely that the primary cue for device detection will be acoustic.

However, it is not known how operational marine renewable devices might modify the acoustic landscape in these areas, or whether they will be audible to marine mammals in time to alert them to the presence of devices.

Figure 2 - Schematic illustration of the inter-relationship between the background noise level and the device acoustic signature for device signal-to-noise ratio.
It was clear from preliminary reading that the baseline background noise levels in shallow water tidal-stream areas were not well known, and neither was the sound output from renewable devices due to the relative infancy of the marine renewable industry. Audibility of the marine renewable device will depend on the relative mix of the device acoustic output, the underwater background noise levels (Figure 2) and the hearing ability of the animal in question.

My thesis will add data to this knowledge gap by measuring and mapping underwater noise levels in tidal stream areas. The generation of noise-maps from measured data is novel (as opposed to mapping modelled data) and therefore the methods used to generate these maps are described in detail. These data will contribute to the baseline data for the renewable device deployment, but these data are also interesting on their own, and can stand alone without the marine renewable context as there are very few data on noise levels in shallow water tidal areas. Additionally, available information (at the time of writing) relating to the noise output of tidal devices is presented and finally this is brought together for a preliminary exploration of the potential audibility of these devices in these environments. These findings will help inform the debate regarding the potential impacts of marine renewable devices.

My thesis hypotheses were that:
1) Tidal stream areas are loud environments.
2) The acoustic output of tidal devices may therefore be masked by the environment and thus not easily detected acoustically.

Consequently, my research questions for this thesis were as follows:
1) What are the noise levels in areas suitable for tidal energy extraction and how varied is the underwater noise field?
2) How does this compare to better quantified deep-water sound levels?
3) What effect does the tidal flow have on the background noise?
4) What is the likely acoustic output from tidal-stream devices?
5) Is it the case that when the turbines turn at their optimum revolutions per minute, the background noise in the area is at its noisiest?
6) Over what range might the signal of tidal devices be greater than the background noise?
1.3 Marine Renewables

The relevance of this work is clear when one considers that sourcing energy from renewable sources is a priority in today’s society. There are many connected drivers for this positive political will; one key driver is that the UK is committed to reducing greenhouse gases by 80% by 2050 (Climate Change Act - www.decc.gov.uk) and renewable energy is seen as one mechanism by which this can be achieved. The world’s population is projected to grow from 6.1 billion in 2000 to 8.9 billion in 2050 (United Nations, 2004) and related to this will be an increased energy requirement. At the same time the world’s fossil fuels are being depleted resulting in an important need to source energy from alternative sources. Energy drives modern economies and as such is key to the development of society (European Union, 2012) and therefore the sourcing of sustainable energy is a priority issue.

To tackle these problems, the European Union (EU) has set ambitious targets to encourage the de-carbonisation of our society. Currently the EU has set out to achieve a 20% reduction in greenhouse emissions by 2020 (compared to 1990 levels) (European Union, 2012) and this aspiration is driving forward renewable development. The EU has stated that 20% of energy should come from renewable sources\(^1\) by 2020. Potentially Scotland has 25% of Europe’s tidal power and 10% of wave power, plus 25% of European offshore wind resource (www.scotland.gov.uk) and it is estimated that 12 gigawatts could be generated in Scotland by marine renewable and offshore wind sources by 2020 (www.scotland.gov.uk). This is potentially a significant resource of energy for Scotland as this is roughly equivalent to six coal-fired power plants, or five gas power plants or four nuclear power plants (based on figures from the European Wind Energy Association www.ewea.org).

Another driver pushing forward the development of renewable industries is energy security. Rather than being dependent on importing energy, especially in the near future with diminishing fuel reserves, it is clearly better to generate the energy required locally.

\(^1\) Renewable in this context relates to; wind, wave, tidal, hydro-electric, solar, geothermal and biomass – marine renewable relates to wave and tidal energy specifically
Connected to this, and of importance to policymakers, is the creation of an industry to foster domestic wealth and prosperity. The generation of electricity from renewable sources presents an opportunity to Scotland and the UK to develop the industry with an additional aim of being able to export expertise.

These factors illustrate clearly the importance of renewables politically, socially and economically and hence the relatively rapid technological push in development and deployment, particularly in resource-high countries such as Scotland. However relevant and important this industry may be to society, it is apparent that the scientific community is working hard to ‘catch-up’ with development so that the effect on the environment can be better understood to enable regulator decisions to be based on the best available evidence at the time.

There are significant challenges to the development of marine renewables (wave, tidal-stream and offshore wind). There is uncertainty in the engineering and grid connectivity, but also in the environmental impact and, understandably, investors are reluctant to put money into a project if there is a chance it would not be allowed to proceed due to environmental concerns. The environment is harsh; salt water, inclement weather and the natural force of the waves and tidal-streams all contribute to making the deployment and operation of these devices a substantial engineering challenge. The Scottish Government has put a variety of mechanisms in place to lessen the financial risk in the development process; however it remains a challenge for the developers to secure funding given substantial uncertainty.

Highlighted environmental stressors of marine renewable developments in the marine environment include increased shipping activity and the resulting increase in noise and collision risk to marine life. Other sources of extra noise introduced into the marine environment include construction noise, operation and decommissioning noise (Sheilds et al, 2009). The effect on the benthic environment during all three stages of development is also not yet well known, nor is the knock-on-effect to fish, marine mammals and birds and there is the potential for entrapment, entanglement and collision (Wilson et al, 2007). However, effects may not necessarily be negative as there is the potential for the devices to enhance biodiversity, by becoming artificial reefs and/or fish aggregation areas (Sheilds et al, 2009) and due to the very presence of the devices these areas may become effectively protected zones from fishing pressure. A
further potential consequence of enhanced biodiversity is that these areas may then become more attractive to predators (Sheilds et al, 2009) and thus bring more animals into close proximity to marine renewable developments.

Also under consideration is the effect of the removal of natural wave or tidal-stream energy out of the marine system on the oceanography of the area. It is not fully understood what this may mean for tidal stream areas if, for instance, 400 turbines are placed in an area to extract energy (e.g. the MeyGen proposed development in the Inner Sound, Pentland Firth; www.bbc.co.uk; www.thecrownestate.co.uk).

These questions are currently receiving attention, and because of the urgent pressure to develop these industries, research effort is increasing in the attempt to answer these unknowns. Research is being funded from several sources, including the Scottish Government (www.scotland.gov.uk), Scottish Natural Heritage (www.snh.gov.uk), and more recently, the Natural Environment Research Council (NERC) and the Department for the Environment, Food and Rural Affairs (www.ukcds.org.uk). Research is targeted at key areas of impact, and more recently at cumulative impact studies relating to multiple device deployments and interactions with neighbouring developments. My research fits neatly into this arena by including an investigation of baseline characteristics of tidal stream areas suitable for energy extraction.

1.4 TIDAL STREAM DEVICES

In this thesis I use the term ‘marine renewables’ to encompass offshore wind, wave and tidal-stream energy generation. I use ‘wet renewables’ to refer specifically to wave and tidal-stream technologies. Here I consider only tidal stream energy generation because conceptually, tidal stream devices present the greater potential hazard to marine mammals due to the combination of multiple rotating turbines in a confined area and the ‘conveyor belt’ analogy of the tidal stream flow.

Ideal locations for tidal-stream generation are within restricted passageways such as narrows and straits, and around headlands where the tidal-stream flow is concentrated. This thesis has focused on these restricted passageways of current tidal energy extraction interest. Initial sites of industry interest have focused on areas of flow through narrow channels because, for example, of the reduced logistical challenges of sheltered waters, clear bidirectional tidal-stream flow and short power cable runs.
There are many different designs of tidal-stream device under development and it is not my intention to describe them all here. The current front runners are variations on the underwater windmill type (e.g. Marine Current Turbines and Andritz Hydro Hammerfest, previously Hammerfest Strøm) and an open centre turbine (OpenHydro) (Figure 3) and are discussed later within this thesis (Chapter Five).

It is also worth noting that all devices will be large, with rotor diameters in the order of 12-20m (Figure 4), as this illustrates the potential size of developments and the resulting underwater space that they will occupy.

Figure 3 - Tidal-stream devices (a) Marine Current Turbine’s twin 2-bladed design SeaGen (www.marineturbines.com) (b) Andritz Hydro Hammerfest 3-bladed turbine (www.hammerfeststrom.com) and (c) OpenHydro’s open centre design (www.openhydro.com).

Figure 4 - Marine Current Turbine’s SeaGen device in Strangford Lough, Northern Ireland, illustrating the size of the rotor in comparison to people on a boat (www.marineturbines.com).
1.5 Collision Risk Parallels

The concern regarding the potential collision risk with marine renewable devices in general and tidal-stream devices in particular, has arisen from existing understanding of other known collision events, primarily with shipping, fishing nets, birds and wind turbines. The marine mammals that may be at risk from these novel technologies in Scottish waters include (but are not limited to) the grey seal \((\text{Halichoerus grypus})\), the harbour or common seal \((\text{Phoca vitulina})\), the harbour porpoise \((\text{Phocoena phocoena})\), the bottlenose dolphin \((\text{Tursiops truncatus})\) and the minke whale \((\text{Balaenoptera acutorostrata})\). This group of animals are a mix of pinnipeds, odontocetes and mysticetes each with their own range of sensory perception and agility.

There are known collision parallels for all of these species. There are records of ship strikes not only for the larger whale species, but also for smaller whales and odontocetes (Silber et al, 2012; Waerbeek et al, 2007; Panigada et al, 2006). Ship strikes are relatively frequently reported (Panigada et al, 2006) but it is not fully understood why these animals become collision victims. Ship speed is thought to be an important factor (Wiley et al, 2011), but although these animals should be able to detect the ships acoustically (Silber et al, 2010) in these cases they may not have detected the hazard at all, or in time to avoid a collision. It is thought that the activity of the animal at the time may be relevant for hazard detection, for example when feeding or resting these animals’ attentiveness to environmental sounds may be reduced (Panigada et al, 2006).

Recently a new type of collision mortality has been reported. There have been incidences of seals being found washed up on the shoreline with significant trauma termed ‘corkscrew injuries’. It is thought that this may be a result of a collision with ducted propellers (Thompson et al, 2010b). The use of vessels with ducted propellers is likely to increase during construction and maintenance of marine renewable developments thus adding to the noise input to the environment and potentially adding a further collision risk.

Marine mammals have also become entangled with fishing nets and the reasons these animals become caught is not fully understood yet (Morizor et al, 1999). Work on captive odontocetes has shown that they are capable of detecting the nets using echolocation (Villadsgaard et al, 2007; Gannon et al, 2005) (see below) but that they still
become entangled. It is possible that they are attracted to the nets through the promise of food.

These collision risk parallels highlight that although marine mammals should be able to detect hazards, they do not always. It may be that the behaviour and motivation plays an important part in hazard awareness (discussed further in Chapter Six), and therefore these parallels are applicable to the potential hazard from marine renewable devices.

The potential for negative consequences from marine renewable devices is not disputed (Simmonds & Brown, 2010). Commonly cited potential issues include entanglement in cables, entrapment in renewable structures and/or collision with, for example, the rotating blades (Simmonds & Brown, 2010; Shields et al, 2009; Wilson et al, 2007). The noise impacts of construction and operation of these devices also have been postulated to include hearing damage, the masking of important biological sounds and disruption of normal behaviour, stress and displacement from habitats as has been demonstrated for example due to boat traffic noise (Simmonds & Brown, 2010).

It is relevant to mention echolocation here. Echolocation is odontocetes bio-sonar and is used for both prey detection and navigation (Villadsgaard et al, 2007; Verfuß et al, 2005) and could therefore play an important part in device detection for odontocetes. However it is not fully understood how wild odontocetes use echolocation in comparison to captive trained animals (Gannon et al, 2005). Verfuß et al (2005) have suggested that harbour porpoise use echolocation to follow a bathymetric contour for spatial orientation. It is probable that odontocetes will be able to detect tidal-stream devices using echolocation, but it is not known how they will perceive the rotating turbine blades.

As not all mammals potentially at risk have, or continually use, echolocation, nor is there any information on how echolocating animals may interpret the moving turbine blades, plus the collision parallels mentioned above suggest that echolocating animals are also at risk from collision, I therefore do not focus on bio-sonar in this thesis, concentrating instead on the balance between environmental background noise and the levels of device noise and on passive detection.
1.6 **UNDERWATER ACOUSTICS**

In this section, I briefly describe the evolution of underwater noise research and why there is very little known about the noise characteristics in shallow coastal areas. I then define terms and the acoustic concepts used in this thesis.

### 1.6.1 A BRIEF HISTORY OF UNDERWATER ACOUSTICS RESEARCH

Even though Jacques Cousteau entitled his 1953 book about underwater diving ‘The Silent World’ it has been known for some time that the underwater environment is anything but silent. Over 2000 years ago the Greek philosopher Aristotle was the first to note that sound could be heard underwater as well as in air, and in 1490 Leonardo da Vinci stated that “if you cause your ship to stop and place the head of a long tube in the water and place the outer extremity to you ear, you will hear ships at a great distance from you” (Bjørnø, 2003).

In 1826, Colladon and Strum ran an experiment on Lake Geneva to investigate the speed of sound. They positioned two boats 10 miles apart, a bell was rung underwater from the first boat and at the same time a pistol was fired as a visual cue. They timed how long between seeing the smoke of the pistol and hearing the bell underwater. From this they calculated a speed of sound underwater of 1435 m/s which is close to accepted values today (Bjørnø, 2003) at roughly 1500 m/s (Tyack, 2008).

The interest in underwater sound increased pace in the early 1900s primarily due to ‘need’.

> “Necessity, is the mother of invention”

---

Plato

As the above Plato’s quote suggests, an important driver of invention (or research) is need, and need has historically been the motivation behind much of the research and thus knowledge to date. (Much of the following information has been taken from Bjørnø, 2003). In the early 1900s, the use of bells as an underwater warning device (for shipping and coastal obstructions) was investigated, but had not been very successful as it had been found difficult to detect the bell against the background noise, an early hint at the levels of background noise present in the environment. Another example of ‘need’ was that the sinking of the Titanic in 1912 spurred on the development of an
echo-ranging device, and in 1914, one such device successfully detected an iceberg at a distance of 2 miles.

The two world wars greatly influenced the work on underwater research, the need to detect enemy submarines and mines stimulated further research into echo-ranging. SONAR (SOund Navigation And Ranging) systems were developed. Echo-ranging requires the understanding of how sound travels underwater; therefore there was a need to better understand the environmental background noise.

In the 1940s, work conducted by Knudsen and colleagues identified three main sources of background noise in the ocean, they labelled these sources ‘water-noise’ (including surf, rain, hail and tides), ‘man-made’ sources (including shipping) and ‘marine life’ (Wenz, 1962). The Knudsen-Wenz curves that describe the contributing sources to underwater noise in the deep sea are still referred to today (see Chapter Four).

Military research slowly became available for civilian use, echo-sounders became commercially available and from the 1920s these were used in fisheries to detect the presence of shoaling fish. The oil and gas industry also started using sound to investigate the sea bed to prospect for fossil fuels as it had been found that emitted sound could penetrate the sea floor and the ‘picture’ made up of the return echoes could highlight characteristic patterns of fossil fuels (Bjørnø, 2003).

There are many more examples of acoustics research development and application that could be described but this description is only intended to illustrate that research into underwater sound has generally been driven by a requirement, either military or civilian.

Historically, much of the research into underwater acoustics has been in deeper, offshore waters because this was the area of interest for the military and shipping, and because of this there is very little data on shallow water areas. The offshore renewables industry is one key driver for a change in focus to shallow coastal waters.

1.6.2 NOISE OR SOUND?

Various acoustics terminology is regularly used interchangeably in the literature, and it is not always clear as to the definition of the term as used (Gill et al, 2012). The use of ‘sound’ and ‘noise’ is one such example. ‘Sound’ is used to refer to the acoustic energy radiated into the environment regardless of source or any reference to its function or particular effect; sound could therefore include both ‘noise’ and ‘signal’. ‘Noise’ can be
described as the acoustic background against which a signal is determined and therefore represents the baseline levels present in the environment. The descriptor ‘noise’ can be used to describe a negative impact (Van der Graaf et al, 2012) and therefore it could be argued that ‘sound’ should be used as a neutral term, however background/ambient levels are always referred to as ‘noise’ rather than ‘sound’. My thesis has measured and mapped the background/ambient acoustic levels present in tidal-stream areas regardless of source, therefore in this thesis I will refer to the environmental sound energy as ‘noise’ which is in keeping with convention.

1.6.3 BACKGROUND OR AMBIENT?
The terms background noise and ambient noise are also used interchangeably. Richardson et al (1995) states that ambient noise is background noise, and then goes on to define ambient noise as “the sounds that exist if the hydrophone were not there”.

Ambient /background noise has various definitions and the following are a few selected examples:

“The noise associated with the background din emanating from a myriad of unidentified sources. Its distinguishing features are that it is due to multiple sources, individual sources are not identified (although the type of noise source – e.g. shipping, wind – may be known) and no one source dominates the received field” (NRC, 2003).

“That sound in the ocean, received by an omni-directional sensor, which is not from the hydrophone itself, or the manner in which it is mounted and/or deployed” (Harland et al, 2005).

Some authors distinguish between the terms, for example:

“Background noise is the combined noise of the environment (ambient) and man-made (apparent) noise at a certain location that is usually present during a measurement” (Götz et al, 2009).
“Background noise is the total noise without contributions of self-noise² usually composed of sound from many sources near and far. Ambient noise is the remaining portion at a given position in a given situation when the specific sounds under consideration are suppressed” (de Jong et al, 2011).

All definitions are variations on a theme, but the definitions that I feel are more relevant to this thesis, are that background noise relates to all noise in the environment (except self-noise) and that ambient noise is related to the noise present when identifiable sources are filtered out. This thesis has measured and mapped the noise present in the environment, against which a marine mammal needs to detect the acoustic signal of a tidal-stream device. Identifiable sound sources such as frequent ferries therefore should also be included.

This approach was also used by Richards et al (2007) in their report to the Scottish Government (then Executive) in relation to marine renewables. Therefore, for the purposes of this thesis, the measured and mapped acoustic data will include all sound present in the area at the time of recording (except self-noise) and be termed ‘background noise’.

1.6.4 Acoustic terminology and concepts

There are many texts available that detail fundamental acoustic theory and how the underwater environmental sound is measured (e.g. Erbe, 2011; Au & Hastings, 2008; Richardson et al, 1995; Urick, 1983).

It is not the intention to repeat this in detail here; however it is useful to include a description of acoustic terminology and concepts used and referred to within this thesis (definitions taken from a combination of the noted authors above).

Sound is a mechanical wave that is transmitted through the medium, in this case, water. The wave is an oscillation of water particles and travels through the water as a longitudinal wave comprised of a series of compressions and rarefactions. These compressions and rarefactions are detected by the receiver (ear or hydrophone) as a fluctuation of pressure.

² Self-noise refers to noise generated by the measuring system itself. This could include electronic noise, and mechanical noise such as cable strumming or noise from the equipment when in movement.
**Frequency** is the rate of oscillation, i.e. the number of cycles per second and is measured in Hertz (1 Hz = 1 cycle/sec). In terms of music (and hearing), frequency is related to pitch therefore a low frequency sound is a low note/tone. Humans are said to have a range of hearing between 20 Hz and 20,000 Hz (but in reality the range of sensitivity is narrower).

**Amplitude** is a measure of the intensity of the sound signal i.e. how loud it is.

**Wavelength** is the length of the sound wave’s oscillation i.e. the distance between one particular point in the wave and the next time it is repeated (e.g. the peak).

**Sound pressure** is the force per area. Underwater acoustic pressure is the deviation from the ambient hydrostatic pressure caused by the sound wave. Measured in micropascals (µPa).

The **decibel** is a relative unit representing a logarithmic scale for sound intensity. Quantities described in decibels (dB) are usually referred to as ‘levels’. The logarithmic scale is used because it is a convenient method of expressing the wide range of underwater sound pressures (for example from 0.0000001 Pa in the quiet deep sea to the 10000000 Pa of an explosive blast (Nedwell & Howell, 2004)).

**Sound pressure level** (SPL) is the overall measure of the level of sound present. It is calculated using the following equation:

\[
SPL \text{ (dB)} = 20 \log \left( \frac{\text{measured pressure}}{\text{reference pressure}} \right)
\]

The standard underwater reference pressure is 1 µPa (in comparison the standard reference in air is 20 µPa). Underwater sound pressure levels are therefore expressed in units of dB re 1 µPa.

The pressure can be measured in different ways depending on the question being asked. For example when measuring an impulsive sound (such as a pile driving event) it is usual to calculate the SPL by using the peak amplitude of the sound or the lower peak to the upper peak amplitude. However, when measuring the background noise (continuous sound) it is usual to take the root-mean-square (RMS) of the time series, for a specified time (Figure 5). This is a measure of the ‘average’ pressure. The amplitudes within the time series are squared (to make all positive), then the mean of these squared values is
calculated and then square rooted to reach the RMS pressure. Thus the method of
determining the measured pressure can have a big influence on the SPL presented. This
thesis measured continuous background noise levels and therefore used RMS measured
pressure (Chapter Three).

![Diagram illustrating the different methods of measuring the pressure of the sound signal Peak-Peak, Zero-Peak and RMS.](image)

Figure 5 - Diagram illustrating the different methods of measuring the pressure of the sound signal Peak-Peak, Zero-Peak and RMS.

It is worth noting that a relatively small numerical increase in dB’s is a large increase in real terms. A doubling of sound pressure is represented by an increase of 6 dB (Erbe, 2011).

![A generic audiogram illustrating the typical U shaped hearing response.](image)

Figure 6 - A generic audiogram illustrating the typical U shaped hearing response. In general, hearing is poorer at lower and higher frequencies with a region of best hearing in the middle. Any sound signal below the line is inaudible and at either end of the hearing range the sound level needs to be relatively higher to be audible.

Environmental sound is a mixture of amplitudes and frequencies that the time series
does not describe. The frequency of the sound is an important characteristic when one
is considering what can or cannot be heard. As with humans, marine mammals have a
range of hearing. This range is represented using an audiogram (Figure 6), a graph
showing the animal’s auditory threshold (the minimum sound level that can be
perceived by the animal in the absence of other sound sources). The auditory threshold varies by frequency (discussed in more detail in Chapter Six).

A mathematical transformation called a **Fourier transformation** can be performed to compute the frequency content (spectra) of the sound measured. Frequency spectra are represented by a graph of frequency versus sound level (Figure 7) from which the frequency characteristics of the recording can be visualised, known as **power spectrum density** (Chapter Four).

![Figure 7 - An example frequency spectral graph. Note frequency is on a log scale. Sound levels have units of dB re \(1\,\mu Pa^2/Hz\).](image)

Figure 7 details the frequency spectra averaged over frequency bands of 1 Hz (in units of dB re 1\(\mu Pa^2/Hz\)) known as a constant bandwidth. These units give a good resolution of the frequency spectra, but cannot be compared to hearing thresholds. However the frequency bands can be further integrated into proportional bandwidths whereby the ratio of the upper to lower frequency of the band remains constant, which results in the bandwidth becoming wider with increasing frequency. Common examples of this are the Octave bands and Third Octave bands (Figure 8). Octave bands are detailed with the units of dB re 1\(\mu Pa\) and are therefore comparable to hearing thresholds. Third Octave analysis is commonly used for the comparison with hearing thresholds because it is considered that marine mammals integrate a range of frequencies in bands similar to third octaves (Thomsen *et al*, 2006; Madsen *et al*, 2006) (also see Chapter Six).

When plotted on the same graph (Figure 8) it can be seen that as more sound is integrated within wider bandwidths, higher sound levels are returned.
Broadband refers to the sound spread over a wide range of frequencies, whereas narrowband describes sound contained in a narrow band of frequencies.

Tone is sound where the energy is confined to a particular frequency.

Source level relates to the sound emitted from a point source (in this thesis relating to the sound from tidal-stream devices – Chapter Five). This is defined as the acoustic pressure at a standard reference distance of 1m. Source level units are dB re 1µPa at 1m (sometimes ‘@1m’ or more recently ‘referred to 1m’) and are usually back calculated from measured received levels at greater distances from the source.

The source level is therefore an effective level and not a true value of the sound emitted from the source, which is complicated due to near and far field considerations. Very close to the sound source different components of the sound interact and produce interference. This ‘near field’ area, called the ‘Fresnal zone’ (Figure 9) is an area with a complicated pattern of peaks and troughs of the sound wave. It is this irregularity and unpredictability that makes the accurate measurement of the source sound difficult. The range of the near field is dependent upon the size or dimension of the source and the frequency of the sound therefore this range varies depending upon the source.
As sound travels away from source, the intensity of the sound diminishes with distance. This is known as **Transmission (or propagation) loss**. There are various mechanisms by which the sound intensity diminishes; these include spreading loss, absorption and boundary interactions.

As the sound signal moves away from the source the energy is spread out over a greater and greater area. With distance, at any one point therefore there is less acoustic energy. This is known as **geometric spreading loss**. Various chemicals in the seawater, including the water itself, cause the sound to be **absorbed**. This loss is proportional to range and is also greater for higher frequencies. The sound wave travels through the environment via many different paths and where the sound wave meets a boundary (sea surface, sea bed and boundaries due to halocline/thermocline characteristics) the wave is scattered, reflected and refracted, resulting in greater transmission loss. A rough sea surface (due to waves) can scatter the sound, as can a rough seabed surface, suspended bubbles and sea bed type *i.e.* mud versus rock, all have an effect on the propagation loss characteristics of an area.

There are many well established models of sound propagation with varying degrees of complexity. From computationally extensive models such as ‘normal mode’, ‘parabolic equations’ and ‘ray theory’ to the more general type models based on the **sonar equations**. The sonar equations are a general representation of a complex environment, and at the most basic are equations in the form of:
Received Level = Source Level – Transmission Loss

where the transmission loss (TL) is calculated using an equation based on geometric spreading.

Where the range is less than the depth of water, the sound is said to spread out spherically, and where the range is greater than the depth, the sound spreads out cylindrically, with a transition zone between the two spreading concepts. TL equations of this form are:

\[ TL = N \log R \]

where \( N \) represents the spreading loss and \( R \) represents the distance from source.

\( N = 20 \) for spherical, and \( 10 \) for cylindrical, or number in between \( 20 \) and \( 10 \), used to represent a combined scenario.

In the literature there are many forms of this type of equation, some use a combination of spherical and cylindrical (\( e.g. TL = 20 \log R_1 + 10 \log R/R_1 \) where \( R_1 \) represents the depth, or the range at which spherical changes to cylindrical – Richardson et al, 1995).

The equation when incorporating absorption as well as spreading is:

\( e.g. TL = 15 \log R + \alpha R \) where \( \alpha \) represents absorption loss, which in itself can take various forms:

\( e.g. \alpha = 0.36f^{1.5} \) (dB/km) (Richardson et al, 1995; Thomsen et al, 2006)

\( \alpha = 0.00049f^2e^{-(T/27+D/17)} \) (dB/km) (Ainsley & McColm, 1998) where \( T \) = temperature (Celcius) and \( D \) = depth (km) and \( f \) = frequency (kHz).

There are many versions of this equation family, and include semi-empirical ones such as the Marsh and Schulkin equation (Richardson et al, 1995) that is depth dependent and uses factors to represent either a sandy or muddy seabed but was limited to the frequency range of \( 0.1 - 10 \) kHz.

Some authors use the sonar equation but use measured received level (RL) at increasing distance from the source to calculate the \( N \) variable. \( N \) can vary widely depending on the location.

\( e.g. TL = 13 \log R \) to \( TL = 35 \log R \) (Madsen et al, 2006; Wahlberg & Westerburg, 2005).
The sonar equations are a useful tool, but they are an approximation as there is no scope to factor-in other key parameters (such as water temperature and sea bed type), they do not accurately represent the propagation characteristics of an environment. Sound propagation in shallow waters is complex and it is difficult to predict the transmission loss due to the many surface interactions and environmental conditions, that themselves may change in relatively short time-scales.

1.7 Thesis structure

This section has discussed the motivation behind my thesis topic by considering the drivers for the marine renewable industry to put the scale of development into context when considering the degree of environmental unknowns. This section has also introduced acoustic concepts used for this project. The rest of this thesis goes on to describe a method of measuring the underwater background noise levels in fast flowing tidal-stream areas, and then presents measured background noise levels in three case study areas. Then, available information regarding the acoustic signatures of tidal-stream devices is reviewed and finally all this information is combined to investigate the possible audible range to marine mammals from operational tidal devices. The structure of the following chapters is as follows:

- **Chapter Two** – details the rationale and methods used in this study to measure and map underwater background noise levels spatially.
- **Chapter Three** – presents the noise-maps generated for the three tidal-stream case study areas: Fall of Warness (Orkney), Sound of Islay and Kyle Rhea (Scotland’s west coast).
- **Chapter Four** – investigates the spectral content of the noise measurements from the three case study areas.
- **Chapter Five** – presents available data on the acoustic output from tidal-stream devices.
- **Chapter Six** – brings together the measured background noise levels with the tidal-stream devices output and marine mammal hearing ability to discuss the potential audibility of these devices in these energetic environments.
- **Chapter Seven** – concludes with a general discussion regarding the output from this thesis in the context of audibility for marine mammals, the magnitude of the issue and the merits and disadvantages of the various mitigation possibilities.
This thesis presents background noise levels from tidal-stream locations and thus adds data to a currently little-studied research area. Maps were generated using measured data illustrating the spatial pattern of the background noise in these areas which to my knowledge has not been presented to date. Data from tidal-stream devices are presented and the potential audibility based on actual baseline background noise levels from relevant tidal-stream locations is estimated.
CHAPTER TWO – UNDERWATER BACKGROUND NOISE-MAPPING RATIONALE AND METHODS

2.1 INTRODUCTION

The potential effect on marine life of increasing levels of underwater background noise due to anthropogenic sources is a current topic of concern (IQOE Draft, 2012). Sound levels are thought to be rising due to increasing industrialisation of the seas (including shipping and marine renewable developments). However there are many gaps in the knowledge of underwater noise and its effect on marine life (de Jong et al, 2011) and baseline underwater noise levels in tidal-stream locations is one such gap.

Concerns often cited with regard to tidal-stream devices, include noise and collision risk. Tidal-stream devices will generate noise during operations (Sheilds et al, 2009; Inger et al, 2009) plus there is the likelihood that there will be increased vessel traffic in the area for maintenance and operational reasons which will also increase the noise input to the area. However, it has been suggested that the high level of natural and anthropogenic background noise in tidal-stream areas may mask (drown out) the signal of the tidal devices (Sheilds et al, 2009) regarding the audibility of these devices to marine mammals.

This thesis has measured and mapped background noise in tidal-stream areas suitable for tidal energy extraction in order to provide baseline information about tidal-stream background noise levels, prior to the deployment of tidal-stream devices. The measured levels were then used to see if tidal-stream areas do have a high level of background noise in comparison to the better understood deeper waters, and to consider the spectral content of this noise (Chapter Four). Mapping the measurements enabled a visual description of the area in terms of noise levels (Chapter Three). This information was then used to discuss what effect tidal devices may have on the acoustic environment, and ultimately, how audible these devices may be to marine mammals (Chapter Six).

Currently there are no standardised methods for measuring and reporting underwater noise (de Jong et al, 2011). This requirement for standardisation is well recognised by the acoustics community and steps are being taken to achieve accepted standards, for example, a recent TNO (independent research establishment in the Netherlands
www.tno.nl) report was produced proposing standard methods for measuring and monitoring underwater noise in connection with wind farm installations (de Jong et al, 2011). However, at the beginning of this thesis, standard methodology did not exist; the methods used to map and analyse these data were developed for this thesis.

This chapter therefore describes the methods and reasoning used in this thesis, and the relative advantages and disadvantages. To begin with, I describe examples of acoustic noise-mapping and the various techniques of underwater noise recording in general, and then I detail the methods used in this thesis.

2.1.1. WHAT IS ACOUSTIC ‘NOISE-MAPPING’?
Maps that illustrate sound levels spatially have been generated for studies in the terrestrial environment (Murphy & King, 2010). These typically use a Geographical Information System (GIS) where areas of interest have been gridded and then the measurements at these points spatially interpolated. This is an emerging new area of terrestrial research and by and large, is in response to EU Environmental Noise Directive (Murphy & King, 2010). Such mapping could also be relevant for marine planning, however to my knowledge noise-maps have not been generated for an underwater environment purely using measured data as presented in this thesis (as opposed to modelled maps). Recently, de Jong et al, (2011) suggested that it is not possible to generate acoustic noise-field maps from measurements alone as it is not practical to resolve sound at all locations in an appropriate time frame. While this may be relevant for impulsive sound input such as marine piling, in this thesis I will show that maps can be generated for background noise from a measurement programme which gives an averaged acoustic picture over the timescale of the survey.

For clarity, in this thesis I refer to the acoustic maps presented as background noise-maps, in preference to the term soundscape. Noise-mapping is a method of presenting measured and/or calculated noise levels in a representative manner over a particular geographical area (Murphy & King, 2010). Terrestrial noise-maps have been generated by measuring sound pressure levels at points in a grid format with a noted time-frame. Irvine et al, (2009) provides an example of this technique. In their study, recordings were made at planned grid points consecutively for 4-5 minute duration at each point. Each study area took approximately one hour to survey and these levels were then interpolated to generate what they termed as ‘noise-maps’.
‘Soundscape’ on the other hand does not only describe the visual representation of sound levels within an area, but includes a description of the acoustic scene, which includes the types of sound present, the sound levels, the spectral composition and the temporal composition of the sound in that location. ‘Soundscape’ terminology has been used in terrestrial studies for several decades (Brown, 2011) with soundscape being described as “the perception of the acoustic environment of a place” by people. Irvine et al, (2009) describes the soundscape as the “overall sonic environment of an area”. Pijanowski et al, (2011) states that “…-scape” refers to an area, scene, space or view, and therefore defined ‘soundscape’ as the “integration of all sounds from all sources in an area”. They also mention that the word soundscape has been used instead of using ‘noise’ to avoid any negative connotations (Pijanowski et al, 2011; Van der Graaf, et al, 2012) as ‘noise’ is often thought of as unwanted sound.

The maps generated in this thesis are a presentation of measured noise levels in each case study location, recorded during a survey period and then interpolated; noise-mapping is therefore an important part of the soundscape description of a particular location.

2.1.2. SOUND MEASUREMENT METHODS IN THE MARINE ENVIRONMENT

Underwater sound is measured using a hydrophone (analogous to a microphone in air) which detects and converts the fluctuating acoustic pressure (sound wave) into an electrical signal. This electrical signal can then be output to a recording device to enable analysis. There are various methods of hydrophone deployment depending upon the location and depth of the area of interest.

2.1.2.1. STATIC HYDROPHONES

Hydrophones can be deployed on a mooring for mid water column measurements, or on a lander type platform for measurements close to the sea-bed (Figure 10). Static hydrophones can be deployed either singly or as arrays. Arrays can be static or towed. The benefit of an array is that directionality to the sound source can be assessed.

Moored hydrophones can be deployed to monitor sound over extended time periods for a variety of objectives. Examples of large scale applications are the SOSUS array, the US Navy’s sound surveillance system originally designed to search for enemy submarines (www.pmel.noaa.gov) and the Comprehensive Nuclear-Test-Ban Treaty (CTBTO) with their global network of sensors (www.ctbto.org) for the detection of low frequency
seismic signals. Other examples of applications include earthquake monitoring and the acoustic tracking of whales (www.whoi.edu; Caudal & Glotin, 2008; Noad et al, 2004).

One further example is the network of sensors used for the project ‘Listening to the deep ocean environment’ (LIDO) (www.listentothedeep; André et al, 2011). In this project moored hydrophones are located in regions around the world, and the real time sound can be accessed over the internet via the project website.

Of relevance to the current concern regarding the increasing levels of anthropogenic noise in the world’s oceans, is legislation within the recent EU Marine Strategy Framework Directive (MSFD). Descriptor 11 of the directive sets out the requirement to monitor sound levels in the ocean, both loud transient noise, and continuous low frequency noise (Van de Graaf et al, 2012). This is still in progress but will most likely call for a long term monitoring programme using static long-term hydrophone deployment.

The Pop-Up Ambient Noise Data Acquisition (PANDA) system (Urn & Potter, 1999) is the last example presented here. PANDA is a bottom mounted array that has been used for the long term monitoring of ship noise.

Nonetheless, these examples of static systems have not been used to map areas with strong tidal flows (and most likely would not be able to due to demanding local conditions, explained in further detail below).
2.1.2.2. Drifting Hydrophones

Measuring underwater noise in tidally active shallow water environments presents a considerable challenge; the flow of water past a static hydrophone generates flow noise analogous to the wind rushing past a microphone, and can also cause the cable to strum (vibrate). Static methods such as moored and bottom mounted hydrophones will be significantly influenced by flow noise past the transceiver (Au & Hastings, 2008) therefore data gained in this environment using static methods may be of limited use depending on the needs of the study. For example, flow noise is low frequency, so if the objective of a study is to locate a higher frequency signal, then the flow noise can be filtered out leaving a useful sound file).

![Diagram showing a hydrophone deployed from a boat platform illustrating the use of an anti-heave buoy (float) and the potential wave slap on the hull and cable strum.](image)

The method of suspending a hydrophone from a free-floating boat (Figure 11) has been employed in a number of recent studies with the intention of minimising the flow and self-noise (Bailey et al, 2010; Bedford & Fortune 2010; Kongsburg, 2010; Senior et al, 2008; Nedwell & Brooker, 2008; Nedwell et al, 2004).

However, other potential sources of self-noise can be introduced using this method, such as the chop of water against the boat hull. Additionally, the opposing action of wind against tide can cause the hydrophone to be pulled through the water and this movement could introduce cable strum.

The natural progression from using a boat as a free-floating platform is to use an autonomous free-floating platform (i.e. drifting sensors). This concept is not new; drifters have commonly been used to collect a variety of environmental data. For example the Argos float has been used to collect conductivity (salinity) temperature and
depth (pressure) data (Roemmich et al, 2004), and free-floating drogues have been used for the Lagrangian measurements of ocean currents (Niiler et al, 1995).

Expendable drifting hydrophones ‘Sonobuoys’ were developed by the military for anti-submarine warfare and were designed to be deployed from an aeroplane and to transmit data via a radio signal. Although their primary purpose was to detect submarine signals, they have also more recently been used to assess underwater background noise levels (Delbalzo, 2011). Interestingly, Delbalzo (2011) stated that the data from the drifting sensors gave a better representation of the background noise in comparison to discrete measurements.

Therefore, for the purposes of this thesis, autonomous drifting hydrophones were the preferred platform to enable the measurement of underwater background noise in tidal-stream environments.

2.2 The ‘Drifting Ears’

The data presented in this thesis were collected using the ‘Drifting Ears’ platform that was developed for a tidal-stream site noise mapping study conducted by the Scottish Association for Marine Science for the European Marine Energy Centre (EMEC) which was funded by the Highlands and Islands Enterprise (HIE) (Wilson & Carter, 2008).

The ‘Drifting Ears’ are autonomous drifting hydrophones designed to track a parcel of water within the tidal-flow thus minimising the influence of flow and self-noise in an energetic environment. Multiple Drifting Ears were used to collect the data from the case study sites.

The Drifting Ears platform (Figure 12) comprised of a floating waterproof housing (‘pod’) which housed the power supply, digital recorder and GPS unit. The pod was attached to the drogue using rope thick enough to minimise strumming, and between the pod and buoy, surface floats were used. Strumming creates noise and is caused by the passage of water flowing past the rope. An area of low pressure is formed behind the rope and as the water rushes in to fill this area, vortices are formed in the wake resulting in noise generation.

The hydrophone cable was attached to the rope but with enough slack such that any pulling on the rope for retrieval would not strain the cable. Between the buoy and drogue, shock cord was attached to the rope to minimise any vertical motion from
surface waves being transferred to the hydrophone. Weights were also attached to the bottom ring of the drogue to improve stability in tidal-stream conditions and care was taken that there was no ‘clanging’ from any of these weights.

![Diagram of the SAMS 'Drifting Ears' and a photo of the platform on deployment.](image)

**Figure 12 -** Diagram of the SAMS 'Drifting Ears' and a photo of the platform on deployment.

The pole and flag was used for visual tracking and a counter weight was attached to the bottom of the flag pole for vertical stability. The GPS was placed in a small Peli-case on the top of the pod, the pods were not tracked in real time but positional data were logged in the unit to be downloaded after retrieval.

The batteries and the digital recorder were housed in the pod. The sound files were recorded on compact flash cards as .WAV files. Power was provided by a 12V battery for the hydrophone and three D-cell batteries generating the 4.5V required for the M-Audio Microtrack digital recorder. The Microtrack’s internal battery did not hold its charge for long enough without plugging in; therefore in the field we needed to be able to replace batteries. We were not able to take charge from the 12V battery using a step-down voltage converter as this was found to generate a high frequency signal.

The hydrophones used were the commercially available C54XRS Cetacean Research Technologies (Seattle, USA) compatible with the M-Audio Microtrack 24/96 digital recorder (Table 1). The GPS units were Garmin ‘etrex’ handheld devices, powered by standard AA alkaline batteries.
Table 1 - Manufacturers published specification data for the hydrophones, GPS and digital recorder used in the drifting hydrophone equipment.

<table>
<thead>
<tr>
<th>Hydrophones</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Make</td>
<td>Cetacean Research Technologies (CRT, Seattle, USA)</td>
</tr>
<tr>
<td>Linear frequency range (±3dB)</td>
<td>0.020 - 44 kHz</td>
</tr>
<tr>
<td>Usable frequency range (+3/-12dB)</td>
<td>0.009-100 kHz</td>
</tr>
<tr>
<td>Transducer sensitivity</td>
<td>-185 dB re 1V/µPa</td>
</tr>
<tr>
<td>Preamplifier gain</td>
<td>20dB</td>
</tr>
<tr>
<td>SPL equiv. Self-noise at 1kHz</td>
<td>46 dB re µPa</td>
</tr>
<tr>
<td>Omnidirectional below</td>
<td>10kHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GPS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Make</td>
<td>Garmin 'etrex' handheld</td>
</tr>
<tr>
<td>Position recorded</td>
<td>Every 3 seconds</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Digital recorder</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Make</td>
<td>M-Audio Microtrack 24/96</td>
</tr>
<tr>
<td>Sample rate</td>
<td>96 kHz</td>
</tr>
<tr>
<td>Bits</td>
<td>16</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>101 dBA</td>
</tr>
</tbody>
</table>

A sampling rate of 96 kHz was selected to enable the drifters to record noise frequencies up to 48 kHz, bit depth was 16 bits and the published dynamic range was 101 dB(A). Underwater noise was recorded in mono and the GPS positional data were recorded every 3 seconds to map datum WGS 84.

The drogue (and hydrophone) was set to track the tidal current at a depth of 5m. This depth was initially chosen because, at the time the drifters were developed, it was thought that the clearance depth between tidal-stream devices and the sea surface would be in the order of 10 m. Therefore a depth of 5 m would allow for repeat surveys pre and post installation. Comparable surveys have been conducted at similar depths (Bailey et al, 2010; Bedford & Fortune, 2010). Matzner et al (2010) suspended hydrophones at depths of 5 and 7m in a water depth of 30m, whereas Robinson et al (2007) deployed hydrophones mid-water column in very shallow waters (up to 14 m).

Underwater background noise is depth dependent in the deep waters (> 200 m depth) (de Jong et al, 2011) but it has been suggested that noise levels in shallow seas are independent of hydrophone depth or water depth and depend rather on wind speed (Au & Hastings, 2008; Kuperman & Ferla, 1985). Therefore, even though many of the upcoming tidal devices would be placed in deeper water, I decided that retaining the hydrophone depth at 5 m was satisfactory for the purposes of this thesis.
2.2.1. DRIFTING EARS DEPLOYMENT

For each survey the survey boat was positioned upstream of the target survey area. Prior to release, the operator ‘spoke’ the time to the hydrophone, therefore recording the absolute time. This allowed synchronisation with the GPS units thus enabling the recordings to be located in time and space. The drifters were then released overboard one at a time, at deployment locations across the survey area designed to achieve the best possible spatial coverage (Figure 13 - Photo of drifting hydrophones deployed across the Kyle Rhea).

The drifters were deployed from small powerboats (both rigid inflatable and small commercial craft, Figure 14).

Once all drifters were in the water, the boat engine(s) and electronics were switched off and the boat and drifters were allowed to drift through the intended survey area. Once the drifters had drifted the extent of the survey area, the boat was restarted to retrieve them. This procedure was repeated for both ebb and flood flows, and over a range of tidal-stream flow speeds. The time taken for each run varied depending on the flow speed, but on average was approximately 20 minutes.

At the end of every run, the pods were opened to stop each recording and the batteries were changed if necessary, and then a new recording was started in preparation for the next deployment.
Figure 14 - Stowage of drifter from (a) MV Challenger (Orkney) and (b) RIB Usige (Sound of Islay and Kyle Rhea) and (c) the deployment of drifters in the Fall of Lora pre survey trials using the SAMS dive RIB (Photos b&c: B.Wilson).
2.3 **METHOD OVERVIEW**

In this section, I detail the acoustic data acquisition and processing methods used in this thesis as summarised in the following flow diagram (Figure 15).

![Flow diagram of data acquisition and processing methods](image)

*Figure 15 - Processes in background noise-mapping expressed as a flow diagram detailing the steps in data acquisition and processing.*

The steps detailed in the following sections include the calibration of the reference hydrophone, against which the drifting hydrophones are compared and adjusted in line with the reference hydrophone (section 2.3.1.1). This is done for two reasons; so that ‘absolute’ underwater background noise levels can be presented, and so that all the data from the drifters will be consistent.

The rationale behind the sound file sample file selection (section 2.3.2) is described, I then detail the processes involved in determining the broadband sound levels (section 2.3.3) for use in the background noise-maps (section 2.3.4) and the subsequent
frequency analysis both as power spectral density graphs and in third octave levels (section 2.3.5).

2.3.1 HYDROPHONE CALIBRATION

So that ‘absolute’ underwater background noise levels can be presented, it is necessary to understand and account for the performance of the complete measurement system. This is done by calibration, which effectively sets the correct scale for the measurements. Each hydrophone, even those of the same make and model can have slightly different responses to the same sound pressure. Therefore calibration is important if comparable absolute levels are required, particularly when using data from more than one hydrophone. The calibration details the system’s response to a sound source at a range of frequencies.

One metric of hydrophone calibration is its sensitivity. This is the ratio of the output voltage and the pressure of the water surrounding the hydrophone, so it is a measure of the hydrophone’s performance. Sensitivity has advantages and disadvantages, generally, the more sensitive the hydrophone the more fragile it may be (Coates, 2006). It is not necessarily best practice to use the most sensitive hydrophone, as this depends on the focus of the study (e.g. a study measuring a loud impulsive noise such as pile-driving will not need a very sensitive hydrophone).

Hydrophone sensitivity is expressed in decibels with units of volts/Pascals. The reference hydrophone was a Brüel & Kjær (B&K) hydrophone (type 8104). The B&K manufacturers specifications quote the voltage sensitivity as -208.1 dB re 1V/µPa (see section 2.2.2.1). The Cetacean Research Technology’s (CRT) hydrophones (model C54XRS used for the drifters) quote an effective sensitivity of -165 dB re 1V/µPa. The negative sensitivity levels can cause confusion - for clarity – the less negative, the more sensitive the hydrophone.

Sensitivity is frequency dependent; therefore it is preferable to use a hydrophone with a flat frequency response as this means that all sounds in the frequency range will be detected at the same level. Figure 16 illustrates the difference in frequency sensitivity between the two hydrophone types used in this study. It can be seen that the C54XRS (drifters) is more sensitive than the B&K 8104 reference hydrophone, but that the C54XRS does not have as flat a frequency response as the B&K, and that the C54XRS
manufacturer has presented frequency response data at much lower frequencies than the B&K manufacturer.

![Frequency Response Graphs](image)

**Figure 16** - Frequency response graphs using manufacturers published data for the B&K 8104 and the C54XRS hydrophones used for this thesis.

The focus of this study was to investigate the background noise levels in shallow water tidal-stream areas; it is thought that shallow water environments could be both quieter and noisier than deep water areas (Richardson *et al.*, 1995) therefore as potentially quiet background noise may be recorded, a sensitive hydrophone was chosen for the task (as well as other factors such as compatibility with the digital recorder and cost).

There are various methods of calibration; the method used depends largely on the intended use of the hydrophone *i.e.* the frequency range of interest. The range of frequencies that can be tested depends upon the calibration platform. In laboratory tank facilities, the range is limited by the dimensions of the tank; for example, a tank of 5 m diameter and 5 m deep will sustain a frequency range of 1 kHz to 20 MHz ([www.npl.co.uk](http://www.npl.co.uk)) due to the dimensions of the tank and the projected sound waveform length. Larger open-water facilities, such as the facility the National Physical Laboratory operates in Wraysbury, Middlesex ([www.npl.co.uk](http://www.npl.co.uk)) enable the calibration of frequencies from 250 Hz upwards. Alternatively, once the hydrophone has been calibrated, a low frequency tone can be emitted by a ‘pistonphone’ to set the absolute value.

Tank rental is expensive, as is the purchase price or hire of a pistonphone, therefore for the purposes of this thesis, the sensible solution was to have a reference hydrophone
calibrated commercially and then to subsequently calibrate the drifting hydrophones in-house by comparison with this reference.

2.3.1.1 Reference Hydrophone

The ‘reference’ hydrophone system comprised of a Brüel & Kjær (B&K) hydrophone – type 8104-D-300 (serial number 2486967) a B&K Nexus conditioning amplifier 2692, a Sound Devices 744T digital audio recorder, and used a combination of bespoke Matlab© code (Mathworks Inc) and commercially available signal processing software (Avisoft SASLab Pro – Avisoft Bioacoustics version 5.2, Berlin) (Figure 17).

![Schematic of the 'reference' recording system, comprising the hydrophone, amplifier, digital recorder and computer analysis.](image)

The reference hydrophone was calibrated to Accredited International Standards at the National Physical Laboratory (NPL) open-water test facility in Wraysbury, Middlesex in March 2010 and January 2011. The calibration of our reference recording system was a two-stage process, the first stage was what is known as an end-of-cable transducer calibration which detailed the response of the hydrophone itself, and the second stage was a complete system calibration. The second stage was important as all components of a recording system can have an effect on the voltage level measured, therefore it is important to know the response of the system as a whole to a sound. In this calibration the measured sound level was compared to the known source level generated by NPL system. This procedure allowed me to assess absolute sound levels and the system response as a whole.

The receiving sensitivity plot of the B&K reference hydrophone is shown in Figure 18 and it can be seen that the NPL calibration extends the range of calibration into lower frequencies and also shows that there is some variation between the manufacturer’s data and the subsequent calibration (+0.9/-1.5 dB). The flat frequency response range is
from 0.25 kHz to 25 kHz with +0.7/-1.6 dB variability. Sensitivity increases by approximately 4dB between 40 kHz and 70 kHz after which the sensitivity reduces significantly.

![Hydrophone Sensitivity Chart](image)

*Figure 18 - Plot of the receiving sensitivity of the B&K reference hydrophone, the manufactures calibration data is shown by the blue line and the NPL end-of-cable calibration data is shown in pink.*

The second stage of the calibration process, the system check, was performed in order to determine the sensitivity of the system as each component processes the signal. NPL generated known sound levels through a range of frequencies from 25 Hz to 20 kHz inclusive. The water temperature was 4.5 degrees Celsius. Temperature can also affect the measurements, it is therefore better to calibrate in water temperature similar to the temperatures within which the field measurements will be made, although this is not always possible.

The NPL test tone generation system (Figure 19) consisted of a Vector Signal Analyser (Agilent 89410A s/n US43310229), an Arbitrary Waveform Generator (Agilent 33120A s/n MY40024204), and Amplifier (B&K 2713 s/n 965216), a 40 dB Attenuator (s/n WL249), a 165 mm Sphere Projector (ITC 1007 s/n 186) and a mounting bracket (number 56).
Figure 19 - Schematic of the equipment set up at the NPL open-water facility to generate tones at a known frequency and level to be recorded and analysed by the B&K reference hydrophone

NPL supplied the sound pressure levels emitted by their system for comparison with the reference hydrophone system recordings and analysis. The reference hydrophone sound pressure levels were calculated for each frequency using the equations as advised by Brüel & Kjaer (Pers. Comm. McTaggart B&K, 2010) as follows;

\[ \text{LPa} = \text{RMS voltage/nexus gain setting} \]

\[ \text{SPL}_{\text{RMS}} = 20 \log_{10} \left( \frac{\text{LPa}}{0.000001} \right) \text{ dB re 1 µPa} \]

The sound pressure levels (SPL) from the reference hydrophone system were in good agreement with the NPL notified levels (Figure 20) from 2 kHz and above, but below 2 kHz the levels obtained from the reference system were higher than the NPL notified levels. This difference highlights the effect a recording system has on the signal and illustrates the importance of considering the calibration of the entire system rather than the hydrophone alone.

Figure 20 - Comparison between the sound levels generated by NPL and the levels determined from the reference hydrophone system.
The calibration and system check meant that the performance of the reference hydrophone was known. The difference in the output for frequencies less than 2 kHz (Figure 20) between the sound levels generated by NPL, and the reference hydrophone system, resulted in an known SPL adjustment for these lower frequencies. This was necessary in order to calibrate the reference system prior to the calibration by comparison for the drifter hydrophones. If this was not considered, it would mean that the SPL levels returned for the lower frequencies would be artificially high.

2.3.1.2. DRIFTING EARS CALIBRATION BY COMPARISON

The individual drifting hydrophones were calibrated by comparison with the reference hydrophone prior to each survey. All hydrophones were deployed at the same time in open water from the pontoon in Dunstaffnage Bay (adjacent to the Scottish Association for Marine Science in Oban) and coincident recordings were made. The recordings were compared to the relevant hydrophone levels to determine the adjustment required to bring the drifters in line (Figure 21); this adjustment was subsequently applied to the drifter sound files recorded during the survey.

![Graph showing reference hydrophone levels (control) and unadjusted drifter levels (D2).](image)

Figure 21 – An example of a comparison graph showing the reference hydrophone levels (control) and the unadjusted drifter levels (D2).

One practical advantage to calibrating the drifting hydrophones by comparison to a reference hydrophone was highlighted during the survey period. In the first year of surveying, two of the CRT hydrophones failed for unknown reasons. As the comparison calibrations were performed before all deployments, it was not important if the individual transducers were different for different surveys. It is possible that the sensitive hydrophones were not quite robust enough for either the deployment
methods (see section 2.2.3 and Chapter Seven) or for travelling with the tidal-stream flow. SAMS are developing ‘Drifting Ears – Mark II’ based on the lesson learnt from the operation of these drifters. However, updated versions were not available within the timescale of my thesis.

Two calibration procedures were conducted using the same hydrophone transducers a month apart and in the same location but under slightly different weather conditions. Both were done at slack water and with no precipitation. During the first calibration there was no wind, but on the second there was a light breeze. The comparison of the paired adjustment factors for each frequency generated (Figure 22) suggests a good level of stability in the hydrophones themselves and in the procedure.

![Figure 22](image_url)

**Figure 22** - Comparison of drifter adjustment factors used in two separate calibration-by-comparison procedures.

### 2.3.2 Sample File Selection

The sound data recorded using this drifter methodology are a continuum of data, therefore in order to analyse and map the sound levels, sample sections of file needed to be cut into manageable segments. There were two aspects of the sample file selection that needed to be considered, the first was the length (in time) of the segment itself and the second was the geographic location of the segment files. The choice of these parameters was to select discrete samples, *i.e.* samples with no overlap either in time or space.
2.3.2.1. Sample file temporal length

There is no standard averaging time for the analysis of sound file segments for continuous noise assessment. For impulse or impact assessment the averaging time is important. For example, if the focus of the study is to assess the sound level of a short-lived impulse sound, the method would be to measure the peak of the sound for its duration. If an average was measured over a longer temporal period than the sound duration, then the resulting sound level would be lower than the impulse level, and therefore not representative. Another example might be if the focus was to understand the level of exposure a receptor (e.g. a marine mammal) might have to a sound source, then the sound exposure level is assessed, which accounts for the length of time of exposure.

Table 2 details selected examples of studies and the sound file duration that was assessed. However, when the sound of interest is the continuous background ambient noise levels, is the temporal length of the segment of relevance?

For this thesis, I therefore considered the relevance of the duration of the averaged time for the sample files by considering a sample sound file (recorded in the Fall of Warness, one of the tidal-stream case study areas, see Chapter Three for more detail). The file was repeatedly analysed at a selection of segment lengths (2, 10, 20, 30, 60, 90, and 120 seconds).

The sample file covered a drift spatial length of 2.8 km with the duration of 21 minutes. The file was cut into 29 sample file start locations (Figure 23) at a separation distance of 150m (see following section 2.2.4.2 for details). Using these start locations, sound files were cut for the selected temporal lengths. The broadband sound pressure level was calculated for all files.

Table 2 - Example studies detailing the sound averaging window used.

<table>
<thead>
<tr>
<th>Sound file segment length (seconds)</th>
<th>Study focus</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>Ambient noise &amp; communication behaviour in humpback whales</td>
<td>Dunlop et al, 2010</td>
</tr>
<tr>
<td>15</td>
<td>Underwater noise, offshore wind turbines, impact zones</td>
<td>Tougaard et al, 2009</td>
</tr>
<tr>
<td>30</td>
<td>Underwater noise, offshore wind turbines, potential effects on marine mammals</td>
<td>Bailey et al, 2010</td>
</tr>
<tr>
<td>60 and 8</td>
<td>Ambient noise, tidal site, Puget sound</td>
<td>Basset et al, 2010</td>
</tr>
<tr>
<td>1</td>
<td>Ambient noise, offshore wind farms</td>
<td>Nedwell et al, 2004</td>
</tr>
</tbody>
</table>
Figure 23 - Map of the selected acoustic recording (Fall of Warness) used to investigate the effect of the length in time of the sound segment used on the sound levels calculated and the variability of these levels throughout the recording. The total length of the run was 2.8 km with 21 minute duration. The average speed of the drifter during the run was 2.2 m/s. (a) Location of the drifter deployment, and (b) drifter retrieval location.

Figure 24 illustrates that the average sound level for the entire run at all temporal segment lengths are broadly similar, but that the levels calculated for the shorter segment lengths are more variable.

Figure 24 - Box and whisker plot illustrating the spread of sound pressure levels measured at different segment lengths during trials at the Fall of Warness. N=29. The lower and upper whisker represents the lower and upper quartiles respectively, thus the minimum and maximum levels measured; the box represents the 25th to the 75th percentile, with the mean value shown by the line in the middle of the box.
The longer sound segment length (in time) smooths the SPL profile greater than the shorter sound segments lengths (Figure 25). The intention behind the mapping of the background noise is to investigate if there is any spatial pattern to the noise field; the noise of interest here is a continuous noise rather than an instant or short-lived sound, but there is a balance to be achieved in smoothing out the data and representing the spatial variability.

Southall et al (2007) state that the average time used for analysis “is any convenient period sufficiently long enough to permit averaging the variability inherent in the type of sound”. Extensive smoothing will hide some of the spatial variability, as can be seen in the 90 and 120 second profiles in Figure 25.

Mapping is a combination of a temporal and spatial component as the drifters are in a different place at a different time. Therefore, the best compromise is to attempt to capture the inherent variability of the area but keep the computational effort realistic.

As well as perhaps over-smoothing the data, segments cut at 90 and 120 seconds overlapped temporally and spatially and therefore this option was rejected. The one and ten second samples were more variable than the other options, and therefore might be susceptible to an over-reliance on a short-lived sound if it occurred coincidentally with the selected sample. Also, the use of a one second segment would mean only 29 seconds would be analysed in a file lasting 29 minutes and there is the potential that using a one or ten second segment window would be more likely to give a variable representation of the same file dependent on which start points were chosen. Both the...
30 and the 60 second segments seem to afford good spatial and temporal resolution. Both capture the variability of the run, but smooth out the potential instantaneous spikes. It is likely that both would be acceptable for this purpose, but the 60 second option was chosen in preference because, based on these data, more of the run was averaged spatially (as well as temporally) without overlapping.

2.3.2.2 Sample file location
The locations of the sample files was determined by considering a series of transect lines across the survey area (approximately perpendicular to the direction of current flow) and extract sample file segments where the drifter track crossed each line (Figure 26). The next step was to determine what the most appropriate separation distance was between the transect lines, again to avoid segment file overlap, but at the same time to be able to sample that area as representatively as possible.

![Figure 26 - Schematic of a sample file selection transect line set up in a fictional area. Blue lines represent the drifter track, the black lines - the grid (should be equidistant), the red dots - the location of the sample file and the tan areas on either side represent land (not to scale).](image)

An example recording was selected at random from the Sound of Islay data set. The recorded track was 2857 m long and it took the drifter approximately 24 minutes to transit the area. Sample files were selected from the track at separation distances of 100 m, 150 m, 200 m and 300 m. The 100 m and 300 m distance options were rejected because there was too much potential for overlap in time and location segment at 100m separation distance (by cutting end to end sections for this track the distance was 119m) and there were too few sample files at the 300m separation (only nine along the track). A 200 m separation distance would have worked, however the 150 m transect separation distance was chosen because this gave the most sample file locations without overlap.
2.3.3 SOUND FILE ANALYSIS

The use of different methods of describing underwater noise and the associated different units in the literature presents an issue for the reporting and comparison of underwater noise levels. At the time of writing there are no standardised methods for measuring and reporting underwater noise (Van der Graaf et al., 2012) as the units and methods are usually tailored to the focus of each individual study. This issue is currently gaining attention as it is recognised that more comparable methods are required in the current climate of increasing human activity in the seas (IQOE draft 2012). A recent example is the report written by de Jong et al. (2011) who have addressed standardisation in relation to the offshore wind industry and there is on-going international collaborative work within the acoustics community regarding standardisation (Pers. Comm. S. Robinson, 2009).

The Sound Pressure Level (root-mean-squared RMS) metric (referred to as SPL hereafter) was used for the mapping of the background noise levels, using the standard equation (Richardson et al., 1995):

\[ \text{SPL (dB re 1 µPa)} = 20 \log_{10} \left( \frac{P_{\text{RMS}}}{P_{\text{ref}}} \right) \]

- \( P_{\text{RMS}} \) is the RMS measured sound pressure
- \( P_{\text{RMS}} = \text{root-mean-squared - all the values squared, then take the average of the squared values, the take the root of the average} \)
- \( P_{\text{ref}} \) is the underwater pressure reference of 1 µPa

The background noise-maps generated in this thesis are a 2D representation of a 5D environment (latitude, longitude, depth, time and frequency). The maps generated represent measured absolute sound pressure levels for each sample point at the depth of 5m. The SPL metric above was used as it is a useful single average over the frequency range measured. However, it does not in itself provide any information relating to the spectral content of the signal. The spectral content is however, highly relevant when considering marine life, as the sounds detected (heard) by animals are frequency dependant. Therefore, as well as presenting maps of the broadband SPL, I also filtered the sound files into frequency band categories using audio-editing software (Cool Edit\textsuperscript{©}) (Table 3).
Table 3 - The frequency band categories used for the background noise-maps.

<table>
<thead>
<tr>
<th>Frequency band category</th>
<th>Frequency band</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>Up to 48 kHz</td>
</tr>
<tr>
<td>Low</td>
<td>Up to 1 kHz</td>
</tr>
<tr>
<td>Med</td>
<td>Between 1 - 10 kHz</td>
</tr>
<tr>
<td>High</td>
<td>10 - 48 kHz</td>
</tr>
</tbody>
</table>

The filtered categories were chosen somewhat arbitrarily, but the intention was that the maps generated using these filters would highlight any frequency dominance within the entire smoothed recorded range. Previous work suggested that there was a dominance of different frequencies in different locations (Wilson & Carter, 2008) which would be smoothed out within the broadband SPL. Within this earlier work, maps were generated for specific frequencies and similarities were seen between the 50 & 100 Hz, the 1, 2, & 5 kHz and for the 10 & 20 kHz maps.

Also considered in the selection of these filtered bands were the known audible frequency ranges of relevance to fish and common coastal marine mammals (see Chapter Six for more detail) and the known frequencies of abiotic noise contributors (see Chapter Four for more detail).

Figure 27 illustrates hearing curves for selected fish and marine mammal species (see Chapter Six). The curves are an indication of the hearing thresholds; therefore if a sound has the same frequency as the animals hearing range and is above the threshold (the plotted line) the sound is audible. The region of greatest auditory sensitivity (best hearing) is the lower area of the curve. The categories allocated above are denoted on the graphs by the dashed lines.

If the known abiotic noise contributors are also considered (Figure 28), low frequency noise below 1 kHz is mainly caused by vessel (traffic) noise and wind noise in very shallow water, as well as any flow noise and/or cable strum. Surface agitation sediment noise, rain and biological noise span all three of the categories chosen (see Chapter Four for more detail).
Figure 27 - Hearing thresholds (audiogram) of selected fish and marine mammals summarised by Nedwell et al, 2004 with the broadband category filters shown by vertical dashed lines [Cod (1) (Offutt, 1974); Cod (2) (Chapman & Hawkins, 1973); Haddock (Chapman, 1973); Herring (Enger, 1976); bottlenose dolphin (Johnson, 1967); harbour porpoise (Kastelein et al, 2002); Harbour seal ((1) (Kastak et al, 1998)); ((2) (Terhune, 1988))].
In general terms, the low filtered band could be influenced by traffic noise and wind noise and be of relevance to fish, while the mid and high filtered categories are likely to reflect sea state, rain, sediment saltation and potentially snapping shrimp (small crustaceans, see section 4.1.1.2 for more detail) and be relevant to marine mammals. This is however a broad-brush generalisation and frequency bands are likely to have a degree of overlap.

2.3.4 Steps taken to map the background noise levels

The process taken to generate the background noise-maps (Chapter Three) was as follows. The drifter files were initially ‘topped and tailed’ to remove the unusable beginning and end of the recordings (prior to deployment and retrieval – i.e. boat noise). The spoken time (and engine on and off times) were used to time-stamp the recordings. The file was then linked to the GPS using the time-stamp. The sample files start-points were then selected by GPS location using the designated transect lines and the 60 second sample files were then cut from the drifter recording and saved for analysis.

Once all sample files were cut, the files were checked visually for contamination, where this was suspected the file was checked aurally. In addition, random files were listened to, to ensure they were clean recordings. Where contamination was found it was removed using an audio-editing software (Cool Edit©) if discrete, but if it was extensive (i.e. a reduction of the usable portion of the file to near 30 seconds, chosen as the limit as the output of a 30 second file was comparable to a 60 second file (section 2.2.4.1)) then the start location of the file was either repositioned, or if this was not practical due
to overlap with another file for instance, then the file was discarded. The complete
discard of a file was rare, as it usually could be edited or repositioned.

Using Matlab (www.mathworks.co.uk), the SPL levels were determined for each sound
file segment in batch files, the low frequency band was adjusted in line with the findings
of the NPL system check (see section 2.2.2.1 above) by including an averaged reduction
in the SPL level to bring it in line with the NPL reference levels.

For each survey site the data were pooled to enable the generation of the maps (see
Chapter Three for more detail into the rationale for pooling the data). The calculated
SPLs were then input into ArcGIS (www.esri.com) and from there the sample file
locations were mapped and the SPL data interpolated into a contour map illustrating the
sound levels measured. Using the ‘Spatial Analyst’ tool the data were interpolated to a
raster layer. The interpolation method used was Ordinary Kriging, using a spherical
semivariogram model with a variable search radius type and a search radius of 12
points. This tool generated a contoured raster layer, which then needed to be confined
to the survey area. This was done using a polygon shapefile with its limits set to the
extent of the survey area, followed by the use of ‘Hawths’ analysis tools
(www.spatalecology.com) to clip the raster layer to the shapefile polygon. This resulted
in a final layer containing the sound level contour plots limited to the survey area. The
sound level contours were then plotted against chart layers obtained from Edina, under
university licence (Edina.ac.uk/digimap).

2.3.5 Frequency Spectral Analysis

The development of the most appropriate methodology for calibrated spectral analysis
was a considerable challenge and took a significant amount of time during the PhD
project. The software available to me was Avisoft SASLab Pro (Avisoft Bioacoustics
version 5.2 Berlin). This software was chosen at the beginning of the project because it
had been used in projects conducted by the University of Aberdeen (Thompson et al,
2010; Bailey et al, 2010) and their methodology was available to me to learn from. This
methodology worked well for the individual B&K reference hydrophone; however it was
not able to cope with multiple hydrophones and the batch processing that would be
required. A further complication for the use of this software was the incorporation of
the drifter calibration-by-comparison methodology.
I was aware from an early stage that it would be possible to generate code (e.g. within the Matlab platform) to perform the spectral analysis required in a more elegant method. During a training programme at the National Physical Laboratory (NPL) (Seiche Basic Underwater Acoustics course, 2009) I broached the subject with staff. Unsurprisingly, as NPL was a commercial organisation, their coding was not available for public use. I also had conversations with Brian Polagye from the University of Washington (during commercial work for Open Hydro 2010) and he kindly forwarded the code that he used for spectral analysis, but unfortunately, I could not make it work for my recordings. Again, the problem was the method of calibration used in this project. During my final year I made good contacts, who would have been able to advise me in this regard, but by then, for this project, it was too late.

The way my project was funded meant that the only way that data could be gathered for use in my thesis was to undertake commercial projects; data acquired for these projects could then be used for my thesis also. This unfortunately restricted the amount of time available to me to learn the programming required for me to design bespoke code. I sought advice from a Matlab expert within SAMS for help in this area, but unfortunately his work priorities meant that advice was not given.

The result was that the analysis was performed manually for each sound segment file using the Avisoft software. Using the calibration recordings I determined the calibration adjustment necessary for each drifting hydrophone. Default (i.e. non calibrated levels) were determined using Avisoft, and these were then exported into Microsoft Excel where the calibration adjustments were applied.

The advantage of this method was that every sample file was observed, but the disadvantage was that it was time consuming which ultimately limited the number of files that could be assessed.

2.4 SUMMARY AND DISCUSSION

The level and characteristics of underwater background noise in shallow coastal seas has gained increased attention recently due to our growing use of coastal waters, and increasing concern about the potential impact of anthropogenic noise. The drifting hydrophone methodology described here is tailored for the challenging tidal-stream environment and is a relatively low-cost method of generating data to inform the current gap in knowledge.
The drifters were developed prior to this thesis for a project that I was involved in for the European Marine Energy Centre (Wilson & Carter, 2008), but the calibration and analysis methods described here were developed during my work.

There is no standard methodology for the analysis and the presentation of underwater noise levels although there are well established calibration and analysis methods. Much of the existing information relating to inshore coastal underwater noise levels has been conducted for commercial purposes, and therefore has not been readily available for scientific analysis.

The methods presented here were born out of necessity, as in-house individual calibrations were not possible. However, by using a commercially calibrated reference hydrophone, this is a relatively low cost method that can add valuable information to the understanding of underwater noise levels in coastal tidal-stream environments (as multiple commercial calibrations would be costly). In addition, the benefit of calibration-by-comparison was that it was possible to calibrate the drifters prior to every survey, which accommodated the repair and replacement of some of the transducers over the season without incurring extra cost.

The signal processing methodology used in this study is laborious and inelegant, but it has worked for this project. Better coding would allow for significant refinement and this would be essential if greater amounts of data were to be analysed.

The drifting hydrophone methodology affords excellent spatial coverage of the survey areas, together with effectively eliminating the influence of flow noise as the hydrophone is drifting with the tidal-stream in comparison to static deployed hydrophones, and reduces the potential wave slapping and cable strumming in comparison to a drifting boat deployment. However, this method is labour intensive in real-time by repetitively deploying and recovering the drifters. The data gathered are related to a relatively short time frame, therefore it is important to note that this is a snapshot method rather than one intended to observe trends over longer time periods.

The broadband noise-maps presented in the following chapter are a useful overview of the sound landscape during each survey, and as mentioned earlier this method averages the data over the survey period and thus blurs the temporal signal within the survey timescales (hours – days). This temporal-spatial relevance will be further explored in Chapter Seven.
The background noise-maps generated in this thesis are based on actual measurements rather than models, and to my knowledge represents the first time this has been attempted.
Chapter Three – Background noise-mapping of Kyle Rhea, the Fall of Warness and the Sound of Islay: Three tidal-stream case study areas

3.1 Introduction

There is very little information available regarding the levels of background noise in shallow water environments in general (Bailey et al., 2010) and very little data relating to tidal-stream areas that are of interest to tidal energy developers. With increasing focus on marine renewables and their environment, this data gap is beginning to gain attention, but mainly in connection to the offshore wind industry. In this section underwater background noise-maps are presented, generated from measurements made using the drifting hydrophone methodology (Chapter Two) for three tidal-stream case study areas, Kyle Rhea, the Fall of Warness and the Sound of Islay (Figure 29). This section consider thesis hypothesis 1) and explore research questions 1) and 3).

Figure 29 – Map of Scotland detailing the locations of the three tidal-stream case study areas, the Fall of Warness, Kyle Rhea and the sound of Islay (Edina Digimap).
Chapter Three

Noise mapping

Thesis hypothesis:

1) Tidal stream locations are currently loud environments.

Research Questions:

1) What are the noise levels in areas suitable for tidal energy extraction and how varied is the underwater noise field?

3) What effect does the tidal flow have on the background noise?

3.1.1 BACKGROUND NOISE-MAPPING

The background noise-maps presented here are a visual representation of the measurements taken at the tidal-stream locations during the period of each survey. The drifting hydrophone methodology (Chapter Two) produces good spatial resolution, but relatively poor temporal resolution in terms of assessing differences over time, as the surveys were conducted over a period of a few days, rather than an extended period over the seasons. Although this is a ‘snapshot’ of the sound pressure levels in these areas, the resulting noise-maps are an informative spatial representation of the character of the acoustic environment of shallow water tidal-stream areas.

This chapter will describe the noise levels in areas suitable for tidal-energy extraction and illustrate the variability within and between the case-study areas. Also the effect of the tidal flow on the noise levels will be considered, and whether the main drivers of the variability can be distinguished.

3.1.2 TIDAL-STREAM CASE STUDY AREAS

The most northerly site is the Fall of Warness in Orkney (59° 8’N 02° 49’W, Figure 29) and is the location of the European Marine Energy Centre (EMEC) tidal-stream test facility. EMEC was set up in 2003 to provide full-scale, grid connected testing facilities for marine renewable developers. The Fall of Warness has seven tidal-stream testing berths at depths ranging from 12 m to 50 m where developers can connect their test devices to the UK grid. The site is on the west side of the Island of Eday and is approximately 4 km long and 2 km wide. Tidal-stream flow speeds can reach up to 4 m/s at spring tides. Marine life known to pass through the area includes harbour and grey seals (Phoca vitulina, Halichoerus grypus) and harbour porpoise (Phocoena phocoena), other transitory species include white beaked dolphin (Lagenorhynchus...
albirostris), minke whale (Balaenoptera acutorostrata) and orca (Orcinus orca) (www.emec.org.uk).

Moving southwest, Kyle Rhea (57° 14’N 05° 39’W, Figure 29) is a narrow strait between the Island of Skye and the mainland coast of Western Scotland and is approximately 4 km long by 0.5 km wide. Tidal flow speed can reach up to 2.3 m/s at springs, and travels northwards on the flood tide and southwards on the ebb. Two developers have identified this area for development; Marine Current Turbines (MCT) and Pulse Tidal. MCT are planning an array of 4 SeaGen devices just north of the ferry crossing with a combined capacity of 8MW (www.seagenkylerhea.co.uk). Pulse Tidal have considered an area just south of this survey area (www.pulsetidal.com). Marine animals frequently in the area include otters (Lutra lutra), harbour and grey seals, harbour porpoise and bottlenose dolphins (www.forestry.gov.uk).

The Sound of Islay (55° 50’N 06° 06’W, Figure 29) is a strait between the islands of Islay and Jura on the west coast of Scotland. The narrowest section of the sound is approximately 11 km long by 1 km wide and experiences a tidal flow speed of over 3 m/s at springs. Scottish Power Renewables have gained consent for an array of ten 1 MW tidal-stream devices to be installed just south of Port Askaig. The proposed device is the Hammerfest Strøm HS1000 device (now Andritz Hydro Hammerfest) that is currently being tested at EMEC (2012). Grey and harbour seals are seen regularly in the area, but cetaceans (harbour porpoise, bottlenose dolphin) otter and basking shark (Cetorhinus maximus) have only been observed in low numbers (Scottish Power Renewables, 2010).

The Sound of Islay and Kyle Rhea were mapped before any proposed tidal-stream development and although the Fall of Warness is an operational tidal-stream test site, there was only one device in place and was not submerged at the time of this survey.

The data gathered at these locations were also used for commercial reports to the Scottish Government (Kyle Rhea and the Sound of Islay), EMEC (the Fall of Warness) and Scottish Power Renewables (the Sound of Islay). Permission was obtained for the use of this data for this thesis and has been subsequently re-analysed for the noise-maps presented in this Chapter.
3.1.3 AVAILABLE DATA ON SHALLOW WATER SOUND PRESSURE LEVELS

Although interest in the acoustic characterisation of shallow water areas is increasing, there is still very little information publicly available (Bailey et al, 2010). Table 4 details a selection of available information. Each author has used slightly different methods to calculate the sound pressure levels making comparisons complicated, but these are valuable nonetheless as they illustrate the range of levels measured.

Table 4 - Broadband background sound pressure levels detailed in available literature (ns – not specified).

<table>
<thead>
<tr>
<th>Background SPL (dB re1 µPa)</th>
<th>Study site</th>
<th>Water depth (m)</th>
<th>Windspeed (m/s)</th>
<th>Calc method</th>
<th>Broadband range</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>115-125</td>
<td>Tidal-stream Strangford Lough</td>
<td>(ns)</td>
<td>5-6</td>
<td>(ns)</td>
<td>1 Hz - 100 kHz</td>
<td>Nedwell &amp; Brooker (2008)</td>
</tr>
<tr>
<td>Average 112</td>
<td>Windfarm North Hoyle (Wales) &amp; Scroby Sands (Norfolk)</td>
<td>7-11</td>
<td>0.9-7</td>
<td>(ns)</td>
<td>10 Hz - 150 kHz</td>
<td>Nedwell et al, (2004)</td>
</tr>
<tr>
<td>Average 117</td>
<td>Tidal-stream Puget Sound</td>
<td>51-52</td>
<td>(ms)</td>
<td>SPL rms</td>
<td>0.02 Hz - 30 kHz</td>
<td>Bassett et al, (2010)</td>
</tr>
<tr>
<td>104 - 119</td>
<td>Windfarm Moray Firth</td>
<td>(nm)</td>
<td>5</td>
<td>SPL rms</td>
<td>10 Hz - 120 kHz</td>
<td>Bailey et al, (2010)</td>
</tr>
<tr>
<td>72 – 108</td>
<td>Ramsey Sound Pembrokeshire</td>
<td>Max 66</td>
<td>Light (1-2)</td>
<td>SPL rms</td>
<td>Up to 22 kHz</td>
<td>Willis et al, (2012)</td>
</tr>
</tbody>
</table>

In the literature it is commonly accepted that background noise levels vary widely both spatially and temporally within the same site (Au & Hastings, 2008), but different authors quote different variations; by 20-30 dB (Cato, 2008; IQOE draft 2012), by 10-20dB (Richardson et al, 1995) and by up to 35dB variation (Das, 2001). All levels quoted are a large increase in background noise levels, and this variability is a consequence of the changing relative contributions from the primary sources of noise (i.e. meteorological, hydrological, biological and man-made) (Ramji 2008; Scheifle & Darre 2005).
This variability can be over relatively short timescales, from seasonally to daily (Cato, 2008) and from second to second (Richardson et al, 1995). It is also acknowledged in the literature that there is a site dependence on the noise levels (Ramji 2008; Kuperman & Ferla 1985; Ignenito & Wolf 1989). In addition, compared to deeper water levels, shallow water levels tend to be higher (Dahl, 2007) by around 5 dB (Wenz 1962).

### 3.2 Methods

All three sites were surveyed using the drifting ears methodology (Chapter two) between September 2009 and June 2011. The surveys were conducted over a period of 2 years, all within the summer season, September 2009 (Sound of Islay), June 2010 (Fall of Warness), May 2011 (Kyle Rhea) and June 2011 (Sound of Islay – slack water) (See Table 5 below). Ideally, for comparison purposes, these surveys should have been carried out in similar weather and at the same time of year, however, this wasn’t possible for this study. It is commonly understood that the weather in Scotland can be highly variable, even within the same month; therefore, this potential source of inconsistency might have been found nonetheless. The timing of these surveys was constrained by the requirements for the Scottish Government, EMEC and Scottish Power reports (section 3.1.2) and the availability of the drifting hydrophones from EMEC (discussed further in Chapter Seven).

Table 5 details the dates that the surveys were conducted, the weather conditions at the time and any anthropogenic activity on-going during the acoustic measurements and Table 6 details the Beaufort wind scale terms used to describe the conditions during the surveys.

The number of sample points used for the generation of the background noise-maps, for each of the case study sites is detailed below in Table 7. These are the number of the individual 60 second sample segments from which the sound pressure levels were calculated from.
Table 5 – Weather and site activity detail at the case study tidal-stream sites; Kyle Rhea Fall of Warness, and the Sound of Islay.

<table>
<thead>
<tr>
<th>Survey Site</th>
<th>Kyle Rhea</th>
<th>Fall of Warness</th>
<th>Sound of Islay</th>
<th>Sound of Islay (slack water)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather</td>
<td>Fine to heavy rain</td>
<td>No rain</td>
<td>Infrequent light rain</td>
<td>No rain</td>
</tr>
<tr>
<td>Sea state</td>
<td>Calm to rough</td>
<td>Smooth to moderate</td>
<td>Calm to slight (moderate to rough on ebb tide N of Port Askaig)</td>
<td>Smooth to moderate</td>
</tr>
<tr>
<td>Wind speed</td>
<td>F0-5</td>
<td>F2-4</td>
<td>F0-5</td>
<td>F2-4</td>
</tr>
<tr>
<td>Tidal state</td>
<td>Flood/Ebb</td>
<td>Flood</td>
<td>Flood/Ebb</td>
<td>Flood</td>
</tr>
<tr>
<td>Site Activity</td>
<td>-Rare-</td>
<td>-Rare-</td>
<td>-Rare-</td>
<td>-Rare-</td>
</tr>
<tr>
<td></td>
<td>Yacht, fishing boat</td>
<td>Distant ferry</td>
<td>Distant ferry, local creel boat, small workboat</td>
<td>Distant ferry, Yacht, distant cargo ship</td>
</tr>
<tr>
<td></td>
<td>-Continuous-</td>
<td>-Continuous-</td>
<td>-Continuous-</td>
<td>-Continuous-</td>
</tr>
<tr>
<td></td>
<td>Local ferry, seal presence</td>
<td>Local creel boat, small workboats, seal scarer</td>
<td>Local creel boat</td>
<td>Local creel boat</td>
</tr>
</tbody>
</table>

Table 6 - Beaufort wind scale (Metoffice)

<table>
<thead>
<tr>
<th>Beaufort wind scale</th>
<th>Limits of wind speed Knots</th>
<th>Limits of wind speed m/s</th>
<th>Wind descriptive terms</th>
<th>Sea state</th>
<th>Sea descriptive terms</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>Calm</td>
<td>0</td>
<td>Calm (glassy)</td>
</tr>
<tr>
<td>1</td>
<td>1-3</td>
<td>1-2</td>
<td>Light air</td>
<td>1</td>
<td>Calm (rippled)</td>
</tr>
<tr>
<td>2</td>
<td>4-6</td>
<td>2-3</td>
<td>Light breeze</td>
<td>2</td>
<td>Smooth (wavelets)</td>
</tr>
<tr>
<td>3</td>
<td>7-10</td>
<td>4-5</td>
<td>Gentle breeze</td>
<td>3</td>
<td>Slight</td>
</tr>
<tr>
<td>4</td>
<td>11-16</td>
<td>6-8</td>
<td>Moderate breeze</td>
<td>3-4</td>
<td>Slight-moderate</td>
</tr>
<tr>
<td>5</td>
<td>17-21</td>
<td>9-11</td>
<td>Fresh breeze</td>
<td>4</td>
<td>Moderate</td>
</tr>
<tr>
<td>6</td>
<td>22-27</td>
<td>11-14</td>
<td>Strong breeze</td>
<td>5</td>
<td>Rough</td>
</tr>
<tr>
<td>7</td>
<td>28-33</td>
<td>14-17</td>
<td>Near gale</td>
<td>5-6</td>
<td>Rough-very rough</td>
</tr>
<tr>
<td>8</td>
<td>34-40</td>
<td>17-21</td>
<td>Gale</td>
<td>6-7</td>
<td>Very rough-high</td>
</tr>
<tr>
<td>9</td>
<td>41-47</td>
<td>21-24</td>
<td>Severe gale</td>
<td>7</td>
<td>High</td>
</tr>
<tr>
<td>10</td>
<td>48-55</td>
<td>25-28</td>
<td>Storm</td>
<td>8</td>
<td>Very high</td>
</tr>
<tr>
<td>11</td>
<td>56-63</td>
<td>29-32</td>
<td>Violent storm</td>
<td>8</td>
<td>Very high</td>
</tr>
<tr>
<td>12</td>
<td>64+</td>
<td>33+</td>
<td>Hurricane</td>
<td>9</td>
<td>Phenomenal</td>
</tr>
</tbody>
</table>
Table 7 - The number of sample points for the Kyle Rhea, Fall of Warness and the sound of Islay used to generated the soundscape maps

<table>
<thead>
<tr>
<th>Survey site</th>
<th>Kyle Rhea</th>
<th>Fall of Warness</th>
<th>Sound of Islay</th>
<th>Sound of Islay (slack water)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of sample points</td>
<td>225</td>
<td>305</td>
<td>497</td>
<td>70</td>
</tr>
</tbody>
</table>

All surveys were timed to coincide with the local tidal cycle, such that the ebb, flood or both tides could be sampled (Table 8) as entirely as possible.

Table 8 - Survey and tidal times for the Kyle Rhea, Fall of Warness and the Sound of Islay

<table>
<thead>
<tr>
<th>Survey site</th>
<th>Kyle Rhea</th>
<th>Fall of Warness</th>
<th>Sound of Islay</th>
<th>Sound of Islay (slack water)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey times (BST)</td>
<td>(17/5) 09:20 – 17:00</td>
<td>(29/6) 08:40 – 14:00</td>
<td>(14/9) 16:10 – 18:05</td>
<td>(6/6) 13:25 – 16:40</td>
</tr>
<tr>
<td>Notes</td>
<td>Both ebb and flood surveyed incorporating slack and full flow. Information from local skipper confirmed that in this location the tide turns 1 hour after published times. Ebb surveyed incorporating slack and full flow.</td>
<td>Both ebb and flood surveyed but not many measurements at slack water. 16/9 not surveyed because there was a cargo ship steaming against the tide all day.</td>
<td>Smaller area in SOI surveyed to incorporate slack water.</td>
<td></td>
</tr>
</tbody>
</table>
3.2.1 DATA POOLING FOR NOISE-MAPS

The data used for the noise-maps were gathered from each survey area over a survey period. The measured levels at each location within these areas, were by necessity obtained at different times within the survey duration, at different flow speeds and when travelling in different directions (flood and ebb). Therefore consideration was required as to the pooling of the data, and whether it was reasonable to generate maps using combined data, collected in potentially different conditions.

The first consideration was whether the direction of flow made a significant difference to the sound levels. Data gathered in the Sound of Islay was visualised (Figure 30), which suggested that although the levels appear to be higher on the flood tide, the range of sound levels were similar.

![Box and whisker plot illustration the Broadband Sound pressure levels split by flood and ebb tide.](image)

The data were further investigated and found to have a normal distribution. An ANOVA GLM model was applied to consider the relative importance of the tide flow direction and the tidal flow speed. The P-values returned (tidal direction 0.092; flow speed 0.000) suggested that flow speed did have an effect on the sound levels present, whereas the tidal flow direction did not.

Previous work (Wilson & Carter, 2010b) considered the potential for difference in the sound levels due to ebb and flood tidal flow direction. This preliminary work suggested that the noise patches were conserved between flow directions (Figure 31) however this was only one attempt at unravelling the patchiness of the sound levels and would benefit from further consideration as this could be a site specific phenomenon (Section 7.7).
The relationship between tidal-flow speed and sound levels was further investigated to ensure that there was no bias in the sound levels due to the flow speed by considering the levels measured for all case study sites. Scattergram plots (Figure 32) illustrate the spread of data and highlight the variability.

Regression lines were calculated for each of the broadband sound pressure levels (SPL) for each location (Table 9). The $R^2$ values illustrate the high degree of variability such that the SPL relationship with flow speed is not clearly evident. The gradients suggest a positive relationship in the Fall of Warness and the Sound of Islay, but a negative relationship at Kyle Rhea and the Sound of Islay-slack water survey.

Figure 31 - Background noise maps generated for the Sound of Islay using ebb and flood drifts, these maps suggest that the noise patches are spatially conserved irrespective of which direction the tide is flowing.
Figure 32 - Scattergram plots of the sound levels versus tidal-stream flow speed for all broadband categories (a) All SPL $< 46$ kHz, (b) High SPL 10-46 kHz, (c) Mid SPL 1-10 kHz, (d) Low SPL <1 kHz) for all case study sites KR – Kyle Rhea, FoW – Fall of Warness, SOI – Sound of Islay and SOI-SW – Sound of Islay slack water.
Table 9 - Regression line characteristics for all study sites and broadband SPL categories KR - Kyle Rhea, FoW - Fall of Warness, SOI - Sound of Islay and SOI-SW - Sound of Islay slack water.

<table>
<thead>
<tr>
<th>SPL Category</th>
<th>Study Site</th>
<th>Gradient</th>
<th>Intercept</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>KR</td>
<td>-0.45</td>
<td>120</td>
<td>0.0016</td>
</tr>
<tr>
<td></td>
<td>FoW</td>
<td>2.11</td>
<td>110</td>
<td>0.0492</td>
</tr>
<tr>
<td></td>
<td>SOI</td>
<td>3.04</td>
<td>96</td>
<td>0.0481</td>
</tr>
<tr>
<td></td>
<td>SOI-SW</td>
<td>-2.71</td>
<td>116</td>
<td>0.0871</td>
</tr>
<tr>
<td>High</td>
<td>KR</td>
<td>-2.28</td>
<td>116</td>
<td>0.0177</td>
</tr>
<tr>
<td></td>
<td>FoW</td>
<td>4.52</td>
<td>92</td>
<td>0.1556</td>
</tr>
<tr>
<td></td>
<td>SOI</td>
<td>5.22</td>
<td>83</td>
<td>0.1002</td>
</tr>
<tr>
<td></td>
<td>SOI-SW</td>
<td>-2.96</td>
<td>104</td>
<td>0.0555</td>
</tr>
<tr>
<td>Mid</td>
<td>KR</td>
<td>-2.13</td>
<td>114</td>
<td>0.0284</td>
</tr>
<tr>
<td></td>
<td>FoW</td>
<td>5.24</td>
<td>82</td>
<td>0.1617</td>
</tr>
<tr>
<td></td>
<td>SOI</td>
<td>5.24</td>
<td>82</td>
<td>0.1617</td>
</tr>
<tr>
<td></td>
<td>SOI-SW</td>
<td>-1.92</td>
<td>108</td>
<td>0.0067</td>
</tr>
<tr>
<td>Low</td>
<td>KR</td>
<td>0.81</td>
<td>100</td>
<td>0.0071</td>
</tr>
<tr>
<td></td>
<td>FoW</td>
<td>2.06</td>
<td>97</td>
<td>0.0349</td>
</tr>
<tr>
<td></td>
<td>SOI</td>
<td>1.03</td>
<td>83</td>
<td>0.0033</td>
</tr>
<tr>
<td></td>
<td>SOI-SW</td>
<td>-3.11</td>
<td>103</td>
<td>0.0912</td>
</tr>
</tbody>
</table>

Based on this analysis, the sound levels are likely to be affected by the flow speed, but there are other factors (predictors) that may influence the sound levels within a defined area and this could include the distance of the sample point from the shore line and the depth of the water.

Therefore the data were analysed in more detail (using the open source statistical programme ‘Tinn-R’ (Faria et al, 2008)). All data were checked for normality, which was found to be the case for the predictors ‘depth’ and ‘flow speed’ but not for ‘distance to shore’. Consequently, the ‘distance to shore’ predictor was square-root transformed. Subsequently all covariates were z-transformed to a mean of zero and a standard deviation of one to achieve easier interpretable coefficients (Schielzeth, 2010). Data diagnostics were performed to check the quality of the data (Cook’s distance, dftbetas, dffits, leverage and variance inflation factors, and the distribution of residuals were plotted against predicted values (Quinn & Keough, 2002; Field 2005)) and all tests suggested that there were no adverse issues with the data. Therefore a general linear model (GLM) was applied to consider the influence of the flow speed, depth, distance to shore and study area on the broadband sound levels measured.

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3 Statistical analysis was conducted with the assistance of Dr Karin Boos from Avitec-Research GbR.
Overall study site and speed clearly influence the measured sound levels (in comparison with the null model $F_{6,1088}=181.83$, $P<0.001$). The model was run for all study sites combined, and for each study site independently and generated correction factors for each scenario (Table 10). The correction factor represents the increase in broadband dB per 1m/s increase in flow speed.

Table 10 - Tidal flow speed correction factors

<table>
<thead>
<tr>
<th>Study Site</th>
<th>Correction factor (dB re 1 µPa)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>All sites combined</td>
<td>1.24</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Kyle Rhea</td>
<td>-0.4583</td>
<td>0.3086</td>
</tr>
<tr>
<td>Fall of Warness</td>
<td>1.15</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Sound of Islay</td>
<td>1.88</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Sound of Islay- Slack water</td>
<td>-0.742</td>
<td>0.034</td>
</tr>
</tbody>
</table>

The P-values for Kyle Rhea and the Sound of Islay slack water surveys suggest that there are other driving factors relating to the sound levels (see discussion in section 3.4.2). There is likely to be a degree of site specificity in the sound levels measured. From the data presented here, where there is a positive relationship between flow speed and noise level, the increase in dB per 1m/s ranges from 1.15 to 1.88 dB, a difference of 0.73 dB. The increase in dB relating to the flow speed may therefore affect the pooling of the noise map data. Therefore the data was normalised using the all sites combined correction factor. The resulting maps were then compared to the maps generated using the non-normalised data (i.e. actual measurements). However, there was very little difference between the normalised noise maps (presented in the Appendix) and the non-normalised maps. The normalised maps returned a reduced range in SPL.

Therefore although the flow speed does influence the noise levels based on these data, the non-normalised noise maps are presented because these SPL levels reflect the absolute levels measured in tidal stream areas.
3.3 RESULTS

Background noise-maps are presented here for all three survey areas, together with maps illustrating the depths and flow speeds at the locations. All maps are colour contoured with individual scales so that the differences in levels within the area are visible. Following this there is a comparison of the SPL between areas.

3.3.1 KYLE RHEA

Kyle Rhea is the smallest of the locations surveyed and is approximately 2 km² in area. The maps were generated from 225 sample points taken from both flood and ebb tides. The maps are individually scaled to emphasize the differences. The maps highlight a heterogenic sound environment, with a slightly different pattern between the broadband filters. Sound levels ranged from 90 – 136 dB re 1µPa (Figure 33) depth ranged from 8 - 60 m and the speed ranged from 1.14 - 3.07 m/s (Figure 34).

The weather was changeable throughout this survey; the day started calm and fine and then deteriorated rapidly towards the end of the survey to heavy rain and rough conditions, survey ended in Force 5 windspeed. All maps highlight a patch of greater sound intensity to the north of the narrows, the depth and flow speed maps suggest this is a shallower area with a slower flow speed. The highest noise levels in the high filter are found at the bend of the narrows. The mid and low filter have higher intensity noise levels at the south end of the narrows, this area, particularly in the mid map coincides with the Kylerhea ferry crossing (Ferry crossing is situated slightly north of the south entrance of the narrows).
Sound Pressure Levels (dB re 1 µPa)

H = High level
L = Low level

Figure 33 – Background noise-maps of Kyle Rhea. Sound pressure levels colour contoured with the red representing areas of more intense sound. (a) Locations of the sample points. (b) All SPL – broadband frequencies up to 48 kHz. (c) high band – broadband filter >10 kHz-48 kHz. (d) mid band – broadband filter 1 – 10 kHz and (e) low band – broadband filter < 1kHz. Levels given in dB re 1 µPa.
Figure 34 - Maps illustrating the (a) depth (m) and (b) flow speed (m/s) at the sample point locations in the Kyle Rhea survey. Darker colours denote deeper depths (a) and faster flow speed (b).

Kyle Rhea is a relatively shallow environment, with a deeper area visible in the bend of the narrows. The faster flow speeds observed during this study are to the north and south of the bend, with the greater flow on the exit to Glenelg bay at the south.

Figure 35 - Locations of the sample points illustrated used in Figure 36 to illustrate the time series characteristics of the sound files.
A subsample of the sound file segments that were used to plot the noise-maps were selected for spectral analysis (Figure 35 and see Chapter Four for further detail). Presented here to show examples of the time series profile of the recordings (Figure 36) and illustrate the variability between the files. The most conspicuous in these examples are file 4918, 7183 and 5401 where there is an increase in sound amplitude. On listening to these files the ferry engine noise is dominant.

Figure 36 - Time-series plots from the subsample points in the Kyle Rhea (Figure 35). These illustrate the amplitude fluctuation within the sound file from which the SPL is calculated. Caution should be taken in any conclusion regarding the difference in amplitude between files as these were from different drifters with individual calibration adjustments (see Chapter Two).
3.3.2 Fall of Warness, Orkney

The survey in the Fall of Warness covered an area approximately 8 km$^2$. The background noise-maps presented in Figure 3 were generated from 305 sample points taken from flood tide measurements. Broadband sound levels ranged from 81 – 132 dB re 1 µPa (Figure 37) the depth ranged from 26 - 50 m and the flow speed ranged from 0.56 - 3.65 m/s (Figure 38). The sound heterogeneity is again visually evident. The lower two sections coincide with the faster flow in the area, and the shallower slower tidal flow area has typically lower SPL levels. The weather on the day of the survey was good, sunny with a wind speed between Beaufort Scale Force 2-4. There was ferry activity approximately 1.5 miles away and there were a few small boats operating in the area (Table 5).

The noise levels in the low broadband filter appear to dominate the full bandwidth (Figure 37(a)). Visually the background noise-maps suggest that the areas of increased sound levels do not appear to be related to the depth of the study area, but do appear to be correlated with the flow speed (as suggested in section 3.2.1).

As with the Kyle Rhea section above, also mapped were the depths at the sample segments and the flow speeds (Figure 38). Followed by a map (Figure 39) detailing the subsample of segment points used in Chapter Four with their respective time series plots (Figure 40). Again the time-series plots highlight the degree of variability between the background noise samples. The weather was reasonably constant during the survey so is unlikely to be the reason for the differences. The field notes recorded that there was a RIB in the area during the run from which the file 245 was taken; however no engine noise can be heard on the playback. In files 525 and 575 the input of a fish farm warning device was heard on the playback and can be seen as broad repetitive peaks.
Sound Pressure Levels (dB re 1µPa)

H = High level
L = Low level

Figure 37 - Background noise-maps of the Fall of Warness. Sound pressure levels are colour contoured with the red representing areas of more intense sound (a) Locations of the sample points (b) All SPL – broadband frequencies up to 48 kHz (c) high band – broadband filter >10 kHz-48 kHz (d) mid band – broadband filter 1 – 10 kHz and (e) low band – broadband filter < 1kHz. Levels given in dB re 1 µPa.

Visually, the background noise-maps suggest that the background noise levels do not appear to be related to the depth of the study area, but possibly related to the flow speed. As with Kyle Rhea, a subsample of sound files (Figure 39) are presented as time-series plots (Figure 40).
Figure 38 - Fall of Warness depths (m) on the left and flow speeds on the right. Darker blues denote deeper depths (a) and dark tan denotes the faster flow speeds (b).

Figure 39 - Fall of Warness locations of the subsample sound file segments used in the background noise-maps selected to illustrate the time series of the signal in Figure 40
Figure 40 - Time series plots from the subsample points in the Fall of Warness (Figure 39). These illustrate the amplitude fluctuation within the sound file from which the SPL is calculated.
Chapter Three

Noise mapping

The time-series plots for the Fall of Warness (Figure 40) show a wide variation in amplitudes and patterns. For example the spiky plot in file 245, on listening to this file, it sounded like loud static with an occasional chain clanking. Also, the amplitude pattern of a fish farm acoustic deterrent can be seen and heard in some of these files, for example 525 and 575.

3.3.3. SOUND OF ISLAY

The Sound of Islay survey was the largest area surveyed at approximately 11 km². The maps were generated from 497 sample points taken from both flood and ebb tides. The weather during the survey was generally good, although there was some infrequent light rain. Of note, when the ebb tide was running the sea surface in the region north of Port Askaig was rough (wind against tide). The Islay-Jura ferry was in operation periodically during this time, and the drifts were timed to minimise this input. There was the occasional creel boat working; however in general the acoustic input from vessel noise was minimal in this survey. The measured sound levels range from 74 – 128 dB re µPa (Figure 41) the depth ranged from 14 - 50 m and the flow speed ranged from 1.38 - 3 m/s (Figure 42). The area north of Port Askaig is a clear underwater noise hotspot and is visible in all four broadband filters (Figure 41) but the hotspot covers a greater area in the AllSPL and Low filters. This region corresponds to the area that was noted to have surface agitation due to the wind against tide conditions on the ebb flow. The high and mid filters highlight an area of increased noise over the deepest area of the sound (south of the proposed location of the tidal array, south of Port Askaig). Also, the increased noise patches to the south of the sound correspond with observed upwellings at during the survey. The increased levels of noise south of Port Askaig in all filters visually correspond with the areas of faster flow. The variation of background noise levels visually do not appear to relate to the depth (compare Figure 41 with Figure 42).

As with the other case study sites, a subsample of the sound file used to generate the background noise-maps is detailed in Figure 43 and the corresponding time series plots in Figure 44.
Sound Pressure Levels (dB re 1µPa)

H = High level
L = Low level

Figure 41- Background noise-maps of the Sound of Islay. Sound pressure levels are colour contoured with the red representing areas of more intense sound (a) Locations of the sample points (b) All SPL – broadband frequencies up to 48 kHz (c) high band – broadband filter >10 kHz-48 kHz (d) mid band – broadband filter 1 – 10 kHz and (e) low band – broadband filter < 1kHz. Levels given in dB re 1 µPa.
Figure 42 – Sound of Islay depths (m) on the left and flow speeds on the right. Darker blues denote deeper depths (a) and dark tan denotes the faster flow speeds (b).

Figure 43 - Sound of Islay locations of the subsample sound file segments used in the background noise-maps selected to illustrate the time series of the signal in Figure 44.
The time series plots (Figure 44) are again an indication of the variability in the noise levels measured during the survey. In general the amplitudes are larger in the segments recorded in the northern part of the survey area. On listening to the recordings, they typically sounded like various levels of static-type noise, with some clicks and some boat noise (e.g. file 12529 – discussed further in Chapter Four).

3.3.4 SOUND OF ISLAY – SLACKENING WATER SURVEY

The Sound of Islay survey (Sept 2009) did not fully represent the sound levels at slack water, the periods of slack water in the area were brief and this time had been used to reset the equipment. However, the original work had highlighted a couple of key points; that the background noise-maps were patchy and that the areas of greater sound intensity (hotspots) occurred in similar locations in all tidal flow speeds measured. It is possible that these hotspots could be generated either by sediment transport or biological input (for example Alphaeid (snapping) shrimps), a signal due to tidal flow would only be present above a sufficient tidal-flow speed, therefore in hindsight it would have been of use to measure the levels at, or as close to slack water as well. The aim of this second smaller scale study (Figure 45) was to investigate the background levels as the water flow slackened to see if the hotspots remained present.

The drifters were deployed upstream of the target area about half an hour before high water. The drifters were allowed to drift with the flow and were picked up and redeployed when they approach the extent of the survey area. As the flow slackened, the drifters were deployed at the approximate location of the ‘hotspot’. The weather was good during the survey, the sea state was predominantly smooth, moderate on occasion (see Table 6 for definitions).
‘Hotspot’ areas are visible on the soundscape maps (Figure 46) on all four of the broadband filters. The sound levels measured are higher than in the previous Sound of Islay study (90 – 123 dB re 1 µPa) possibly due to an increased anthropogenic site activity in comparison to the original Sound of Islay survey (Table 5) as there was continuous creel boat activity close to the survey area. The area covered by the drifters in this survey was slightly further in-shore than the initial survey. The depth of the water was shallower and the flow speed was slower than the original survey (Figure 47 vs. Figure 42). Visually the sound hotspots do not appear to be related to the depth or flow speed.

The locations of the subsample points are detailed in Figure 48 with the corresponding time series plots in Figure 49.
Chapter Three

Sound Pressure Levels (dB re 1µPa)

H = High level
L = Low level

Figure 46 - Background noise-maps of the Sound of Islay. Sound pressure levels are colour contoured with the red representing areas of more intense sound (a) Locations of the sample points (b) All SPL – broadband frequencies up to 48 kHz (c) high band – broadband filter >10 kHz-48 kHz (d) mid band – broadband filter 1 – 10 kHz and (e) low band – broadband filter < 1kHz. Levels given in dB re 1 µPa.

Figure 47 - Sound of Islay depths (m) on the left and flow speeds on the right. Darker blues denote deeper depths (a) and dark tan denotes the faster flow speeds (b).
The broadband sound levels recorded in this sub-survey were higher than the previous Sound of Islay survey (however the amplitudes presented in the time series plots, Figure...
49, are smaller than those presented in Figure 44. This is due to different drifters being used; the broadband levels are calibrated, the time series plots are at default settings, therefore these differences were accommodated in the calibration adjustments).

### 3.3.5 Comparison of the Sound Pressure Levels Between the Three Case Study Locations

The range of sound levels and the depth and flow speed characteristics are summarised in Figure 50 and Table 11. The depths in these survey areas ranged from 7 to 60 m, the flow speeds during sampling ranged from 0.03 to 3.65 m/s and the calibrated broadband SPL levels ranged from 74.85 to 136.13 dB re 1 µPa.

![Sound pressure levels comparison between the three study sites by broadband SPL category](image)

Figure 50 - Sound pressure levels comparison between the three study sites by broadband SPL category (a) All SPL – < 48 kHz, b) High SPL 10-48 kHz, c) Mid SPL 1-10 kHz, d) Low SPL <1 kHz) KR – Kyle Rhea (n=225), FoW- Fall of Warness (n=305), SOI- Sound of Islay(n=497) and SOI-SW – Sound of Islay slack water (n=70).

The SPLs presented here by broadband category and by study location are all roughly similar. The SOI levels are markedly lower than the other three studies, particularly in the low frequency broadband category (including in comparison to the SOI-SW repeat study in the same case study site). The frequency content of the background noise measured in these areas will be further analysed in Chapter 4.
Table 11 - Summary table of the range of sound level measurements, the depth and flow speeds for all study sites.

<table>
<thead>
<tr>
<th>Survey Site</th>
<th>Kyle Rhea Max</th>
<th>Kyle Rhea Min</th>
<th>Fall of Warness Max</th>
<th>Fall of Warness Min</th>
<th>Sound of Islay Max</th>
<th>Sound of Islay Min</th>
<th>Sound of Islay (slack water) Max</th>
<th>Sound of Islay (slack water) Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>AllSPL (dB re 1 µPa)</td>
<td>136.13</td>
<td>105.53</td>
<td>132.31</td>
<td>99.39</td>
<td>128.73</td>
<td>81.57</td>
<td>122.98</td>
<td>105.52</td>
</tr>
<tr>
<td>Mean All SPL (dB re 1 µPa)</td>
<td>118.99</td>
<td>114.88</td>
<td>102.47</td>
<td>113.91</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HighSPL (dB re 1 µPa)</td>
<td>135.69</td>
<td>89.05</td>
<td>120.11</td>
<td>81.26</td>
<td>123.57</td>
<td>74.85</td>
<td>114.72</td>
<td>90.60</td>
</tr>
<tr>
<td>MidSPL (dB re 1 µPa)</td>
<td>126.21</td>
<td>92.34</td>
<td>113.59</td>
<td>85.96</td>
<td>121.03</td>
<td>77.21</td>
<td>114.48</td>
<td>98.21</td>
</tr>
<tr>
<td>LowSPL (dB re 1 µPa)</td>
<td>123.93</td>
<td>90.27</td>
<td>120.75</td>
<td>95.70</td>
<td>114.20</td>
<td>78.30</td>
<td>110.93</td>
<td>100.69</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>59.44</td>
<td>8.30</td>
<td>50.60</td>
<td>0.15</td>
<td>49.85</td>
<td>14.19</td>
<td>23.00</td>
<td>7.00</td>
</tr>
<tr>
<td>FlowSpeed (m/s)</td>
<td>3.07</td>
<td>1.14</td>
<td>3.65</td>
<td>0.56</td>
<td>3.01</td>
<td>1.38</td>
<td>1.95</td>
<td>0.03</td>
</tr>
</tbody>
</table>

3.4 SUMMARY AND DISCUSSION

3.4.1 UNDERWATER NOISE MAPPING

Underwater background noise levels were measured and mapped for three tidal-stream case study sites, all of which are of interest to tidal-energy developers. The data were acquired using drifting hydrophone technologies so that the influence of flow noise could be minimised. This technique also had the advantage of being able to spatially cover a survey area in reasonable timescales.

The maps generated, all highlight a spatial heterogeneity. The mapping methodology is an averaged picture of the underwater noise field. The sound pressure levels are calculated from a 60 second segment of recording, and then pooled over the survey timeframe. The Geographic Information System (ArcGIS – www.esri.com) further interpolates these measured levels in order to generate the maps. These factors smooth the influence of any short timescale acoustic contributor (e.g. a small fast passing boat or an isolated biological sound such as a marine mammal vocalisation). Even with the smoothing the maps still illustrate a ‘patchy’ noise field. The difference in levels is therefore probably a result of site specific characteristics.

Although the noise levels are ‘smoothed’ temporally within the noise-mapping process, the noise maps presented in this study show extreme spatial heterogeneity. This may
be due to a number of reasons. The seabed topography and composition may have this
delineating effect which result in the discrete noisy patches, but also, this could be due
to turbulence generated by the flow in particular locations. Boils and upwellings were
noticed in an area south of Am Meal in the Sound of Islay (Figure 46) which coincided
with a localised noisy patch. However, the possibility that the extreme delineation may
be due to an artefact in the ArcGIS interpolation process/pooling of data process cannot
be discounted. But, the Sound of Islay noise maps (Figure 41) show that there is what
seems to be a line of higher sound levels in the middle of the Sound, to the south of Port
Askaig, which correlates with a change in flow speed (Figure 42) across the Sound in this
area. This is an area for further research to disentangle the causes of the noise
patchiness in these areas (see section 7.7).

3.4.2 What effect does the tidal flow have on SPL measured?
The effects of environmental variables (e.g. water depth) on the sound levels were
considered as factors, but the results from this thesis’ data were not conclusive. When
the background noise maps and the depth and flow speed maps are compared visually
(Figures 33, 34 & 46, 47) there does not appear to be a connection with either depth or
flow speed in the Kyle Rhea nor the Sound of Islay slack water survey. However, there
looks like there could be a connection between flow speed and sound levels in the Falls
of Warness and the Sound of Islay main survey (Figures 37, 38 & 41, 42) which is in
keeping with previous studies (Willis et al, 2012; Bassett et al, 2010). The visual analysis
(Figures 33, 33 & 46, 47 & 37, 38 & 41, 42) supports the regression analysis (Table 9) as
the slope gradients here suggest that there was a positive relationship in the Falls of
Warness and the Sound of Islay but not in Kyle Rhea or the Sound of Islay-slack water.

The statistical model run suggested that there was a positive relationship with flow
speed, and generated a normalising factor; for all sites combined, for every 1 m/s
increase in flow speed there was a corresponding increase in noise levels by 1.24 dB re 1
µPa. However, this relationship was not clear from these data, and in reality is probably
affected by a number of factors. The weather was much worse during the Kyle Rhea
study than in any of the other surveys, and this may have masked the influence of flow
speed on the sound pressure levels in this survey. However, but this was not the case in
the Sound of Islay slack water survey, as the weather was good. But, the Sound of Islay
slack water noise levels were measured over a much slower flow speed therefore there
is the potential of a threshold whereby there is a particular flow-speed after which the
noise levels are affected by the flow speed (self-noise is not considered to be a contributing factor here because drifting platforms were used).

The normalised maps presented in the appendix show a remarkably similar spatial pattern to the non-normalised data maps. This would suggest that the noise ‘hotspots’ are spatially consistent. The non-normalised data was presented within this chapter because these data are representative of the actual noise levels in the environment and therefore give a better indication of the range of levels.

3.4.3 WHAT ARE THE NOISE LEVELS AND HOW DO THEY VARY?

The noise levels presented here have a mean value of 114 dB re 1 µPa (with a variability of approximately ± 20-30 dB) which are in the same numerical region as those levels presented in Table 4 from other studies.

The studies from Strangford Lough (Nedwell & Brooker, 2008) Puget Sound (Bassett et al, 2010) and Ramsey Sound (Willis et al, 2012) are most applicable for comparison purposes as they were also measured in tidal-stream areas of interest to tidal-stream energy development. Strangford Lough has a narrower range of levels that those presented here (115 to 125 dB re 1 µPa) and Bassett et al (2010) presented an average broadband level of 117 dB re 1 µPa and Willis et al (2012) presented a range between 72 to 108 dB re 1 µPa.

Bassett et al (2010) calculated their levels over the frequency range 0.02 to 30 kHz and as well as detailing the average level, they described levels of 138 dB re 1 µPa when shipping was prevalent, 112 dB re 1µPa during rain and 105 dB re 1 µPa in a quieter period. They suggested a relationship between the noise levels and the flow speed but linked it to what they called ‘pseudosound’ or flow noise, as they were measuring the levels with a static hydrophone. Willis et al, (2012) also found a relationship between tidal flow speed and measured SPL. They used a drifting boat as the sensor platform to reduce self-noise. Bassett et al (2010) quoted mean broadband of SPL 117 dB re µPa, which compares well with this study’s figures: 118.99 dB re 1 µPa from Kyle Rhea; 114.88 dB re 1 µPa from the Falls of Warness; 102 dB re 1 µPa from the Sound of Islay; and 113.91 dB re 1 µPa from the slack water survey in the Sound of Islay (Table 12). Willis et al (2012) published SPL range of 72 to 108 dB re 1µPa also compares well to the range found in this thesis (72 dB re 1 µPa (High broadband category) to 136 dB re µPa (AllSPL)).
Table 12 - Comparison of published background noise levels with average levels presented in this study

<table>
<thead>
<tr>
<th>Study Site</th>
<th>Strangford Lough</th>
<th>Puget Sound</th>
<th>Ramsey Sound</th>
<th>Kyle Rhea</th>
<th>Fall of Warness</th>
<th>Sound of Islay</th>
<th>Sound of Islay – Slack water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background noise levels</td>
<td>115 – 125 dB re 1 µPa</td>
<td>117 dB</td>
<td>72 – 108 dB</td>
<td>119 dB</td>
<td>115 dB</td>
<td>102 dB</td>
<td>114 dB</td>
</tr>
</tbody>
</table>

The first Sound of Islay survey returned noise levels that were quieter than the other three surveys including the slack water survey done in the same location. It is likely that the main reason for this was that the recording runs were timed for when there was no ferry activity and minimal other vessel activity. It can be seen from Figure 50 that the biggest difference between the study areas is in the lowSPL broadband category (which would concur with vessel noise - see Chapter Four). The first Sound of Islay survey was the first one completed for this thesis, and vessel noise was excluded as much as possible, partly due to the uncertainty as to what should or should not be included as background noise (See Chapter Seven for further discussion). Following this survey however, my opinion settled to prefer the inclusion of any and all persistent noise present in the area because this was part of the noise landscape against which the tidal devices would be detected. All other areas do have persistent ferry noise included.

At this stage it is unclear what may be the combined factors resulting in the ‘hotspots’ observed in these maps. For example, in the Sound of Islay, it was noted that the area to the north of Port Askaig was affected by wind against tide and the sea surface was agitated, probably leading to the increased noise levels. In the south, the spots of increase noise levels were linked visually to areas of upwelling observed during the survey. Other contributing factors may include sediment transport and/or localised biological noise (e.g. snapping shrimp).

3.4.4 Are tidal stream locations loud environments in comparison to deep water locations?

Although there is a significant body of work regarding background noise levels in deeper water, the levels are represented as frequency spectra rather than a broadband SPL level which makes the comparison to the broadband levels presented here a challenge.
However when Richardson et al (1995) discuss the zone of audibility they use the ambient (background) noise level of 80 dB re 1 μPa as the level. Additionally there is reference on-line to the levels at Sea State 0 of 60 dB re 1 μPa and at Sea State 4 of 100 dB re 1 μPa (http://www.arc.id.au/SoundLevels.html). Another reference to broadband levels was found at http://wildwhales.org/noise-and-cetaceans/ where the open ocean levels were noted at 74 – 100 dB re 1 μPa for sea states 3-5. These values were referenced to Urick 1983 and 1986 but the full reference was not supplied. There is no way to know how these levels were obtained so any conclusion based on these levels must be cautious. However, it would seem likely that the noise levels in these shallow water tidal-stream areas are noisy environments. Wenz (1962) stated that shallow water levels were 5 dB higher than deep water values and Nedwell & Howell (2004) stated that shallow water noise levels could be significantly higher and lower than deep water values depending upon the environmental conditions. This question will be considered further in Chapter Four where the spectral levels measured in the tidal-stream areas are compared with commonly used frequency curves (Wenz curves).

4.1 INTRODUCTION

In the previous chapter, the measured background noise levels were presented as spatial noise level contour maps. These maps presented a visual perspective of the acoustic sound field in the case study areas and highlighted the spatial heterogeneity of these tidal-stream locations. Underwater noise is comprised of sound from numerous sources that merge together. Different sources have characteristic spectral profiles, i.e. they can be identified by considering which frequency or frequency range is dominant.

The frequency range of underwater background noise or signal is biologically relevant because it is the particular frequencies of the signal or noise that will determine whether the sound is audible to marine life. It is likely that marine animals gather important information from the sound that they hear (Richardson et al, 1995) (for example, hearing surf noise may highlight the location of the coastline and sounds from predators may alert them to a potential danger). For a signal to be detectable it must be within the animals’ threshold of hearing and be above the background noise levels (Figure 2– Chapter One). It is therefore important to understand the frequency characteristics of the background noise as well as the levels.

In this chapter the sound files used to generate the broadband sound pressure levels background noise-maps (Chapter Three) are analysed further to produce frequency spectra for each of the case study locations. Prior to this the known characteristics of common underwater noise contributors are outlined to provide context. Then, frequency spectra from each of the case study locations are presented together with spectra generated from opportunistic recordings of known sound sources during the case study site surveys. Finally the results are discussed and compared to known frequency spectra.

4.1.1 KNOWN BACKGROUND/AMBIENT NOISE CONTRIBUTORS

The benchmark underwater noise frequency spectra plots are known as the Wenz, or as the Knudsen-Wenz curves (Figure 51). Wenz (1962) built on the seminal work by Knudsen and colleagues and created a template frequency spectrum of underwater
background noise which is still frequently referred to today. Cato (2008) added data to these curves by extending the sea state curves into the lower frequencies.

The sound levels depicted in the Wenz curves are typically considered to be deep water levels, as most of the data were gathered at offshore locations, but some of the data were also collected from ports and harbours (Wenz, 1962) although considered as ‘shallow’ these were from depths far greater than are being considered in this study (up to 200m in comparison to < 60m depths). The Wenz curves illustrate clearly the combination of background noise sources and the frequencies at which they contribute sound and illustrate the upper and lower limits of prevailing noise. They also highlight the noise level dependence on wind speed, shown on these curves as sea state.

Common underwater noise contributors fall into one of three categories; physical, biological or anthropogenic.
4.1.1.1. Physical background noise contributors

Physical contributors are natural sources such as sea surface noise (wind and wave action), precipitation, and geological sources including earthquakes and sediment movement by the tidal-flow.

Wind dependent sea surface noise is produced by wave action; the dominant mechanisms are waves breaking and bubbles breaking. Wind dependent noise can be detected over a wide frequency range, from a few hertz to greater than 30 kHz (Cato, 2008) and the varying levels are presented in the Wenz curves as sea state. The parallel nature of the sea state levels in relation to wind speed (see Figure 51) suggests that noise level increases across all frequencies equally as the wind speed increased. Wave action crashing on the shore also increases the noise levels in the local area.

Surface waves described as 2\textsuperscript{nd} order pressure effects in Figure 51, relates to the noise generated by the fluctuation of the sea surface height which creates subsurface pressure fluctuations that contribute to the noise at low frequencies.

Precipitation; for example rain and hail produce impact noise by hitting the sea surface resulting in bubble formation. The frequency spectral shape due to precipitation is identifiable and can be seen as a broad peak at approximately 15 kHz, but the peak frequency varies due to precipitation drop size (Nystuen, 1986).

Turbulent pressure fluctuations caused by the flow of water past obstructions (at the sea surface and at depth) are detected at low frequencies (Richards \textit{et al}, 2007). Additionally, in the coastal regions relevant to this study, noise is generated by the water’s interaction with the shore, with waves impacting the shore and the resulting turbulence past the shore line. Turbulence generates bubble formation (increasing the sound in the mid frequency range (100 Hz – 10 kHz) and bubble cavitation generates sound in the 100 Hz to 1 kHz range (Tonolla \textit{et al}, 2010). Turbulence is also created by the tidal-stream flowing past obstructions, such as rocks or bathymetric depth changes.

The movement of sediment due to the flow of water is a pertinent physical contributor to this thesis, but is not represented in the Wenz curves. Sediment transport may be a significant contributor of noise within areas that have a substantial tidal-flow as found in this thesis’ case study areas, and is therefore introduced in more detail. Sediment transport influences the noise levels in the frequency range 2 to 16 kHz (Tonolla \textit{et al}, 2010) although this is dependent on the sediment grain size (smaller size – higher
frequency) (Rouse et al., 1994; Thorne, 1990). Noise associated with the sediment transport is due to the sediment particles colliding with one another and the seabed itself, and noise due to sediment collision is particularly noticeable in areas with high tidal flow and coarse sedimentary material (Thorne, 1990). The flow of water causes the sediment to become mobile, either by bedload rolling or sliding, or if the flow is of sufficient speed, by moving particles into the water column. The sound pressure levels generated by sediment transport are related to the flow speed and the mass of the sediment being transported (Thorne, 1985) and Thorne (1990) suggested that the noise levels due to sediment transport are considerable and are comparable to the noise levels due to sea surface agitation observed for moderate to high winds.

4.1.1.2. Biological Background Noise Contributors

Biological noise encompasses a wide range of frequencies and levels, emanating from fish, marine mammals and invertebrates. Many of these sounds are individual and transitory, but can also combine to become a continuous noise when the sounds from many individuals merge into a chorus (Cato, 2008). Chorusing fish can, for example, raise the background noise levels by 20-30 dB (Hildebrand, 2009).

A variety of sounds are generated by seals, cetaceans and fish. Seals bark and grunt, cetaceans whistle, moan, sing and click (echolocating odontocetes) and fish grunt (e.g. Cod (Nordeide & Kiellsby, 1999) and herring have been found to communicate using bubbles (Wilson et al., 2004)). However these sounds tend to be transitory, and as such have not been focused on for this thesis.

One continuous sound thought to be of biological origin, is a prevalent ‘snapping’ and ‘crackling’ sound, and was heard in the recordings done for this study. If Scottish waters were warmer a prime contender for this noise would be snapping shrimps, these are small crustaceans often referred to as pistol shrimps (Alpheidae sp.). Snapping shrimp are generally found in water depths of less than 60m (Au & Hastings, 2008; Ferguson & Cleary, 2001; Everest et al., 1948), they are bottom dwelling and prefer habitats where they can burrow and hide in crevices and holes, in coarse gravel coral or other similar substrates (Radford et al., 2010; Finfer et al., 2007; Johnson et al., 1947) such as might be found in tidal-stream areas.

This noise contributor is of interest because the noise they generate is similar in form to that of sediment transport. The snapping spectrum is broadband up to approximately
200 kHz (Au & Hastings, 2008) with a peak in frequency around 2-15 kHz (Radford et al, 2008). At low sea states, snapping shrimp can be heard for approximately a mile away from the boundary of the shrimp bed (Everest et al, 1948). The noise is most frequently described as a crackling and popping sound, often compared to the sound of frying fat (Radford et al, 2008; Ferguson & Clearly, 2001; Au & Banks, 1998; Johnson et al, 1947). At a distance away from source the sounds merge into a sizzle and then a hiss (Johnson et al, 1947).

Snapping shrimp are known to be present in temperate waters, but are usually found in warmer temperatures than the waters around the Scottish coast. There is no cited reference to their presence in Scotland. The Marine Biological Association’s online resource (MarLIN) lists snapping shrimp presence at the Isle of Man, but not any further north. However, there is anecdotal evidence of their presence in Scottish waters from local fishermen. The snapping type noise heard in underwater noise recordings off Scotland is consistent with snapping shrimp, but to date the actual origin is unknown.

4.1.1.3. ANTHROPOGENIC BACKGROUND NOISE CONTRIBUTORS

Man-made background noise contributors include vessels; shipping, fishing and pleasure craft, industrial noise (e.g. oil rigs, coastal developments and fish farms) geophysical surveys, sonar use, military operations and the use of acoustic deterrent devices. Table 13, details typical frequency ranges and source levels of common anthropogenic contributors. We can see that there is significant sound input from these sources. Vessels, dredging and drilling all tend to input energy at frequencies less than 5000 Hz, and at source levels between 145 to 190 dB re 1 µPa @1m. Sonar is emitted at a higher frequency of up to 500 kHz with source levels between 180 to 230 dB re 1 µPa @1m. Acoustic deterrents have a narrower frequency range of between 8-17 kHz with source levels of 130 to 210 dB re 1 µPa @1m. The most intense inputs are explosions, seismic airguns and marine piling; broadband frequencies at source levels of 230 to 260 dB re 1 µPa @1m.

Humans’ use of the oceans and coastal areas is widespread and increasing (IQOE draft, 2012). Traffic noise (shipping) is a major low frequency contributor to underwater noise (IQOE draft, 2012). Commercial shipping generates noise predominantly at frequencies between 50-300 Hz (Richards et al, 2007) and as such adds very little to the background noise in shallow areas because the bathymetry acts as a wave guide and cannot support the long wavelength of low frequency sound (Richards et al, 2007).
Table 13 - General frequency and source levels of common anthropogenic noise contributors (not an exhaustive list).

<table>
<thead>
<tr>
<th>Anthropogenic contributors</th>
<th>Frequency</th>
<th>Source level (dB re 1µPa)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile-driving</td>
<td>20Hz&gt;20kHz</td>
<td>243-257 (p-p)</td>
<td>Götz et al, 2009</td>
</tr>
<tr>
<td>Small vessels</td>
<td>37 - 5000 Hz</td>
<td>145 – 170 (RMS)</td>
<td></td>
</tr>
<tr>
<td>Ships (tankers /freighters)</td>
<td>&lt; 500 Hz</td>
<td>172 – 190 (RMS)</td>
<td></td>
</tr>
<tr>
<td>Marine dredging</td>
<td>20 - 1000 Hz</td>
<td>150 – 160 (RMS)</td>
<td></td>
</tr>
<tr>
<td>Drilling</td>
<td>&lt;5000 Hz</td>
<td>150 – 160 (RMS)</td>
<td></td>
</tr>
<tr>
<td>Seismic airguns</td>
<td>Broadband</td>
<td>230 – 260 (p-p)</td>
<td>Richardson et al, 1995</td>
</tr>
<tr>
<td>Explosives</td>
<td>Broadband</td>
<td>260 – 280(peak)</td>
<td></td>
</tr>
<tr>
<td>Depth finding sonar</td>
<td>12 kHz</td>
<td>180+ (peak)</td>
<td></td>
</tr>
<tr>
<td>Bottom profiling sonar</td>
<td>0.4 - 30 kHz</td>
<td>200 – 230 (peak)</td>
<td></td>
</tr>
<tr>
<td>Side scan sonar</td>
<td>50 - 500 kHz</td>
<td>220 – 230 (peak)</td>
<td></td>
</tr>
<tr>
<td>Military search &amp; surveillance</td>
<td>2 – 57 kHz</td>
<td>230+ (peak)</td>
<td></td>
</tr>
<tr>
<td>Acoustic deterrent devices</td>
<td>8 – 17 kHz</td>
<td>130 – 210(peak)</td>
<td>Gordon &amp; Northridge, 2002</td>
</tr>
</tbody>
</table>

The combination of the various contributors is summarised below (Figure 52). It is likely that the relevant background noise contributors in this thesis ‘case study areas will be local vessels, i.e. leisure craft, ferries and inshore fishing vessels, the weather (wind and rain), sediment transport due to tidal-flow, surf and shore noise and potentially biological.

Figure 52 - Summary flow chart of underwater background noise contributors.
The aim of this Chapter is to consider the frequency spectral shape of the background noise recorded in the tidal-stream case study areas, to help explore this study’s Thesis Hypothesis 1) and Research Questions 1 and 2 (Chapter One) as detailed below.

**Thesis hypothesis:**
1) Tidal stream locations are currently loud environments.

**Research Questions:**
1) What are the noise levels in areas suitable for tidal energy extraction and how varied is the underwater noise field?
2) How does this compare to well-known deep water levels?

### 4.2 Methods

Frequency spectra were generated using a sub-sample of the sound files selected for the background noise-maps (Chapter Three). The sub-sample files were carefully selected by initially considering the noise-maps themselves. Files were chosen for their spatial location and the sound level at that location to ensure that the files were spatially representative and captured a range of sound levels. Where there was a choice of sample files at these locations, the selected file was chosen randomly. It is worth reiterating here that these chosen files are a 60 second segment from the continuous sound recording and therefore during the 60 seconds will have travelled along the drift track (see Chapter Two) rather than a being confined to a specific point.

Power spectrum density plots were generated using the commercially available software Avisoft SASLab Pro (Avisoft Bioacoustics Version 5.2 Berlin). Avisoft has a suite of power spectrum analyses to suit the temporal and frequency compromise preference required for the output. For this thesis, the aim was to explore which frequencies were dominant in the sound files and at what spectral levels. The files analysed were of 60 seconds duration, as the sound file was more than a few seconds in length Avisoft’s recommended parameter was the ‘Power Spectrum (Spectrum level units, averaged)’.

The FFT size was 32768, as higher values result in a high frequency resolution (but weaker temporal resolution) (Avisoft). The FFT algorithms assume that the signal is periodic, however natural sound is not periodic, therefore this results in an issue called
leakage, whereby the FFT can generate a distorted frequency spectrum. The use of a ‘window’ reduces this effect. There are a number of different windows that can be used depending on the signal to be analysed, and the one chosen can affect the resulting spectral shape. Here the Hamming window was used in line with the Avisoft recommendation that this was the best choice in most cases.

Avisoft was set to default values for all files (rather than a calibrated setting – see Chapter Two) the resulting frequency spectra were then exported into Microsoft Excel, where the calibration factors for each frequency relevant to the drifter were then applied. Summary plots are presented for each area, together with a breakdown of comparison plots. All files were analysed aurally as well as visually to attempt to match what was heard with the respective spectral profile.

4.3 RESULTS

The frequency spectra plots for each of the case study areas are presented and illustrate the spectrum levels measured for frequencies up to 48 kHz.

These results illustrate the variability between sites and within site (Figure 70) and in general the average spectral profiles are close to the upper Wenz curve or higher, especially for frequencies above 2 kHz.

4.3.1 KYLE RHEA

Nine sample files were selected from the Kyle Rhea survey for spectral analysis (Figure 53) and the survey conditions are detailed in Table 14.

The seabed in this area is tidally swept bedrock; the bedrock is ridged with occasional boulders and patches of cobbles and pebbles (Emu Ltd, 2006). The north end of Kyle Rhea has cobbles and gravel at depths of around 15 m (Wilding et al, 2005). The depths of the sample files ranged from 11 to 33 m (median 14 m) and the flow speed relating to these points ranged from 0.18 to 3.08 m/s (median 1.73 m/s). Sample files have been taken from both the flood and ebb tidal flows. The survey weather conditions deteriorated throughout the day, at the beginning of the survey the weather was fine with a sea state of 0-1 (Beaufort Scale – see Table 6 Chapter Three) at the end of the survey there was heavy rain with a sea state of 5. At this point for reasons of visibility and safety the survey was ended. Of note, the Kylerhea ferry was in almost constant operation throughout the survey.
Figure 53 - Locations and ID numbers for the sample files in Kyle Rhea used for the frequency spectral analysis shown together with the All SPL background noise-map presented in Chapter Three.

Table 14 - Survey conditions present in relation to each sample file measurements in Kyle Rhea. Ebb tide flows from the north to the south.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>IDno.</th>
<th>Flow speed (m/s)</th>
<th>Tide</th>
<th>Depth (m)</th>
<th>Site activity</th>
<th>Weather</th>
</tr>
</thead>
<tbody>
<tr>
<td>17/5/2011</td>
<td>09:37</td>
<td>5197</td>
<td>2.63</td>
<td>Ebb</td>
<td>14</td>
<td>Two sailing boats in area under power plus the ferry</td>
<td>Fine (SS 0-1)</td>
</tr>
<tr>
<td></td>
<td>09:48</td>
<td>5401</td>
<td>3.08</td>
<td>Ebb</td>
<td>11</td>
<td></td>
<td>Fine (SS 2)</td>
</tr>
<tr>
<td></td>
<td>10:44</td>
<td>3083</td>
<td>1.73</td>
<td>Ebb</td>
<td>15</td>
<td>Ferry</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11:45</td>
<td>8672</td>
<td>1.04</td>
<td>Ebb</td>
<td>13</td>
<td></td>
<td>Clouding over (SS3)</td>
</tr>
<tr>
<td></td>
<td>11:33</td>
<td>6648</td>
<td>1.29</td>
<td>Ebb</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>14:09</td>
<td>4402</td>
<td>1.95</td>
<td>Flood</td>
<td>33</td>
<td>Ferry and fishing boat</td>
<td>Rain (SS 3-4)</td>
</tr>
<tr>
<td></td>
<td>15:22</td>
<td>7183</td>
<td>1.30</td>
<td>Flood</td>
<td>25</td>
<td></td>
<td>Rain increasing (SS 4)</td>
</tr>
<tr>
<td></td>
<td>15:31</td>
<td>4918</td>
<td>0.18</td>
<td>Flood</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16:57</td>
<td>10111</td>
<td>2.86</td>
<td>Flood</td>
<td>14</td>
<td>Fish farm Well-boat</td>
<td>Heavy rain (SS 5)</td>
</tr>
</tbody>
</table>
Figure 54 presents the summary of spectra measured in Kyle Rhea from the selected sample files.

To consider the potential contributors to these frequency spectra, files have been presented within similar groupings (Figure 56). The ferry noise is particularly observable in files 4918, 5197 and 8672 as a raised spiky signal in the frequency range 30 Hz to 2 kHz. The ferry noise is clearly heard in these recordings, including file 8672 which was recorded at some distance from the ferry crossing.

Figure 55 - Time series plot of file 5401 detailing spikes of increased amplitude.
Files 4918, 5197 and 8672 show a spiky signal between 30 Hz and 2 kHz, ferry engine noise is clearly audible in these recordings.

Files 5401 and 10111 were recorded at faster tidal-flow speeds (3.08 m/s and 2.86 m/s respectively) in comparison to file 8672 (1.04 m/s). These highlight the flatter profile from approximately 1 kHz.

Files 4402 and 10111 were recorded in increasing rain and sea state (SS4-5) and also show a flatter profile from approximately 1 kHz in comparison to file 8672 where there was no rain (but ferry noise).

The frequency spectra from the sample files 5401 and 10111 have a relatively flatter profile from 2 kHz and above. A crackling and popping sound can be heard in these files represented in the time-series plots as high amplitude signal spikes (Figure 55).

Files 10111 and 4402 were recorded with an increasing level of wind and rain, and their spectral profile also is flatter than recordings made with no rain.
There were many seals present during the flood runs, they appeared curious in the drifting hydrophones and on some of the recordings there were sounds consistent with ‘seal barks’ audible. The ‘barks’ were in the frequency range of 100-600 Hz (Figure 57) which concur with a low frequency growl between 100 – 500 Hz reported in Asselin et al, (1993).

![Zoomed in section of the spectrogram for file 7183 highlighting the seal 'barks' (encircled).](image)

This seal vocalisation signal is not identifiable from the frequency spectra plots, which is to be expected given that the spectra is averaged over a relatively long period of time in comparison to the time of the seal ‘bark’.

### 4.3.2 Fall of Warness

Fourteen sample files were selected for frequency spectral analysis (Figure 58) and the survey conditions that related to each of these sound files are detailed in Table 15. The seabed in the Fall of Warness survey area is mainly ridged bedrock, as the area is mainly swept of any sands or gravel, there may also be occasional boulders (Aurora Environmental, 2005). The selected sample files depths ranged from 26 to 44 m (median 34 m) and the tidal-stream flow speed ranged from 0.51 to 3.31 m/s (median 2.42 m/s).
Figure 58 - Locations and ID numbers for the sample files in the Fall of Warness used for the frequency spectral analysis, shown alongside the All SPL background noise-map presented in Chapter Three.

Table 15 – Survey conditions present in relation to each sample file measurements in the Fall of Warness. Flood direction from the North West, wind direction predominantly south-westerlies

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>IDno.</th>
<th>Flow speed (m/s)</th>
<th>Tide</th>
<th>Depth (m)</th>
<th>Site activity</th>
<th>Weather</th>
</tr>
</thead>
<tbody>
<tr>
<td>29/6/2010</td>
<td>09:14</td>
<td>120</td>
<td>0.51</td>
<td></td>
<td>26</td>
<td>Creel boat working</td>
<td>Sunny, no rain, wind steady at F3/4</td>
</tr>
<tr>
<td></td>
<td>10:33</td>
<td>319</td>
<td>3.01</td>
<td></td>
<td>39</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>11:43</td>
<td>349</td>
<td>3.31</td>
<td></td>
<td>44</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>08:44</td>
<td>121</td>
<td>1.08</td>
<td></td>
<td>29</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>08:51</td>
<td>125</td>
<td>0.97</td>
<td></td>
<td>33</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10:41</td>
<td>345</td>
<td>2.73</td>
<td>Flood</td>
<td>34</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>09:40</td>
<td>225</td>
<td>2.29</td>
<td></td>
<td>29</td>
<td>Creel boat in area plus ferry in distance, RIB and small work boat in area</td>
<td></td>
</tr>
<tr>
<td></td>
<td>09:45</td>
<td>233</td>
<td>2.46</td>
<td></td>
<td>33</td>
<td></td>
<td>SS3 Conditions consistent during survey</td>
</tr>
<tr>
<td></td>
<td>09:53</td>
<td>245</td>
<td>2.11</td>
<td></td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>09:48</td>
<td>229</td>
<td>2.74</td>
<td></td>
<td>34</td>
<td>Creel boat hauling, ferry approx. 2 miles away</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11:23</td>
<td>437</td>
<td>2.84</td>
<td></td>
<td>34</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12:28</td>
<td>525</td>
<td>2.54</td>
<td></td>
<td>44</td>
<td>Two small boats travelling in area</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12:32</td>
<td>543</td>
<td>2.21</td>
<td></td>
<td>33</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12:41</td>
<td>575</td>
<td>2.37</td>
<td></td>
<td>44</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 59 presents the spectra for the sample files and illustrates the variability in spectral levels and in the spectral profiled. The decreasing spectral slope from low frequencies is typical for underwater background noise (see Wenz curves - Figure 51).
Figure 59 - Summary frequency spectra of background noise levels measured in the Fall of Warness.

From these selected sample files it can be seen that there is variability in levels between measurements. These differences in spectral profile are investigated further in Figure 60. However simply looking at the difference in levels between the lowest spectra and the highest we can see that there is approximately 35 dB re 1 µPa²/Hz difference across all frequencies.

Figure 60 (a) shows the spectral profile indicative of small boat noise, which is audible in the sample files. The frequency range is similar to that found in Kyle Rhea. Plot (b) illustrates the frequency profile when there are no small local boats present, but there was a ferry in the distance, the higher levels at frequencies of around 500Hz and less are indicative of distant shipping. Plot (c) compares two files recorded on a fast tidal flow (> 3m/s) with two files recorded in a slower flow (<1 m/s). At approximately 1 kHz the spectral profiles separate, with the fast flow levelling out and the slow flow continuing to decrease in level with increasing frequency.
(a) Example sound files recorded when two small boats were travelling in the area. The spiky section between 50 Hz and approximately 2 kHz relates to the boat noise (spike at ~10kHz not related to boat noise – see (d) below).

(b) Example recordings small boats were not in the area, but recorded when there was a creel boat present at a distance and a passing ferry also at distance. The higher levels at the frequencies below 300 Hz are indicative of low frequency engine noise.

(c) Files 319 and 349 were recordings taken at higher flow speeds, both at greater than 3m/s. When compared to two files taken at low flow speeds (120 and 125 – less than 1 ms) an increase in levels can be seen in the frequencies above 1 kHz in the fast flow sound files.
These two files illustrate the signal of an acoustic deterrent at approximately 10kHz.

Contrast with these two files where the acoustic deterrent is not present.

Figure 60 - Frequency spectra measured in the Fall of Warness detailing (a) boat noise (b) without boat noise (c) Differences between recordings at a fast tidal-flow speed and at a low flow speed (d) with an acoustic deterrent and (e) without an acoustic deterrent.

Figure 60 Plot (d) illustrates two files that have a clear acoustic deterrent signal on listening to the file. This is shown in the spectral profile with a peak at around 10 kHz. This is also suggested by the pattern in the time series plots (file 575 as an example - Figure 61). This is a similar time series plot to those presented in Gordon & Northridge (2002) relating to a Ferranti-Thompson device (although not at the same frequency).

Figure 61 - Sample file 575 from the Fall of Warness showing a characteristic pattern of sound that suggests output from an acoustic deterrent.
Certainly when listening to the sample files there is a characteristic pulsed sound audible that is not present in files 120 and 345 (Figure 60 Plot (e)). The files that do not have the acoustic deterrent signal are on a broad south westerly line from the island of Muckle Green Holm to the island of Eday (Figure 58) suggesting that the island may be blocking the signal forming an acoustic shadow.

4.3.3 SOUND OF ISLAY

Fourteen sample files were selected from the Sound of Islay survey, their locations are detailed in Figure 62. The conditions during the survey relating to these sample files are detailed in Table 16.

Figure 62 - Locations and ID numbers for the sample files in the Sound of Islay used for the frequency spectral analysis shown alongside the All SPL background noise-maps presented in Chapter Three.
Table 16 - Survey conditions present for each sample point measurement in the Sound of Islay. Ebb tide ran from the north to the south, flood tide from the south to north. Wind direction predominantly funnelling up the Sound from the south.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>IDno.</th>
<th>Flow speed (m/s)</th>
<th>Tide</th>
<th>Depth (m)</th>
<th>Site activity</th>
<th>Weather</th>
</tr>
</thead>
<tbody>
<tr>
<td>14/9/09</td>
<td>16:18</td>
<td>3378</td>
<td>2.14</td>
<td>Ebb</td>
<td>42</td>
<td>Occasional ferry, no other boat activity observed during measurement runs.</td>
<td>Calm, SS0</td>
</tr>
<tr>
<td></td>
<td>17:25</td>
<td>4036</td>
<td>1.20</td>
<td>Ebb</td>
<td>40</td>
<td></td>
<td>Grey, cloudy slight rain, SS2</td>
</tr>
<tr>
<td>15/9/09</td>
<td>18:01</td>
<td>7016</td>
<td>1.23</td>
<td>Ebb</td>
<td>12</td>
<td></td>
<td>Light breeze SS1-3</td>
</tr>
<tr>
<td></td>
<td>17:46</td>
<td>8011</td>
<td>2.19</td>
<td>Ebb</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>09:54</td>
<td>11970</td>
<td>1.94</td>
<td>Flood</td>
<td>24</td>
<td>North of Port Askaig the surface water was noticeably choppy due to tidal flow, particularly when wind was against flow</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10:57</td>
<td>12529</td>
<td>1.88</td>
<td>Flood</td>
<td>46</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10:54</td>
<td>12572</td>
<td>2.13</td>
<td>Flood</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12:09</td>
<td>12801</td>
<td>1.99</td>
<td>Flood</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17/9/09</td>
<td>18:38</td>
<td>17573</td>
<td>2.78</td>
<td>Ebb</td>
<td>18</td>
<td></td>
<td>Light breeze SS1-3</td>
</tr>
<tr>
<td></td>
<td>17:20</td>
<td>17933</td>
<td>2.69</td>
<td>Ebb</td>
<td>33</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>17:28</td>
<td>18080</td>
<td>2.60</td>
<td>Ebb</td>
<td>34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18/9/09</td>
<td>09:16</td>
<td>23405</td>
<td>1.68</td>
<td>Ebb</td>
<td>20</td>
<td></td>
<td>Moderate breeze, SS3</td>
</tr>
<tr>
<td></td>
<td>13:49</td>
<td>26101</td>
<td>3.18</td>
<td>Flood</td>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>13:42</td>
<td>28233</td>
<td>2.98</td>
<td>Flood</td>
<td>33</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The seabed in the Sound of Islay is a mix of scoured bedrock and some gravel and sand patches. There are also scattered boulders; most numerous in the middle region near to Port Askaig, plus evidence of coarse grained sediment being transported by the tidal flow (Scottish Power Renewables, 2010).

The depths of the selected sample points ranged from 12 to 46 m (median 28.5 m) and the flow speeds ranged from 1.2 to 3.18 m/s (median 2.14 m/s). During the survey, the sea state varied from flat calm to SS 3, there was infrequent light rain at times, wind speed varied from calm to a moderate breeze.

Figure 63 illustrates the frequency spectra for the sample files selected and again the variability in the spectrum levels is shown. Between the lowest and highest levels, there is around 50 dB re 1 µPa²/Hz difference at 100 Hz reducing to 30 dB re 1 µPa²/Hz. Figure 64 presents a subsection of these files for comparison purposes.
Figure 63- Summary frequency spectra of background noise levels measured in the Sound of Islay.

Figure 64 Plot (a) again shows boat signature noise and the ferry can clearly be heard in these files. Plots (b) and (c) show the difference between sample files from the north and the south of the Sound of Islay. Files recorded at the north have a greater low frequency signal. This range coincides with either low frequency vessel noise or shallow water wind induced noise (Figure 51).

Plot (d) highlights the difference in the flow speed spectral profile with the files recorded at the faster flow becoming flatter in profile from about 2 kHz in comparison with the file measured in a slower flow.

Plot (e) is a mystery profile, audibly there was nothing distinguishable on the sound file, but there seems to be a series of harmonic spikes every 100 Hz interval, from about 50 Hz to 2.5 kHz. It is also much lower than the other spectra at frequencies below approximately 1000 Hz.
(a) These files have a spiky signal in the frequency range of approx. 30 Hz to 2 kHz suggesting vessel noise present.

(b) Files recorded in the north area of the Sound of Islay.

(c) Files recorded in the south of the Sound of Islay. These files do not appear to have as high a signal at frequencies below 100 Hz.

(d) Example files contrasting flow speed differences. Files 17573 (2.78 m/s) 17933 (2.69 m/s) 26101 (3.18 m/s) and 28233 (2.98 m/s) all increase in levels from 2 kHz in comparison to file 7016 (1.23 m/s).
File 4036 was recorded in the south of the sound of Islay at a flow speed of 1.2 m/s. It is a lower spectrum level than the other recordings and has a series of spikes in the approx frequency range 40 Hz to 2 kHz, possibly indicative of a fault with the hydrophone.

4.3.4 Sound of Islay slackening tide survey

There were seven sample files chosen from this survey (Figure 65) and the conditions during the survey detailed in Table 17. The aim of revisiting this study area was to take measurements at a slower tidal flow speed as this had not been captured in the previous study. Also this location was targeted as the previous survey had highlighted that this was an area with a sound ‘hotspot’. Therefore the recordings here were intended to investigate the spectral profile at low tidal flow speeds and to determine if the ‘hotspot’ was independent of flow speed.

Figure 65 - Locations and ID numbers for the sample files in the Sound of Islay slackening tidal flow speed survey used for the frequency spectral analysis shown alongside the All SPL background noise-maps presented in Chapter Three.
Table 17 - Survey conditions present for each sample point measurement in the Sound of Islay slackening water survey. Ebb tide ran from the north to the south, flood tide from the south to north. Wind direction N / NE.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>IDno.</th>
<th>Flow speed (m/s)</th>
<th>Tide</th>
<th>Depth (m)</th>
<th>Site activity</th>
<th>Weather</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/6/2011</td>
<td>13:29</td>
<td>1550</td>
<td>0.55</td>
<td>Ebb</td>
<td>22</td>
<td>Islay-Jura ferry running and a cargo ship entering SOI</td>
<td>Cloud cover with sunny spells SS0</td>
</tr>
<tr>
<td></td>
<td>13:41</td>
<td>1790</td>
<td>0.47</td>
<td>Ebb</td>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>14:19</td>
<td>1990</td>
<td>0.38</td>
<td>Flood</td>
<td>11</td>
<td>Creel boat operating, Yacht and Kennacraig ferry entering area from Port Askaig</td>
<td></td>
</tr>
<tr>
<td></td>
<td>14:29</td>
<td>2190</td>
<td>0.69</td>
<td>Flood</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16:05</td>
<td>2810</td>
<td>1.95</td>
<td>Flood</td>
<td>15</td>
<td>Kennacraig ferry moving out of sight</td>
<td>Wind increasing SS1</td>
</tr>
<tr>
<td></td>
<td>16:10</td>
<td>2890</td>
<td>1.37</td>
<td>Flood</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16:28</td>
<td>1250</td>
<td>1.34</td>
<td>Flood</td>
<td>18</td>
<td>Upwellings observed near Am Meall headland</td>
<td></td>
</tr>
</tbody>
</table>

The weather was relatively consistent during this survey, there was no rain, and the sea state was calm to smooth SS 0 – 1. The range of tidal flow speed was 0.38 to 1.95 m/s (median 0.69 m/s) and the range of depths of the sample files was 7 to 23 m (median 15 m). During this survey there was boat and ferry activity, and it was observed when the tidal flow speed increased that the area near Am Meall headland became dominated by round pancakes of water, presumably upwellings.

Figure 66 - Summary frequency spectra of background noise levels measured in the Sound of Islay slackening tidal flow speed survey.

There is some variability in these example spectra (Figure 66) but the difference is much less than for the other surveys (around 20 dB re 1 µPa²/Hz). The spiky signal of boat
noise can be seen in file 1990 plus the flattening of the profile due to tidal flow speed (file 2810, flow speed 1.95 m/s).

(a) Plot detailing the spectral profile of files 2190 and 1990 that relate to flow speeds 0.69 m/s and 0.38 m/s respectively and file 2890 a relatively faster flow speed of 1.95 m/s.

(b) Plot detailing the fastest and slowest drift in this survey. Slow flow speed file 1790 (0.47 m/s) and fast flow file 2810 (1.95 m/s).

Figure 67- Frequency spectra measured in the Sound of Islay slackening water survey comparing (a) sound files near to the broadband ‘hotspot’ and in a lower intensity area and (b) the fastest and slowest flow in this survey.

Figure 67 Plot (a) considers the spectra from the files that were related to the broadband ‘hotspot’ and one file that was out-with that area. The spectra are remarkably similar, with a notable difference in file 1990 (and to a lesser degree file 2819) where a spiky signal between 100 – 1000 Hz is observed suggesting boat noise.

Plot (b) compares the spectral profile of the fastest and slowest drift speed in this survey and the comparatively fast flow speed, file 2810 has the flattening profile from 1 kHz and above, whereas the slower flow file 1790 continues to decrease with increasing frequency.

There was the crackling and popping sound present in all of these sample files, the loudest of these was file 2810 (flow speed 1.95 m/s) just off Am Meal headland, the amplitude spikes can clearly be seen in the time series plot (Figure 68).
4.3.4 Recordings of Known Sound Sources

During each of the surveys there was the opportunity to record known sound contributors. In Kyle Rhea, ferry engine noise was recorded, in the Falls of Warness the power-washing of a tidal-stream test device, the operating creel boats (chain noise) and an acoustic deterrent device were also recorded. In the Sound of Islay the ferry and a passing Ridged Inflatable Boat (RIB) were also recorded. These spectra are presented in Figure 69 along with the average background noise spectra estimated from the selected sample files. The noise levels are all measured as the levels present at the position of the receiver; they are not intended as an indication of the source levels of the contributors, but are presented to illustrate the characteristic shape of the profile.

The signal of the ferry and the RIB is clearly seen in the spectral profile as a spiky signal in the frequency range of 50-1-2 kHz (Figure 69 plot (a)). The KR ferry is not necessarily louder; it was possibly simply closer to the recording location. The power-washing signal is a spiky raised profile from approximately 200 Hz to a peak at 1 to 8 kHz and then decreases with increasing frequency (plot (b)). The acoustic deterrent is again a clear signal in the spectral profile as a narrow peak at 10 kHz (also harmonics at 5 kHz & 20 kHz) (plot (c)). The spectral example of a working creel boat (plot (d)) has a broadband undulating profile.
Figure 69 - Frequency spectra of identifiable sound sources recorded opportunistically in the case study areas (a) ferry & ridged inflatable boat, (b) power washing, (c) an acoustic deterrent device and (d) the sound of chains being hauled from a creel boat.
4.4 SUMMARY AND DISCUSSION

This chapter has explored the background noise frequency spectra present in three case study sites, Kyle Rhea and the Sound of Islay (west coast of Scotland) and the Fall of Warness (Orkney Islands) (see Chapter Three for more detail on their locations). Using a subsample of the acoustic sound files used to generate the background noise-maps (Chapter Three) frequency spectra plots were generated.

4.4.1 WHAT ARE THE NOISE LEVELS IN AREAS SUITABLE FOR TIDAL ENERGY EXTRACTION?

It is clear that the spectral profile is a complex mix of sound contributions. In these case study areas, the likely contributors include the weather (wind and rain), local vessels, fishing boats and from the flow of the water. It is also clear that it is not always easy to distinguish each individual noise contributor when the characteristic frequencies overlap (e.g. wind noise in very shallow water and the low frequency components of vessel noise; also rain, sediment transport and snapping shrimp). A further complication is that the noise profiles presented here are a mix of contributors with no specific source e.g. weather, and definable sources such as ferries. For definable sources, it is useful to bear in mind the distance away from that source, as a recording made close to a ferry will be louder, than a recording made at distance.

It is likely that this discussion has not covered all relevant contributors such as shore/surf noise, which will also contribute to the frequency spectra in the frequencies below 1 kHz (Deane, 2000).

Vessel noise was present in all survey area, ferries of various sizes and smaller boats. The ferry noise was constant in Kyle Rhea. All sites exhibited the same profile difference between a faster flow speed and a slower flow. The spectrum levels were raised for the faster flow speeds from the frequency 1 kHz and above, resulting in a flattening off or in some cases, a raised bump in the spectral profile. The threshold for this characteristic appears to be around 1.5 to 2 m/s flow speed based on these spectra, below this speed the flattening profile is not apparent.

Rain also raises the levels in a similar frequency band (Figure 56). In the Fall of Warness acoustic deterrent(s) are also a major contributor to the frequency spectra. Of note, the files that the acoustic deterrent were not present, followed a path from the island of Muckle Green Holm to the Island of Eday, in a south westerly direction, this is also
clearly visible from the background noise-maps as a corridor of less intense background noise (Figure 58).

There are examples of a snapping and crackling sound observed in Kyle Rhea and the Sound of Islay. This is most likely due to sediment transport as these sites, although tidally swept benthic habitats; there is evidence of cobbles and coarse sediment. The Sound of Islay slackening water survey had this noise present in all files, which were recorded at lower flow speeds, which could suggest a source other than the transport of sediment.

4.4.1.1. SITE VARIABILITY

The visual comparison of the frequency spectra (Figure 70) suggests that there is a large within site variability even within the relatively short time frame of the surveys. The Sound of Islay has the largest spectral level difference in low frequencies of approximately 70 dB re 1 µPa²/Hz. This is an immense difference when one considers that a doubling of sound pressure is represented by an increase of 6 dB (Erbe, 2011 – Chapter One). One reason for this difference may be due to the variability in vessel traffic in the area.

Kyle Rhea has the largest spectral level difference in the high frequency area of the spectrum, a difference of approximately 40 dB re 1 µPa²/Hz. This difference may be due to the onset of rain and stronger wind during the survey. The Fall of Warness has more of a constant difference in spectrum levels across all frequencies (more at the lower frequencies) from 100 Hz the difference is about 20dB re 1 µPa²/Hz. The Sound of Islay slackening water survey has the least variability in spectrum levels, this is likely to be due to the survey being on a much smaller scale both temporally (4 hours) and spatially (approx. 1km²). The average for the Sound of Islay survey is lower due to the influence of much quieter levels. This is likely to be because although there was vessel noise recorded during this survey the majority of the files were recorded without vessel movement.
To look at the range of variability within sites, the standard deviation of the data was determined for all case study sites (Table 18). A low standard deviation indicates that the data points tend to be close to the average, a high standard deviation indicates that the data points are spread out more widely. Kyle Rhea has the greater variability due to the influence of the frequencies above 1 kHz due to the deteriorating weather throughout the survey period.

Figure 70 - Frequency Spectra comparison between (a) Kyle Rhea (b) Fall of Warness (c) Sound of Islay and (d) Sound of Islay Slackening water survey. Detailing the average (in dB), maximum and minimum spectral levels.
Table 18: Standard deviation of the spectrum level data from the average levels for each case study site. A lower number indicates a lesser variability.

<table>
<thead>
<tr>
<th>Case study site</th>
<th>Standard deviation (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kyle Rhea</td>
<td>11.16</td>
</tr>
<tr>
<td>Fall of Warness</td>
<td>9.20</td>
</tr>
<tr>
<td>Sound of Islay</td>
<td>10.87</td>
</tr>
<tr>
<td>Sound of Islay slackening water survey</td>
<td>5.59</td>
</tr>
</tbody>
</table>

4.4.2. Are tidal stream locations loud environments in comparison to the deep water environment?

The broadband sound pressure levels presented in Chapter Three suggested that these tidal stream areas may be a loud environment when compared to the deep water environment. The average frequency spectral levels were plotted against the Wenz curve (Figure 71). This shows that all averages are above the upper Wenz curve above 2 kHz. The Fall of Warness and Kyle Rhea and the Sound of Islay Slackening water survey are all noisier than the Wenz levels, with the Sound of Islay survey being lower than the upper Wenz curve at frequencies less than 2 kHz, but tending towards the curve.

It should be noted that the upper Wenz curve relates to a sea state significantly rougher than the conditions within which these data were collected. Sea state 6 relates to near gale to gale force. The levels compared here are therefore not like-for-like in terms of sea state conditions. What this means is that the difference between tidal-stream areas and deep water areas is greater than is suggested by comparison to the upper Wenz curve. Figure 71 also shows the curves applicable to sea state 4, to compare the levels found in this study with deep sea levels in similar sea state conditions.

The spectral profiles measured in the tidal-stream case study areas all tend towards a flatter profile than the Wenz curves, with increased levels in the higher frequencies, which may be due to an increase surface agitation due to the tidal flow motion and sediment transport.
Chapter Four

Figure 71 - Average frequency spectra from Kyle Rhea (KR) the Fall of Warness (FOW) and the Sound of Islay (SOI) compared to the upper (SS6) and lower background noise level curves as generalised by Wenz, also shown is the Sea state 4 (SS4) to illustrate the levels similar to sea state conditions measured in this study. The averages are of similar slope and level up to around 2 kHz. At higher frequencies the levels in the tidal stream sites flatten in profile at a higher spectrum level.

A flatter spectral profile was also found by Bassett et al, 2010. In their study they found a positive relationship between the tidal-flow speed and the sound level measured. However, they discuss the input of what they call ‘pseudosound’, they used a static hydrophone which was subject to noise input from the flow of water past the hydrophone. The method of using drifting hydrophones should avoid this issue and therefore the noise recorded should be the background noise rather than flow noise. Bassett et al, 2010 also mention that the noise may also be elevated by cobbles shifting on the seabed.

The spectrum level plots presented here, suggest a currently loud environment, with a variability of up to 40 dB re 1 µPa²/Hz. These results suggest there may be as much variability within site as there is between sites depending on the local conditions at that time (i.e. vessel activity and or weather). Anthropogenic inputs such as power-washing were not included in the averaged spectra, but it is important to acknowledge that these inputs will raise the local background noise levels. This is of relevance when considering the potential noise input during the maintenance of marine renewable devices.

Marine life within these environments will be well adapted and used to the current noise levels and the temporal and spatial variability of the noise levels. Therefore, the audibility of tidal-stream devices will depend on their sound level and output frequency characteristics in comparison to background noise levels and this will be investigated further in Chapter Five.
CHAPTER FIVE – A REVIEW OF AVAILABLE TIDAL-STREAM DEVICES
ACOUSTIC OUTPUT SIGNATURE

5.1 INTRODUCTION

The marine renewable industry is currently at a relatively early stage in development (Todd, 2012) and as such there is a lack of available information detailing the acoustic output of marine renewable devices (PersObs). At this stage the industry is still very much testing their devices’ performance and survivability, and acoustic output seems to be considered further down the development process once the developers have established and tested their devices (PersObs). The majority of existing environmental data, including operational acoustic recordings, are typically held ‘Commercial in Confidence’ i.e. publically unavailable (PersObs). Whilst this confidentiality is completely understandable from a business viewpoint, it is a frustration when attempting to gather data to inform the debate regarding the possible marine renewable device interaction with the marine environment.

This chapter reviews what is known about tidal-stream device output, from data that is publically available, and commercial data from two developers with their permission. As there is general paucity of information available regarding device acoustic output, I first consider the likely signature output from tidal devices by reviewing what is known from the offshore wind turbine development and by describing relevant example tidal-device noise modelling studies. Then information from three leading tidal-stream developers is presented. This review aims to elucidate the likely sound levels and spectral content output from tidal-stream devices to investigate further my thesis Research Question 4.

Research Question;

4) What is the likely acoustic output from tidal-stream devices?

It is likely that device developers will endeavour to minimise the noise output as any noise generated represents a loss in the efficiency of the device (Faber Maunsell & Metoc, 2007). Acoustic output will probably be device specific and there are numerous devices in development (Carbon Trust, 2011). It is possible that all will have individual
acoustic output signatures due to various engineering design specifics, such as number and size of blades, type of generation motors and size of device. Machinery in general characteristically emits low frequency noise (Richardson et al, 1995).

5.1.1 NOISE OUTPUT FROM OFFSHORE WIND TURBINES

The offshore wind industry is much further developed than tidal-stream or wave devices (www.snh.gov.uk).

Although the sound pathway for offshore wind turbines and tidal turbines to the underwater environment will have differences (Figure 72), as the working machinery for wind turbines is separated from the water column, and the transmission path is more convoluted (air, pile, substrate). Whereas, tidal turbines will have their working machinery within the water column ensuring more direct sound transmission. Wind turbine output may give insight to the characteristics of tidal-stream turbines in lieu of tidal turbine data. Information regarding wind turbine acoustic output is available in the published and grey literature (i.e. commissioned reports rather than peer reviewed in journals). Table 19 details available offshore wind turbine source levels and the dominant frequency range. However, it is difficult to compare these source levels directly as different authors have used different methods to determine source levels. Notwithstanding this difference, wind turbine broadband source levels are between 120 to 153 dB re 1µPa and spectrum levels relevant to the dominant frequencies range from 90 to 150 dB re 1 µPa²/Hz.
The noise from wind turbines has also been measured as a performance diagnostic tool (Urbanek et al., 2012). In their study, Urbanek et al. (2012) found that the vibration signal generated by wind turbines dominated the lower frequency range up to 5 kHz, and was mostly related to gear mesh components. They suggested that the frequency measured from the turbine could be used to diagnose bearing faults. Urbanek et al. (2012) only assessed frequencies up to 12.5 kHz, supporting the concept of low frequency dominance of turbine acoustic output.

### 5.1.2. NOISE OUTPUT FROM TIDAL-STREAM DEVICES

There is very little information available on the acoustic output of tidal-stream devices. However, there are a few references in reports and literature that are of interest. The OSPAR report (Götz et al., 2009) quotes general tidal turbine source levels of 165 to 175 dB_{RMS} re 1 µPa @ 1m with the broadband frequency range of 10 Hz to 50 kHz, and describes the noise as omnidirectional and continuous. This is a broader frequency range than is suggested by the wind turbine analogy.

A paper written by Lloyd et al. (2011) considered the modelled noise output of tidal turbines and their potential impact on the marine environment. They identified potential turbine noise sources and modelled the resulting noise levels. They estimated that a typical turbine will emit 119 dB re 1 µPa (Third octave levels) at 20 meters from the turbine and suggested that the dominant frequencies would be up to 500 Hz. Much of the following is taken from the Lloyd et al. (2011) paper.

### Table 19 - Published offshore wind turbine noise output detailing dominant frequencies and maximum turbine source levels.

<table>
<thead>
<tr>
<th>Dominant Frequency</th>
<th>Max source levels (units as presented in reference)</th>
<th>Wind turbine size</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 – 800 Hz</td>
<td>128 dB re 1 µPa^{2}/Hz</td>
<td>Simulated 2 MW</td>
<td>Koschinski et al, 2003</td>
</tr>
<tr>
<td>50, 160 &amp; 200 Hz</td>
<td>90-150 dB re 1 µPa^{2}/Hz</td>
<td>2 MW</td>
<td>Thomsen et al, 2006</td>
</tr>
<tr>
<td>Below 1 kHz</td>
<td>145 dB_{RMS} re 1 µPa</td>
<td>Not specified</td>
<td>Masden et al, 2006</td>
</tr>
<tr>
<td>Below 1 kHz</td>
<td>90-150 dB re 1 µPa^{2}/Hz</td>
<td>0.2 – 1.4 MW</td>
<td>Wahlberg &amp; Westerberg, 2005</td>
</tr>
<tr>
<td>23 – 30 Hz</td>
<td>120 dB</td>
<td>&lt; 1 MW</td>
<td>Vella et al, 2001</td>
</tr>
<tr>
<td>Below 100 Hz</td>
<td>153 dB re 1µPa</td>
<td>&lt; 1 MW</td>
<td>Nedwell &amp; Howell, 2004</td>
</tr>
</tbody>
</table>

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5.1.2.1. Potential tidal turbine noise sources

The output levels and characteristics are likely to be dependent on the device and deployment site, and influenced by features such as blade design, water depth, tidal-flow speed and the local bathymetry. Potential noise sources will include; rotating machinery, flexing joints, structural noise, moving water, moorings, electrical and instrumental noise (Faber Maunsell & Metoc, 2007). The potential key tidal-stream tidal noise generators are illustrated in Figure 73.

![Figure 73 - Potential sources of noise for a generic horizontal axis tidal turbine (Lloyd et al, 2011).](image)

The major difference between the offshore wind turbine and tidal turbine sound pathway into the marine environment is that for tidal turbines, noise is either transferred directly into the water column or via the seabed. Unlike offshore wind turbines, there is no airborne element. Although the contribution that airborne noise will make to underwater noise will be minimal, due to the poor transmission of sound through the air-sea interface (PersCom B. Marmo Xi-Engineering). Aside from the rotating machinery and the structural vibration, the main noise sources discussed here are related to the interaction of the movement of the device and the flow of water.

Noise generation due to rotating machinery and structural vibration are relatively easy for the lay-person to appreciate. However, the interaction of the device with the flow of water is not as obvious, and so is described in more detail (Figure 74 adapted from Lloyd et al, 2011).
Figure 74 - Categorisation of the potential noise sources from an operating tidal turbine (Lloyd et al, 2011) categories described in the text.

1) Steady loading relates to the distribution of force along the blade. Noise from this source will generate broadband noise behind the rotor between the axis of rotation and the plane of the rotor.

2) Unsteady loading relates to the in-flow turbulence and the changing flow velocity (tides) past the device itself. This will generate low frequency noise of less than 1 kHz, the maximum noise levels will be in the direction of the axis of rotation. This suggests a degree of directivity of the noise emissions (see further discussion below).

3) Thickness relates to the blade geometry and is connected to unsteady loading, i.e the shape and thickness of the blade affects the way the flow of water interacts with the turbine. As with unsteady loading this will generate noise in the axis of rotation.

4) Trailing edge relates to eddies generated as the water passes the blade edge and the resulting turbulence leads to vortices being shed and blade singing\(^4\). This interaction generates broadband and tonal noise downstream of the turbine.

\(^4\)‘Singing’ is a term often heard in connection with propellers and relates to a vibration set up in the blades due to resonance which generates a tone.
5) Cavitation occurs when the relative speed of the blade through the water is sufficiently fast to cause a drop in pressure that allows the formation and subsequent collapse of bubbles.

Lloyd et al (2012) state that the occurrence of cavitation would be unlikely in tidal turbines, but another study Wang et al, (2007) suggested that the potential for cavitation was being overlooked. However, Fraenkel (2007) stated that the speed of the underwater blades is generally low (in comparison to either wind turbines or ship propellers) because of the requirement to avoid cavitation. Therefore it is probable that tidal turbine developers will seek to minimise the likelihood of this happening, as cavitation, apart from representing inefficiency, can cause damage to the blades.

It is clear that tidal-stream devices will generate noise both due to the mechanical motion and the resulting vibration of the device, and the flow of the water past the device. It is likely that noise will be generated in the axis and plane of rotation suggesting a degree of directionality (Lloyd et al, 2011). In this thesis the background noise was measured at locations in tidal-stream locations with no reference to where any of the sound was coming from. Background noise is made of a combination sounds from various sources, without necessarily knowing where they originated. But as all sound propagates from its source, there will be a directional element.

Based on this limited review, there appears to be regions within a turbine structure where there is greater sound generation in a particular direction in comparison to other parts of the structure.

There are two main mechanisms for the noise to be transferred into the underwater environment; direct coupling and via the seabed (Lloyd et al, 2012);

1) Direct coupling is the mechanism by which the noise is transferred by direct contact with the environment e.g. the blades in the water.

2) Seabed coupling is when the noise is being transferred through the structure unto the seabed and then up into the marine environment.

The information on the potential noise emissions from Lloyd et al (2011) was drawn from the shipping propeller literature, although analogous, the fundamental difference is that ships propellers are driven by an engine to turn in the environment thereby pushing water backwards to generate ship movement. Whereas, tidal turbines are
turned by the flow of water thus generating movement which then results in the ability to capture the kinetic energy contained in the tidal-stream. This may be a significant difference in itself, as well as the difference in respective sizes and revolutions per minute. As time progresses and more tidal devices are deployed and acoustically monitored, our understanding of the differences will improve and this difference may be better resolved.

Whilst developers will aim to minimise noise emissions, because noise generation will reduce the efficiency of the device, increased noise levels during faulty conditions are intuitively inevitable (Faber Maunsell & Metoc, 2007). A faulty bearing, for example, would generate elevated levels of both broadband and tonal noise. Worn gear boxes and anti-vibration mounts will generate extra noise and affect the efficiency of the device, and worn rubber seals may generate squeaks (Faber Maunsell & Metoc, 2007). Lloyd et al (2011) suggest that biofouling may also be a potential noise source due to increased friction on the device with the flow of water. This suggestion has been extrapolated from the level of flow noise from a ship that can be linked to the degree of fouling on the hull.

Engineers are able to model tidal-stream turbine noise. Lloyd et al (2012) based their model on inflow turbulence and trailing edge noise only, rather than including all sources. Nonetheless, their model predicted a maximum turbine source level of 141 dB re 1 µPa @1m (based on a three (20 m diameter) bladed device). In contrast, Wang et al (2007) model predicted a device source level of 131 dB re 1µPa @1m (also based on a three bladed, 20 m diameter device). Both studies acknowledge that not all potential noise sources were included in the models, and propose that the device acoustic output in reality could have higher source levels.

Of relevance to my study Lloyd et al (2011) also modelled the directivity of the acoustic output and found that the least sound was generated in the plane of the rotor and they suggested that this may be an issue for marine mammal detection. This suggestion will be discussed further in Chapter Seven.

5.2 Acoustic output from tidal devices

There are currently limited data regarding the acoustic output from tidal-stream devices because of the relatively immature status of the industry. There is a huge diversity in device types (see www.emec.org.uk) and most are at the testing stage with few at full
scale development. The diversity in device types and designs may mean that each device could have a characteristic acoustic output.

In this section acoustic data from three leading tidal-stream developers are presented. The acoustic signatures of these devices are compared, and although the methods and analysis are not consistent in the respective reports, as the measurements were conducted by different organisations, generalities are drawn based on this information.

The three devices reviewed here are the Hammerfest Strøm HS300 (now Andritz Hydro Hammerfest), Marine Current Turbine’s Seaflow and SeaGen and the OpenHydro tidal test turbine.

5.2.1 Andritz Hydro Hammerfest

Hammerfest are currently testing their HS1000 device (Autumn 2012) at the European Marine Energy Centre (EMEC) in advance of deployment in the Sound of Islay (proposed for 2013), but at the time of writing, they are not yet in a position to quantity the acoustic output of this device (PersCom). However, there is publically available data on their prototype test turbine HS300 recorded in Kvalsund, western Finnmark, Norway. I obtained this data from within the Environmental Statement for the Sound of Islay (Scottish Power Renewables, 2010) Appendix 9.4 contained a report prepared by Akvaplan-niva (2009). The full scale 1 MW HS1000 is a scaled up version of the 300 kW HS300.

![Artistic impression of the Hammerfest Strøm HS300 device](www.emec.org.uk)

Here information from that report relevant to this thesis is reviewed. The three bladed HS300 (Figure 75) has a blade diameter of 10m, the blades maximum rotation rate is detailed as 7.2 revolutions per minute (Akvaplan-niva, 2009).

Kvalsund (70°30’ N 24°E) in northern Norway is a narrow strait between the mainland and the island of Kvaløya (Figure 76). The developer has an office at Hammerfest, a
town located in the western part of the island making Kvalsund an idea location for initial testing.

The strait is 4 km long by 0.6 km wide and up to 70 m deep. The HS300 was installed at a depth of 50 m. The seabed in the narrows is typically U shaped, and consists of rock, gravel and stone (mhk.pnnl.gov). The description of the seabed is general and does not specify where the areas of rock and gravel and stone are. There is no specific detail in Akvaplan-niva’s report of the flow speed during the measurement period, instead the current is described as ‘strong’ ‘weakening’ or ‘calm’; however, Kvalsund’s maximum tidal-stream flow speed was listed as 2 m/s.

The device acoustic output was recorded about 4 days after spring tides on the 22nd and 23rd October 2009, during one night and the following morning, using a handheld hydrophone deployed from 14 foot drifting boat platform. The depth of the hydrophone was 17 to 19 m. The position of the boat during the drift was logged using a handheld GPS unit. The weather during the survey was calm, no precipitation, westerly winds 1-3 m/s. The water column was well mixed with no stratification.
Measurements were taken at the sampling frequency of 48 kHz (therefore resulting in the upper frequency of 24 kHz being reported) and a flat frequency response in the bandwidth 20 Hz to 22 kHz was noted. Total Broadband Sound Pressure Levels were given as a function of time during one of the drifts. Total times of the drifts were approximately 8 minutes. Third octave SPLs ranged from 130 to 150 dB re 1 µPa. Disappointingly there was no estimation of source level. They reported the main contribution to the tidal turbine sound output was tonal between the frequency range of 50 to 3000 Hz. Peaks at 150 to 800 Hz were also highlighted. Akvaplan linked many of these tones with the turbine gear box, in particular the number of shafts and gear wheels within the gear box. Turbine noise recordings were compared to background noise recordings of Kvalsund and were considered attributable to the turbine in operation.

5.2.2. MARINE CURRENT TURBINE

Marine Current Turbines (MCT) deployed their device Seaflow off the coast of Devon, England, in May 2003 in a pilot project to develop and test a commercially-sized tidal-stream turbine. Their second generation device SeaGen was deployed in Strangford Lough, Northern Ireland, in April 2008. Data presented here is derived from reports prepared by Subacoustec, Kongsberg and SMRU ltd by permission of David Ainsworth, of MCT.

5.2.2.1. SEAFLOW

MCT’s Seaflow device was a horizontal axis turbine with an 11 m diameter rotor (Figure 77). This device was rated to generate 300 kW in a current flow speed of 2.7 m/s and was operational in both ebb and flood tide directions due to reversing pitch blades. Seaflow was installed at a depth of 15 m (at the lowest tide) therefore at the minimum depth there was 2 m clearance to the seabed and sea surface (European Commission, 2005).

Seaflow was installed during May 2003 (www.seageneration.co.uk) about 1 km off Foreland point, near Lynmouth on the North Devon coast of England (51°15’N 003°47’W) (Figure 78).
Acoustic recordings were made in March 2005 (Richards et al., 2007). The weather was calm, steady south westerly wind at 2 m/s. Measurements were made in the frequency range 1 Hz to 175 kHz. The report does not mention a drifting platform type specifically, but it is inferred as they state measurements were taken on a westerly course from a distance of 1300 m away from the turbine. Recordings were of 10 second durations. Seabed and flow speed characteristics were not detailed within the report.

The report stated that turbine noise was evident with tones at frequencies 11 - 100 Hz, and a broadband signal between 150 Hz to 50 kHz. Prominent noise peaks were seen at frequencies 12, 350, 150, 5000 Hz indicative of low frequency mechanical noise. In addition the authors noted noise energy from 300 to 3000 Hz; they suggested the source was either turbulence or mechanical noise.
Broadband SPLs ranged from 123 to 140 dB re 1 µPa and the authors back-calculated the source level to be 166 dB re 1 µPa, determined from measured received levels at increasing distance away from the turbine, thus accommodating the transmission loss characteristics of the area. Extrapolating this figure the authors suggest the turbine would be above background noise levels up to a range of approximately 4 km. They found that the low frequency components that dominated the device signal rapidly decayed with range. Also noted was that there was a large variability in sound pressure levels even at similar distances away from the turbine (Richards et al., 2007). Richards et al. (2007) reviewed this data for their report to the Scottish Executive and stated that on listening to the recordings they could hear a large amount of shore surf noise plus shipping noise and commented that this would have had some influence on the measured levels. Also noted was a narrowband tone at 5 kHz believed to be a switching frequency in the power conversion system within the generator (Richards et al., 2007) and there was a peak at 100 Hz believed to be due to a faulty bearing, leading to a conclusion that the noise levels reported may therefore be higher than ‘normal’ (Richards et al., 2007).

5.2.2.2. SeaGen

MCT’s second generation device SeaGen is significantly larger than Seaflow. SeaGen has twin 16 m diameter rotors set on a 3 m diameter pile (Figure 79) and has a 1.2 MW output capacity. The blades have adjustable pitch and have a maximum 14 rpm resulting in a tip speed of approximately 12 m/s. The device was deployed in Strangford Lough in April 2008 (Figure 80) is grid connected and is capable of generating electricity from current speeds of 1 m/s.

Strangford Lough is a fjord situated on the east coast of Northern Ireland (54°26′N 05°35′W). It is the largest inlet in the British Isles at approximately 150 km² and the resulting tidal flow (of 350 cubic meters of water) through the narrows every tide is substantial. The name Strangford Lough is derived from Old Norse Stranr-fjǫrðr which means ‘strong fjord’ relating to the strength of the currents (at 3-4 m/s) flowing through the narrows (jncc.defra.gov.uk). The seabed type in the narrows is mainly tidally swept rock (jncc.defra.gov.uk).
Recordings of the devices’ acoustic output were made in November 2009 by Kongsberg (Kongsberg, 2010). They deployed their hydrophone at a 5 m depth from a drifting boat platform and using an anti-heave buoy. During the drift the engine and all boat electronics were switched off. The frequency range of the recordings was between 10 Hz and 250 kHz. Power spectrum levels were produced using 1 second averaging. They concluded that the device generated narrowband tones as well as a broadband signal.
Operational tones were observed at 110, 143, 224, 331, 716, 1413, 2089 and 2291 Hz. Unweighted broadband SPLs ranged from 126.4 to 140.8 dB re 1 µPa. The back calculated source level was 174 dB$_{\text{RMS}}$ re 1 µPa @1m (Götz et al, 2011).

Measurements were pooled from both the ebb and flood tide to generate a sound field map, although there is no information on the flow rate at the time of the measurements. Received levels presented were highly variable in the surveyed area. Specifically, there were pockets of high levels extending linearly north and south of the device’s location (Götz et al, 2011). Also noted in the report was that the noise energy output was not symmetrical, with energy extending further north than south (Götz et al, 2011) and the authors linked this to a local bathymetry effect. This information in their report suggests a directivity of noise output. They supported their preference for using broadband Source Pressure Levels (RMS) rather than considering the acoustic output by frequency because this reflected the noise-field in general terms and therefore was more suitable for visual representation in what they called a sound field map.

The authors also found, in agreement with Richards et al, (2007) that the tonal components, although low frequency, decayed faster with distance than the broadband noise (Kongsberg, 2010).

5.2.3. OpenHydro

The data presented in this section were collected during commissioned research for OpenHydro by the Scottish Association for Marine Science (SAMS). The field work was conducted by Jim Elliott (SAMS), analysed by myself and presented in our report written by Ben Wilson (Wilson et al, 2010). Permission to present this data within this thesis was kindly given by Sue Barr of OpenHydro.

OpenHydro’s test device (OCT0665) has been deployed at the European Marine Energy Centre’s (EMEC) test site since 2006. It is a 6 m diameter, open-centre device with the blade tips contained in an outer housing (Figure 81). For ease of testing the device is situated on a twin-piled structure in Orkney, but the commercially installed units will be situated on gravity bases with no part of the structure above the sea surface.
Chapter Five

Tidal stream devices

Figure 81 – (a) OpenHydro tidal turbine situated on a twin pile structure at EMEC and (b) an artist’s impression of the device deployed on a gravity base (www.openhydro).

The tidal test site in Orkney is the Fall of Warness, situated on the west side of the island of Eday (59°8’N 49°W) (Figure 82). The OpenHydro device is situated in a shallow test berth at approximately 18 m depth. The seabed type in the area is predominantly tidally swept rock. Peak spring tides through the Fall of Warness are in excess of 3.5 m/s.

Figure 82 - Circle illustrates the location of the OpenHydro test device in the Fall of Warness - EMEC tidal test site in Orkney, box illustrates the location in the Orkney Islands.

The recordings were collected on the 23rd August 2010 using the drifting hydrophone methodology (see Chapter Two). The frequency range was up to 48 kHz. The weather during the survey was a wind strength Beaufort scale force 3 in an Easterly direction, sea-state 2-3 and there was light rain towards the end of the survey. There were 23 drifts in total deployed between 07:39 and 20:39 hrs. The flow speed during the measurements was 1.66 to 2.58 m/s.

Unfortunately, the majority of recordings were contaminated by vessel noise from unrelated activities, working in and around the tidal test site, and were therefore unusable. Vessel activity ceased after 18:00 hrs, and after this time six usable recordings (equal to 17 minutes of clean data) were available for analysis.
In these files, a rhythmic clicking noise could be heard, particularly evident in recordings made closer to the turbine. This clicking was a semi-intermittent but regular ‘rattling tick’ noise with approximately 20 ‘ticks’ per second. The ‘ticks’ were visually clear as illustrated in the spectrogram (Figure 83). The turbine was in operation at this time, and it was reported by OpenHydro as rotating at approximately 17 revolutions per minute. The ‘ticking’ noise was not observed in the area’s background noise recordings, made when the device was not operating.

Analysis of the ticking noise showed that it was broadband but with the majority of the energy between 400 and 5000 Hz. In addition there was a narrowband tone present that varied between 50 and 110 Hz with a prominent harmonic at twice that frequency. Also present in all recordings was an obvious noise source not connected to the device, this was an intermittent pulse at around 10 kHz which was consistent with a fish farm acoustic seal-scarer device (see Chapter Four). This characteristic signal was observed during background recordings in the Fall of Warness when the OpenHydro device was out of the water and therefore is not attributable to the device.

Broadband SPLs ranged from 116 to 127 dB re 1 µPa (excluding the fish farm related pulse at 10 kHz). The device source level (using third octave levels, calculated over the frequency range up to 4 kHz) was estimated to be 125 to 148 dB re 1 µPa@1 m. A range was presented in our report because two methods of back-calculation were used, the first used a standard transmission loss equation that takes into consideration both circular and spherical spreading relative to the local water depth \[ TL = 20 \log_{10} R_2 + 15 \log_{10} (R/R_1) \] (Koschinski et al, 2003) and the second, was back-calculated using measured received levels and plotted against distance from the OpenHydro device (Wilson et al, 2010).
5.3 SUMMARY AND DISCUSSION

At present, information detailing the acoustic characteristics of tidal-turbines is scarce. However, I have been able to bring together some information from three of the leading tidal-stream device developers. Data are presented here for three underwater ‘windmill’ type devices and one open-centre device. Although some generalities can be made I think that each device is likely to have its own characteristic acoustic signature. For example, the ticking sound observed for the OpenHydro device is likely to be specific to that device, although at this stage the precise source of the noise is unknown.

The acoustic output of the devices reviewed here is summarised in Table 20. In general, tidal stream devices appear to input into the marine environment a tonal and broadband signal. The tonal inputs are reported at below 5000 Hz. Although the broadband received level is listed, caution must be taken with comparing these values as the ranges to each device for each measurement are variable. These are an indication of the range of possible received levels within a development site.

Table 20 – Acoustic output summary for tidal-stream devices, modelled tidal-stream devices and offshore wind turbine acoustic output

<table>
<thead>
<tr>
<th>Device</th>
<th>Hammerfest Strøm (HS300)</th>
<th>MCT (Seaflow)</th>
<th>MCT (SeaGen)</th>
<th>OpenHydro (OCT 0665)</th>
<th>Offshore wind turbine</th>
<th>Modelled tidal turbines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power output</td>
<td>300 kW</td>
<td>300 kW</td>
<td>1.2 MW</td>
<td>--</td>
<td>&lt;2MW</td>
<td>--</td>
</tr>
<tr>
<td>Device type</td>
<td>3 blade</td>
<td>2 blade</td>
<td>Twin 2 blades</td>
<td>Open centre</td>
<td>3 blades</td>
<td>3 blades</td>
</tr>
<tr>
<td>Back calculated Source level (dB re 1 µPa @1m)</td>
<td>--</td>
<td>166</td>
<td>174</td>
<td>125-148</td>
<td>120-153</td>
<td>131-141</td>
</tr>
<tr>
<td>Main frequency contribution range (Hz)</td>
<td>Tonals 50-3000</td>
<td>Tonals 12-5000 &amp; broadband</td>
<td>Tonals 110-1500 &amp; broadband</td>
<td>Tonals &lt;5000 &amp; broadband</td>
<td>&lt;1000</td>
<td>&lt;500</td>
</tr>
<tr>
<td>Broadband received SPL (dB re 1 µPa)</td>
<td>130-150</td>
<td>123-140</td>
<td>126-140</td>
<td>116-127</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Estimated source levels from measurements made of actual tidal-stream devices range from 125 to 174 dB re 1 µPa @ 1 m. Offshore wind turbines source levels range from 120 to 153 dB re 1 µPa @ 1 m (note these relate to a larger power output than tidal turbines) and the modelled tidal turbine source levels ranged from 131 to 141 dB re 1 µPa @1m. In comparison, to known source levels from other anthropogenic inputs
(Chapter Four – Table 13) tidal turbines appear to be in a similar frequency range and source level to smaller vessels (145-170 dB re 1 µPa @ 1 m) larger ships are louder (172 to 190 dB re 1 µPa @ 1 m) and acoustic deterrents, depending on which type, could be louder again (up to 210 dB re 1 µPa @ 1 m).

The presented source levels for the OpenHydro device were a range because different propagation equations were used within our report (Wilson et al, 2010). The higher source level was estimated using the first method, the standard transmission loss equation. Also of note, was that the larger MCT device was estimated to be 8 dB louder than the smaller version. It is therefore likely that the larger Hammerfest device planned for deployment will be louder than the test device acoustic output presented here. Broadband SPL for the HS300 were louder than the other devices in general, it is therefore unhelpful that there was not an estimated source level for comparison purposes. OpenHydro is the quietest of the devices considered here.

Based on these examples, tidal-stream device acoustic output is dominated by low frequency energy, which is consistent with existing understanding of man-made machinery. It is interesting to note however that the low frequency tones did not appear to propagate as far as the broadband signal (Kongsberg, 2010; Akvaplan-niva, 2009). This may be an effect of the depth of the area, as shallow areas cannot sustain low frequency propagation. The frequency that this characteristic may relate to, will vary depending on the depth of the development site.

Also, highlighted from this review was that tidal device acoustic output is likely to be directional rather than omnidirectional as suggested by the Ospar report (Götzt et al, 2009). The MCT analysis found that the acoustic output was concentrated around the turbines; mainly aft of the device, that the sound field was not symmetrical and appeared to depend on the bathymetry (Götzt et al, 2011). The Lloyd et al, (2011) modelling study also suggested directivity (discussed further in Chapter Seven).

Isolating what is and what isn’t attributable to the tidal-stream device is not straightforward. Measurements made in the natural environment where there are numerous sounds and sources all in combination and as such, will include elements of background noise not directly related to device noise. So that any such device acoustic signature can be teased from the recording, it will be important to make recordings in the same location when the said device under scrutiny is present, but not operating.
Then recordings should be made with the device in operation and with knowledge of how it is performing (e.g. number of revolutions per minute, or that device is not turning) which can be compared to the non-operating recording.

The methods and metrics used to assess underwater background noise and tidal-stream devices are variable making direct comparisons problematic. Therefore, the following information is suggested as a minimum in order to consider the acoustic output of a tidal device;

1. **Background noise baseline** – at the development location but when the device is not in operation:
   a. The range (and/or average) of unweighted Broadband SPL$_{RMS}$ in the area over a period of time.
   b. Together with the related Power Spectral density plots.

2. **During device operation:**
   a. Detail of device activity, on/off, various rpm etc.
   b. Unweighted broadband SPL$_{RMS}$ plotted at increasing distance from the device location.
   c. An estimation of the device source level.
   d. Related Power spectral density plot.
   e. A spectrogram plot.
   f. Time series plot.

3. **For both scenarios the following should be noted:**
   a. Ancillary data, such as weather, wind speed and direction, tidal-flow speed and direction, sea state, geographic/bathymetric characteristics of area, water depth, and approximate size of location, visualisation of area surveyed, details of vessel movement and any other anthropogenic input at the time. Measurement methodology – including platform (drifting boat/hydrophone) and depth of hydrophone.

4. This should allow detail of the temporal and spectral structure to be presented.

5. **Additionally, for all measurements** – the frequency range, sound file averaging period and analysis window should be noted, plus hydrophone system calibration detail should be included.
This chapter has presented what little information there is available regarding the acoustic output from tidal-stream turbines. Despite imminent development, there is very little in the public domain to refer to. However, the measuring and reporting of tidal turbine acoustic output will be a requirement within developments environmental statements, therefore the availability of data is likely to improve in the next few years.
CHAPTER SIX — SIGNAL-TO-NOISE RATIO OF TIDAL-STREAM DEVICES VERSUS BACKGROUND NOISE LEVELS, AND THE POTENTIAL FOR DETECTABILITY BY MARINE MAMMALS USING PASSIVE HEARING

6.1 INTRODUCTION

The deployment of marine renewable devices, particularly in Scotland, is largely expected to accelerate in the near future. Marine renewables are well placed to provide a significant contribution to our energy needs in the future because of the abundance of wave and tidal-stream resource in UK coastal waters (Chapter One). However, one potential barrier to the widespread deployment of tidal-stream devices is the perceived collision risk to marine mammals. Marine mammals have excellent sensory perception and underwater agility, but existing collision parallels have shown that marine mammals - though capable - do not always avoid hazards; fatalities due to ship-strikes and by-catch are well documented (Pace et al, Panigada et al, 2006; Read et al, 2006; Laist et al, 2001). Marine mammals’ primary sense is hearing; sound is used for communication, navigation, prey detection and obstacle avoidance. Hence the consideration of how detectable these devices may be in tidal-stream locations is of relevance. If audible, what might the detection distance be and therefore how much warning time could be available? Conversely, if sufficiently noisy, might these devices act as a barrier and therefore exclude animals from passing through or using the habitat.

Tidal-stream devices were the focus in this thesis because they conceptually present the larger collision risk compared to other types of marine renewable devices, due to the combination of turning blades, flowing tidal-stream current and their siting in restricted passageways. Richardson et al (1995) states that audibility “is determined by the radiated power (source level), the propagation efficiency, the background noise levels and the hearing sensitivity of the subject species”. Therefore, this chapter will firstly consider how marine mammals hear (including brief discussion on odontocetes echolocation), how noise impact is assessed for marine mammals and what is known about behavioural responses to anthropogenic stimuli. Then, using data from Chapter Three (background noise levels), Chapter Four (spectral characteristics), and Chapter Five (tidal-stream acoustic output), a basic tidal-stream signal-to-noise model is presented for each of the three case study locations, Fall of Warness, Kyle Rhea and the Sound of Islay. This chapter will address the following Thesis Hypothesis and Research Questions (Chapter One).
Thesis hypothesis;

2) The acoustic output of tidal devices may therefore be masked by the environment and therefore not easily detected acoustically.

Research question;

6) Over what range might the signal of tidal devices be greater than the background noise?

6.1.1 Marine Mammal Hearing

Marine mammals are well adapted to their underwater environment, with good vision and hearing capabilities, but the operating range of vision is limited by the transmission of light underwater. This range varies, but could be limited to only a few metres in turbid coastal waters. Conversely, sound can travel through the water extremely well (Apel, 1988). It is well understood that marine mammals use sound and hearing as a primary sense for communication, foraging and navigation and therefore acoustic cues are likely to be the most important sensory component of device detection and avoidance. This section gives a summary of marine mammal hearing and how this resembles and differs from terrestrial mammals.

Marine mammals have evolved from terrestrial mammals and as such their ear is functionally similar to a terrestrial mammal’s ear (NRC, 2003; Wartzok & Ketten, 1999) with an outer, middle and inner ear (Figure 84) (Nedwell et al, 2004). The outer ear comprises of a sound collector (the size and shape of the ear varies between species) plus an auditory canal that funnels the sound waves to the tympanic membrane (the ear drum). The tympanic membrane is the start of the middle ear. Sound waves cause the membrane to vibrate thus conveying the sound into mechanical movement, the vibration is passed along the ossicular bones (the malleus, incus and stapes) the last of these, the stapes vibrates the oval window, the boundary of the inner ear, and transmits the vibrations into the fluid filled cochlea. The fluid movement bends cilia within the cochlea and this movement is converted into the electrical signals that the brain interprets as sound (Numela et al, 2007).
In evolution timescales, marine mammals have adapted the terrestrial ear to the marine environment. Cetaceans lead a fully aquatic lifestyle and as such the external ear is lost (Figure 85), the external auditory canal is still present but much reduced and plugged with biological tissue; there is debate as to whether this canal is functional in any case as there is no observable connection to the Tympanic membrane (Ketten, 1992). The middle and inner ears have migrated outwards away from the skull (within the Auditory Bullae). In most odontocetes the auditory bullae are suspended by ligaments in a foam filled cavity, effectively acoustically isolating the ear from sound conduction through the skull (Wartzok & Ketten, 1999). But it is thought that sound is channelled from the environment to the middle ear through the jaw (Nedwell et al, 2004), the mandible is a concave bone with a fatty tube leading to the auditory bullae. There is on-going debate as to the pathway through the middle ear, with two main possibilities; bone conduction and the more conventional ossicular motion (Ketten, 1992; Cranford et al, 2010) and although much is understood from anatomical models and post-mortem dissection, the complete acoustic pathway has not been definitively determined as yet (Schusterman et al, 2000; Au & Hastings, 2008).
The pinniped ear is similar to the terrestrial ear, but because pinnipeds are semi-aquatic their hearing has had to adapt for both in air and in water. Their acoustic pathway may be more complex than either terrestrial or wholly aquatic animals (Au & Hastings, 2008) or it may be more of a compromise (Wartzok & Ketten, 1999). Humans hear underwater by bone conduction (Au & Hastings, 2008) so it is reasonable to assume that pinnipeds hear underwater the same way (but this pathway not yet experimentally verified (Au & Hastings, 2008)).

It is clear that while the acoustic pathway in marine and terrestrial mammals is derived from the same ‘blueprint’, there are significant differences and despite extensive research in this area, marine mammal hearing is still poorly understood (Cranford et al, 2010).

Animal hearing capability is typically described using a graph of hearing sensitivity versus sound frequency on a log scale (Wartzok & Ketten, 1999). This graph is known as an audiogram. In basic terms, the subject being tested is presented with tones at known frequencies, the level of which is adjusted until the subject can no longer hear the tone. This gives an indication of the hearing threshold. The audiogram is basically a U shaped curve (Figure 86) that covers a range of frequencies and represents the lowest level of sound that can be heard at each frequency. Sound within the hearing range of frequencies will be audible provided the sound level is greater than the hearing threshold.
Currently the best way to assess what marine mammals hear is to test them. In humans this is typically done by wearing headphones, in an acoustically controlled environment, and the subject presses a button when a sound can be heard. Such a test is clearly not as straightforward for marine mammals. Therefore the two methods currently employed to test marine mammal hearing are 1) by behavioural assessments, or 2) by direct measurements of the electrical response to the sound in the subject's brain.

Behavioural methods use trained captive individual animals. The animal responds to an audible signal by pressing a button or panel of some sort and in doing so are rewarded by food. This method can involve a lengthy training period and requires the compliance of the individual.

Evoked auditory potential (EAP) method is a measurement of the electrical response in the auditory nerves using subcutaneous electrodes. A less invasive method is the auditory brainstem response (ABR) where electrodes are placed on the head. Both of these methods have the advantage that untrained or stranded animals can be tested opportunistically and thus taking a much shorter time to obtain results. Additionally, it does not require a secondary level of interpretation by the animal, thus reducing the potential of unintended filtering.

Combined data from audiograms and models show a wide variation in hearing range and sensitivity (NRC, 2003). Hearing spans several decades of frequency; humans for example hear between 20 Hz and 20 kHz while marine mammals, particularly odontocetes, are thought to have a much greater hearing range. Recordings of the
sounds emitted by marine mammals give an indication of the frequency ranges that are audible to those animals, but are not the whole picture as it is likely that emitted sounds are modified against the background noise levels (Wartzok & Ketten, 1999; Barber et al, 2009). Additionally, it is thought that animals commonly hear a broader range of frequencies than they use vocally (Barber et al, 2009).

Audiogram and anatomical modelling provides an indication of marine mammal hearing abilities. However, audiometric data is not without limitations. There are only audiograms available for 10 species of odontocetes and 11 pinniped species. All are small species that were tested in captivity; this number, out of approximately 119 marine mammal species (NRC, 2003) (128 sp Southall et al, 2007), means we do not have hearing ability data for the majority of marine mammal species (NRC, 2003; Southall et al, 2007). In particular there is no data for any mystecete (NRC, 2003) or marine otters (Wartzok & Ketten, 1999).

Further limitations include; 1) variability associated with the test conditions (there is no underwater equivalent of an anechoic chamber), 2) individual variability as audiogram data has only been gathered from a few individuals from within the species tested. It is likely that there is variability by individual as well as by species, just as can be found in humans, due to age, illness and injury (Nedwell et al, 2004) therefore it is not certain whether the data obtained is entirely representative of the species in question, and 3) audiogram data obtained in test circumstances may not reflect the hearing abilities in the natural environment as there may be other factors at play, for example whether the individual is paying attention.

Figure 87 details generalised audiograms for species of interest in the case-study tidal-stream areas and based on these graphs this suggests that the dolphin and porpoise peak hearing band ranges from about 1 kHz to 200 kHz with most sensitive hearing between 10 to 100 kHz. In comparison, seals have a flatter audiogram with better hearing than the dolphins and porpoise at lower frequencies. Their peak hearing band ranges from about 100 Hz to 70 kHz.
The discussion thus far has concentrated on passive hearing. However odontocetes (toothed whales) have the ability to echolocate. Echolocation is bio-sonar; odontocetes can emit pulses of sound and then listen for the returning echoes. Significantly, it is thought echolocation is used for obstacle avoidance as well as tracking food and navigation. Therefore for odontocetes, echolocation could play a big part in mitigating the collision risk with tidal turbines.

There is well documented experimental evidence of echolocation abilities in odontocetes, however little is known about its use in the wild (Barrett-Lennard et al, 1996). Echolocation is highly directional; the beam of sound pulse has been likened to the beam of a head torch, which will mean that only a small area is ensonified at any one time. Additionally it is thought that odontocetes do not scan the area constantly with echolocation, and that if echolocation is being used to track prey, then it is unlikely to define approaching obstacles at the same time. Barrett-Lennard et al (1996) detailed
two studies in their paper; one suggested that recently captive or untrained animals were unable to use echolocation for obstacle avoidance, another showed that a blindfolded bottlenose dolphin was able to track a live prey fish without using echolocation. However, it is commonly accepted within the acoustics community that an echolocating animal will be able to ‘see’ the environment (Martin B. 2012 PersComm; Au & Hastings, 2008). But it is not clear however ‘how’ an echolocating animal using pulses of sound will ‘see’ a rotating machine, the structure is static, but the blades are moving in a stationary location.

Therefore the decision was to focus on passive hearing in this thesis, based on the knowledge that not all marine mammals use echolocation, together with the uncertainty regarding its use in the wild, plus the understanding that odontocetes also use passive listening for prey detection and navigation (Barrett-Lennard et al, 1996). Koschinski et al (2006) suggest that harbour porpoises do not use their bio-sonar continuously and Gannon et al (2005) suggest that bottlenose dolphins use their echolocation sparingly in the wild and that they also listen passively for sounds of interest (i.e. prey) and then use their echolocation to pursue and capture. It is likely that pinnipeds use passive hearing for spatial orientation and navigation (Bodson et al, 2006).

Carstensen et al (2006) however, suggest that captive porpoises may not use their echolocation as much in captivity compared to the wild, due to their being in known surroundings with good visibility and no need to hunt for food. These different findings therefore make it difficult to assess the situation. However, it is likely that echolocation could play an important role in tidal-stream device detection for odontocetes, but perhaps not in all cases. The effectiveness of using echolocation for obstacle detection may depend on the animals’ activity in the area; whether they are transiting, socialising, mating or foraging.

Also worthy of consideration is that background noise levels and acoustic characteristics may have bearing on marine mammals’ ability to detect a noise source passively in a noisy environment. The Cocktail Party Syndrome is the inability of an individual to distinguish a sound against the background noise (McDermott, 2009). The syndrome is well understood for humans, for example, it is common for an individual not to hear conversation in noisy environment such as a pub or restaurant. It is likely that this syndrome may also be relevant to marine mammals in areas of higher background noise, such as within tidal-stream locations. Notably, the syndrome gets worse with age, also
that the individuals’ attention is of key importance in the ability to distinguish the sound (McDermott, 2009).

This section has discussed marine mammal hearing and highlighted that much of our understanding of marine mammal hearing has been extrapolated from human hearing knowledge, and although the auditory mechanism has evolved from terrestrial hearing marine mammal hearing has differences and is not yet fully understood. Marine mammal audiograms give an indication of their hearing abilities but must be considered in the context of 1) the number of individuals that this information is based upon, and 2) whether the testing methods are representative of hearing ability in the wild and 3) how much the animals’ activity and attention may have on the ability to detect signals in the environment. Also discussed was the reasoning behind not considering echolocation in detail in this thesis. The aim of this section was to highlight although there is a vast reservoir of information regarding marine mammal hearing abilities, there is also a large degree of uncertainty.

6.1.2 Noise Impact Assessment
The effect of anthropogenic noise on marine life is a current area of concern (IQOA draft, 2012) and it is widely understood that there are many uncertainties (de Jong et al, 2011). Underwater noise impact is an area that has had focus for many years; therefore this section considers methods of assessing noise impact on marine mammals. The full range of acoustic impacts (including auditory injury) is considered here for completeness, even though this thesis has focused on the operational noise from tidal turbines in relation to their detectability. Richardson et al (1995) described the potential zones of noise influence from a sound source, from acoustic injury to audibility. These are discussed here together with two examples of suggested criteria used to assess noise impact on marine mammals (Nedwell et al, 2007; Southall et al, 2007) so that the potential audibility of marine renewable devices can be placed in the wider context. In addition to the uncertainties with regard to marine mammal hearing thresholds, this section will highlight the degree of uncertainty with regard to how noise effects on marine life is perceived.

6.1.2.1 Sound Source Zones of Influence
Sound source zones of influence relate to the levels of noise with distance from a discrete sound source, and were first suggested by Richardson et al (1995). There are four zones that relate to the intensity of the noise and the effect that it may have (Figure
The effects of the noise and the range over which the noise may impact depends on the type of noise, its level, frequency content, duration, and temporal pattern, the background noise, the propagation characteristics of the location and of course, the animal under consideration.

Zone (a) – The zone of hearing loss, discomfort or injury. This is the area closest to the sound source. It assumes that marine mammals (in a similar manner to terrestrial animals) suffer hearing loss when exposed to intense sound. Where the noise is sufficiently intense, damage occurs to the inner ear resulting in a permanent threshold shift (PTS) of hearing ability whereby the animals’ hearing is permanently reduced. (Extreme noise levels can also cause physiological damage to an animal’s internal organs (Richardson et al, 1995)). Where the sound is not intense enough to cause PTS, the animal may suffer a temporary threshold shift (TTS) whereby sensitivity to sound is not permanently reduced and normal hearing returns after a period of time.

Zone (b) – The zone of masking. This describes the area where the noise is sufficiently intense at similar frequencies as a signal of interest to a marine animal, so as to mask or hide the signal (for example – intraspecies communication vocalisations). The extent of the interference depends on the temporal and spatial relationship between the signal
and the masking noise, and the characteristics of the sound (which may change with distance from source).

**Zone (c) – The zone of responsiveness.** This describes the area where the sound level is enough to cause the animals’ behaviour to alter (considered in more detail in section 6.1.3). Behavioural responses to sound are highly complex and this altered behaviour could be just to move out of the area, or conversely, to approach out of curiosity (Southall et al, 2007). It may not necessarily be the absolute sound intensity that causes the response; there could be other motivational factors at play (see section 6.1.3). From an impact perspective, *i.e.* when considering collision risk, the behavioural response is more important than audibility (see section 6.1.2.3).

**Zone (d) – The zone of audibility.** This is where the received level of sound from the source is audible to the animal. The zone of audibility is the zone of primary interest in this thesis.

Southall et al (2007) noted a distinction between audibility and detectability, in that a receiving system may detect a signal before it is able to meaningfully process the sound.

There are a number of definitions for audibility (for example);

“*.the range at which an animal can barely detect the sound source...it is assumed the sound source will be possible when the received level either matches the hearing threshold at that given frequency or the third octave level of the ambient noise*” (Madsen et al, 2006).

“*.when a sound can be perceived amidst background noise levels*” (Southall et al, 2007).

However, there is no consensus on the criteria that should be used to assess audibility. Erbe (2011) proposed that the zone of audibility could be assessed by comparing the third octave levels of the sound source and the background noise and the marine mammals’ audiogram in the same bandings, if the difference is greater than zero then the sound source is deemed audible at this location (similar to the Madsen et al, 2006 definition).

It is not straightforward to assess when a sound can be perceived against background noise and audibility is more complicated than this brief summary suggests. The sound source may be tonal or broadband in nature or have components of both. If tonal then
detection may be possible at some level below background noise levels (Madsen et al, 2006). Conversely, a broadband signal against a broadband background noise levels may be more difficult to distinguish even if the level is slightly higher than background.

If there is a low signal to noise ratio (SNR) then a signal may just be audible above the noise. A higher SNR is needed for this signal to be discriminated. The level of SNR that is required to detect a specific sound source against the background noise is called the Critical ratio (CR). Just as hearing varies with frequency, so does the CR as it tends to increase with increasing frequency. For example, for bottlenose dolphin the ability to discriminate a tone at 6 kHz, the level needs to exceed the background noise by 22 dB in that frequency range. However, a signal at 70 kHz, will need to exceed the background noise by ~40 dB (Richardson et al, 1995). Variable definitions illustrate that there are different levels of complexity that can be used to assess audibility.

6.1.2.2. Metrics used to estimate acoustic zones of influence

In this section, metrics are discussed relating to how noise impacts are assessed in all four zones, to put the amount of uncertainty in assessing the impact of noise on marine mammals into context. There are a number of proposed acoustic impact criteria; two of these that are commonly discussed within the acoustics community are the Nedwell et al (2007) suggested metric of dB$_{in}$ as a “measure of the behaviour and auditory effects of underwater noise” and Southall et al (2007) proposed criteria within “marine mammal noise exposure: initial scientific recommendations”. Both have arisen from the requirement to assess and manage the impact of man-made noise of marine life and both have used what is understood about human hearing as the basis of their criteria and propose a version of a frequency weighted scale.

Mammals (terrestrial and marine) do not hear equally well in all frequencies; hearing is less sensitive at either ends of the hearing range (Section 6.1.1). Noise at these frequencies therefore has to contain much greater energy - than noise within the range of best hearing - to have any effect. To accommodate this in human noise assessments, frequency weighting curves (or filters) are used. These filters mimic the way ears respond to sound. For human hearing there are two commonly used weighting curves known as A-weighting and C-weighting. A-weighting replicates the ears’ response to low and medium levels of sound and it is the filter that is used most often in in-air environmental checks (e.g. in office noise). Weighting excludes sound energy in the frequencies that we cannot hear. However, as noise levels increase the ear has trouble
differentiating the ‘loudness’ per frequency. The C-weighting filter represents this effect and results in a flatter curve (Figure 89). This filter includes more low frequency sound than the A-weighting curve.

![Figure 89: The A and C weighting curves for human hearing.](image)

Based on the understanding of human hearing, Nedwell et al (2007) proposed a frequency weighted dB$_{ht}$(Species) metric for the assessment of behavioural and audiological effects on underwater animals. Sound levels in dB units are a ratio determined by the measured sound pressure divided by the reference pressure. Nedwell et al (2007) have generated a method that uses the animals’ audiogram as the reference pressure. This relates the dB unit to the hearing ability of the animal. In human audiology, the weighting filters are applied using a relative pressure that relates to the human hearing threshold at 1 kHz. The relative pressure is 20 µPa, used as the in-air reference pressure. Underwater, the common reference pressure is 1µPa which has no relationship to the hearing ability of marine animals, hence the use of the audiogram. dB$_{ht}$(Species) is therefore a frequency dependent non-dimensional ratio of the measured pressure to the hearing threshold of the animal.

Nedwell et al (2007) promote the dB$_{ht}$(Species) metric as a ‘perception’ unit as there is a distinction between loudness and perception. Perception is the awareness of sound above the animals’ hearing threshold. Loudness is a subjective assessment of the noise by the animal. They further promote the metric as simple to understand and use, that it can be applied to a range of marine animals and fish as long as there is an audiogram, and therefore should be widely acceptable to industry, pressure groups, regulators and government.

Based on the proposed methodology Nedwell et al (2007) state that the likelihood of a behavioural avoidance (aversion) using dB$_{ht}$(Species) levels is from 55-90 dB$_{ht}$(Species).
Auditory injury follows prolonged exposure to levels of $90\ \text{dB}_{\text{re}}(\text{Species})$ and above with an increased likelihood at levels above $100\ \text{dB}_{\text{re}}(\text{Species})$. Nedwell et al (2007) also suggested that a few seconds at $130\ \text{dB}_{\text{re}}(\text{Species})$ has been shown to cause auditory injury in marine mammals, thus illustrating that the length of exposure is therefore also relevant.

It is important to bear in mind that this metric is species specific. A $90\ \text{dB}_{\text{re}}(\text{Species})$ level for a porpoise and a seal will not be the same level of sound, as the reference levels for different species are different and that it is entirely dependent on the audiogram.

Alternatively, Southall et al (2007) proposed their marine mammal noise exposure criteria within a special edition of the journal *Aquatic Mammals*. This publication was the product of a series of workshops attended by experts in acoustical research from the disciplines of behavioural, physiological and physical. They reviewed existing scientific literature regarding marine mammal exposure to noise and effects to put together the criteria based on best knowledge at that time.

Marine mammals have different hearing capabilities across species; therefore Southall et al (2007) split marine mammal species into functional hearing groups (Table 21 & Figure 90). The groups are organised in relation to their auditory bandwidth capability.

<table>
<thead>
<tr>
<th>Category</th>
<th>$f$ range</th>
<th>Example sp.</th>
<th>No. of sp/subsp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low frequency cetaceans</td>
<td>7-22000 Hz</td>
<td><em>Balaena</em></td>
<td>13</td>
</tr>
<tr>
<td>Mid frequency cetaceans</td>
<td>150-160000 Hz</td>
<td><em>Delphinus, Orcinus</em></td>
<td>57</td>
</tr>
<tr>
<td>High frequency cetaceans</td>
<td>200-180000 Hz</td>
<td><em>Phocoena</em></td>
<td>20</td>
</tr>
<tr>
<td>Pinnipeds in water</td>
<td>75-75000 Hz</td>
<td><em>Phoca, Halichoerus</em></td>
<td>41</td>
</tr>
</tbody>
</table>

Figure 90 - Functional marine mammal hearing groups illustrating auditory bandwidth as used in Southall et al, 2007.
Chapter Six

The criteria are based upon human C-weighting frequency weighting theory. The M-weightings correct for the frequency dependent hearing function and are calculated using an algorithm that uses the estimates of hearing sensitivity at the lower and upper frequencies of functional hearing. The M-weighting curves therefore represent the bandwidth over which noise exposure may have effect. They are flattened curves similar to the human C-weighting curve for loud noise (Figure 91). The M-weighting deemphasises the frequencies near the upper and lower limits of the hearing range, and assumes that the full audible band is relevant.

Figure 91- the M-weighting functions for low, mid and high cetacean categories and for pinnipeds in water (Southall et al, 2007).

Southall et al (2007) recommended using the two metrics to assess potential auditory damage (i.e. within the ‘zone of influence’ (a) as suggested by Richardson et al, 1995; Figure 88) Sound Pressure Level (SPL) using the peak pressure should be used to assess an impulse sound, and the Sound Exposure Level (SEL) for assessing the effect of sound input over a period of time. Based on this methodology, Southall et al (2007) suggest auditory injury levels as detailed in

Table 22 below.

<table>
<thead>
<tr>
<th></th>
<th>PTS</th>
<th>TTS</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cetacean</td>
<td>230</td>
<td>224</td>
<td>SPL (dB re 1µPa)</td>
</tr>
<tr>
<td>Pinniped</td>
<td>218</td>
<td>212</td>
<td>SPL (dB re 1µPa)</td>
</tr>
<tr>
<td>Cetacean</td>
<td>198</td>
<td>183</td>
<td>SEL (dB re 1µPa²·s)</td>
</tr>
<tr>
<td>Pinniped</td>
<td>186</td>
<td>171</td>
<td>SEL (dB re 1µPa²·s)</td>
</tr>
</tbody>
</table>
Southall et al (2007) stated that they did not support the use of the animal’s audiogram as a filter (as in Nedwell et al, 2007) to assess impacts because the auditory threshold does not characterise the equal-loudness perception with increasing sound levels, and because the audiogram data upon which the filter is based on a relatively small sample size. They state that it is unclear how useful or appropriate this method would be and think that it would generate too much filtering at lower frequencies.

Southall et al (2007) were clear in their report that there is a major lack of relevant data, and what available data there are on the effects of noise on marine mammals are variable in quality and quantity. They state that there is insufficient data to predict criteria for non-auditory injuries, and in particular with regard to behavioural studies, the interpretation of existing results is limited by uncertainty. Laboratory and field studies are not directly comparable, the in-field studies lack adequate controls and precision, whereas in the lab, conditions can be controlled, but lab conditions are not found in the field. Nedwell et al (2007) also highlight these data gaps.

Southall et al (2007) state that their “method is a rudimentary method of analysing effect”, but that current data do not support a more sophisticated approach. Both methods are therefore best guess methods based on current knowledge, however the academic community appear to prefer the Southall Criteria for the reasons stated above. The Southall criteria method provides comparable noise levels, with different dB levels for each hearing group which make sense in that the radii of the zones of influence will vary dependant on the species in question. Nedwell dB$_{in}$ (Species) method details a dB level that is the same number for all species, but relates to different noise levels which could be open to misinterpretation. It is relevant to remember that this understanding is an on-going process; for example in 2010 J Finneran published work assessing the TTS threshold for bottlenose dolphins which predicted a greater sensitivity to high frequency sounds that would be predicted using the Southall et al, (2007) M-weightings.

There are a number of suggested levels for auditory injury and behavioural response levels (Table 23) from other sources in addition to Nedwell et al, (2007) and Southall et al, (2007) (e.g. Lucke et al, 2009; NMFS, 1995; HESS, 1997; Yelverton & Richmond, 1981) all are slightly different and not considered in detail here, because the focus of this thesis is on audibility rather than auditory damage. What is clear is that there is not a defined consensus with regard to noise impact criteria.
Table 23 - Examples of the different published criteria for behavioural reactions to anthropogenic sound.

<table>
<thead>
<tr>
<th>Behaviour and species</th>
<th>Level and metric</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aversive behavioural reaction in harbour porpoise</td>
<td>174 dB re 1 µPa pk-pk</td>
<td>Lucke et al, 2009</td>
</tr>
<tr>
<td>Aversive behavioural reaction in harbour porpoise</td>
<td>145 dB re 1 µPa2s SEL</td>
<td>Lucke et al, 2009</td>
</tr>
<tr>
<td>Behavioural disturbance, Level B - Harassment in cetaceans and pinnipeds</td>
<td>160 dB re 1 µPa (RMS)</td>
<td>NMFS, 1995</td>
</tr>
<tr>
<td>Low level disturbance in cetaceans and pinnipeds</td>
<td>140 dB re 1 µPa (RMS)</td>
<td>HESS 1997</td>
</tr>
<tr>
<td>Strong behavioural reaction</td>
<td>90 dB above species specific hearing threshold</td>
<td>Nedwell et al, 2005</td>
</tr>
<tr>
<td>Mild behavioural reaction</td>
<td>75 dB above species specific hearing threshold</td>
<td>Nedwell et al, 2005</td>
</tr>
</tbody>
</table>

6.1.2.3. Behavioural reactions to sound

The criteria for behavioural reactions are even more difficult to quantify than for auditory injury due to a greater lack of data (Southall et al, 2007; Bailey et al, 2010). Very little is known about noise effects on marine mammals’ behaviour (Tyack et al, 2003). Although a wide range of behavioural reactions to noise have been documented in studies, for example; in considering the reactions to marine piling (e.g. Thompson et al, 2010; Bailey et al, 2010), to acoustic warning devices (e.g. Leeny et al, 2007; Kastelein et al, 2006b; Johnson, 2002; Culik et al, 2001; Cox et al, 2001) to vessel noise (e.g. Erbe, 2002; Lemon et al, 2006) and to offshore wind farm noise (e.g. Tougaard et al, 2009; Madsen et al, 2006) and these studies encompass a wide range of reaction from complete avoidance of the area, to habituation and attraction.

The marine mammal response to sound is highly variable and dependent on context (Thompson et al, 2010; Götz & Janik, 2010) possibly also dependent on the type of sound, whether it is a ‘rough’ sound⁵ or a more neutral sound⁶ (Götz & Janik, 2010) and is therefore very difficult to predict. Southall et al, (2007) suggested in the absence of a more appropriate metric for behavioural studies, that the broadband Sound Pressure Level should be used, and is in fact the metric that has been quoted in the majority of behavioural studies.

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⁵ ‘rough’ sound - one that is uncomfortable to listen to – a frequency modulated signal that has a relatively high ‘loudness’ for the bandwidth.

⁶ ‘smooth’ sound - white noise, or a pure tone.
Southall et al., (2007) also suggested a severity scale for behavioural reactions from 0 – no observable response to 9 – outright panic and stranding. Table 24 details some examples of received levels of sound together with the behavioural severity score of selected marine mammals from Southall et al., (2007).

Within these studies, there is a wide range of behavioural responses to the same stimulus (Table 24). Other studies have also documented a variable response to sound stimuli. Thompson et al (2010) and Bailey et al., (2010) found that bottlenose dolphin and porpoise (respectively) avoided the area when piling was occurring. This is a noisy activity with documented source levels of 225 to 250 dB re 1 µPa @ 1m (p-p) and these studies suggested behavioural responses were possible up to 50 to 70 km away (Thompson et al., 2010; Bailey et al., 2010).

<table>
<thead>
<tr>
<th>Species</th>
<th>Source</th>
<th>Received Level (dB re 1 µPa)</th>
<th>Severity score</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minke whale</td>
<td>Vessel noise</td>
<td>110 – 120</td>
<td>3</td>
<td>Palka &amp; Hammond, 2001</td>
</tr>
<tr>
<td>Bottlenose dolphin</td>
<td>Vessel noise</td>
<td>110 – 120</td>
<td>2</td>
<td>Buckstaff, 2004</td>
</tr>
<tr>
<td>Killer whale</td>
<td>Acoustic deterrents</td>
<td>140 – 150</td>
<td>8</td>
<td>Morton &amp; Symonds, 2002</td>
</tr>
<tr>
<td>Killer whale</td>
<td>Low frequency</td>
<td>160 – 170</td>
<td>6</td>
<td>NRL 2004a, 2004b</td>
</tr>
<tr>
<td></td>
<td>Military sonar</td>
<td></td>
<td></td>
<td>NMFS, 2005</td>
</tr>
<tr>
<td>Harbour porpoise (wild)</td>
<td>Acoustic deterrents</td>
<td>80 – 120</td>
<td>0,6</td>
<td>Culik et al., 2001</td>
</tr>
<tr>
<td>Harbour porpoise (captive)</td>
<td>Acoustic deterrents</td>
<td>80 – 120</td>
<td>0,4,6</td>
<td>Kastelein et al., 1997</td>
</tr>
<tr>
<td>Harbour seal</td>
<td>Acoustic deterrents</td>
<td>120 – 130</td>
<td>0</td>
<td>Jacobs &amp; Terhune, 2002</td>
</tr>
<tr>
<td>Harbour seal (captive)</td>
<td>Pulsed sounds</td>
<td>80 – 110</td>
<td>0,6</td>
<td>Kastelein et al, 2006b</td>
</tr>
</tbody>
</table>

Avoidance behaviour was also documented for bottlenose dolphin and harbour porpoise in studies considering the behavioural response to acoustic warning devices (Leeny et al., 2007; Kastelein et al., 2006c; Johnson, 2002; Culik et al., 2001). The range of avoidance area was between 130 – 1140 m (Culik et al., 2001) for Source Levels of between 109 –
256 dB re 1 µPa. In addition to the avoidance reaction, Cox et al, (2001) during the period of their study, they observed habituation in harbour porpoise, but another study did not see evidence of habituation (Johnson, 2002). Götz & Janik (2010) suggested from their study considering the reactions of harbour seals to different types of acoustic warning device output, that the animals motivation was of key importance as where there was the promise of food, the animal tolerated the level of sound.

Marine mammals response to vessel noise is also not clear (Richardson et al, 1995). Observed responses could be a result of the sound of the vessel or the sight of one, or a combination of both stimuli. Odontocetes in particular are thought to be tolerant of vessel noise in open waters, as they may react when in a confined space (Richardson et al, 1995). It has been suggested that in general vessels are avoided when the animals are resting, they are ignored when the animals are foraging and may be approached when socializing (Richardson et al, 1995) again highlighting the importance of context and the animals' activities at the time.

Of relevance to this thesis, there has been some work undertaken that considered the range of audibility from operational offshore wind turbines. In comparison to the other anthropogenic noise inputs as detailed above the noise levels from these devices are relatively quiet with estimated source levels of below 145 dB re 1 µPa @ 1 m (Madsen et al, 2006). Tougaard et al, (2005) estimated the audible range of an operational wind turbine, for a harbour porpoise to be 83 m. Madsen et al, (2006) detailed ranges for harbour porpoise and bottlenose dolphins to be in the order of a few hundred meters. Tougaard et al (2009) estimated the audible range for the harbour seal to be much greater at 100 m. This is probably because the harbour seal has a better low frequency hearing than the odontocetes (see Figure 87) and because the main frequency input from offshore wind turbines is low frequency, below 500 Hz (Tougaard et al, 2009).

It is clear that animals’ behaviour can be affected by anthropogenic sound in the marine environment. The nature of the reaction and responses to noise appears to depend on the type of noise, its level, duration, whether it is impulsive or continuous, and perhaps also whether the animal perceives the sound to indicate a threat.

There is a wide uncertainty on the levels of received sound at which animals may respond to anthropogenic sound (Thompson et al, 2010). Behavioural context is highly relevant and includes animal motivation and previous experience (Thompson et al,
2010; Götz & Janik, 2010) as well as age, gender and health. Response can also vary widely within species as well as between species, and the response may have another unknown causal factor other than the sound.

This section has highlighted the uncertainty in understanding the behavioural reactions to anthropogenic sound in the marine environment and therefore the difficulty in its prediction. For this thesis, I therefore chose to consider the potential audibility of tidal-devices; this will then be discussed in light of other documented audible ranges from existing studies.

### 6.2 Tidal-stream device audibility

For a tidal-stream device to be audible to a marine mammal, in basic terms, the sound from the device at the location of the receptor needs to be within the marine mammals’ hearing abilities and above the background noise levels (Figure 92).

![Figure 92](image)

**Figure 92** - Illustration of the relationship between the device sound level, the environmental background noise levels and the marine mammals’ hearing abilities. The detection distance depends on the device signal being above background noise levels and within the animals hearing abilities.

#### 6.2.1 Background noise level comparison with marine mammals’ audiograms

The first variable to consider is how noisy the tidal-stream area is in relation to marine mammal hearing abilities. Marine mammal audiograms are determined from the presentation of pure tones and are described using the units dB re 1 µPa, background noise levels are usually presented as spectral levels by frequency in units of dB re 1µPa²/Hz. It is thought that the mammal hearing can be approximated by one-third octave filter bands (Richardson *et al*, 1995; Jensen *et al*, 2009; Section 1.6.4) which are described in the units of dB re 1µPa, these are the same units as in the audiogram and therefore should be used for comparison purposes.
6.2.1.1 METHODS

Third octave levels (TOLs) are computed from the spectral levels by integrating the spectral levels (Chapter Four) into third octave bands in the following steps.

1) First the upper and lower frequencies for each third octave band \( n \) are calculated using the following equations (Erbe, 2011);

\[
\begin{align*}
    f_{\text{low}}(n) &= 10^{1/20} \times f_c(n) \\
    f_{\text{up}}(n) &= 10^{-1/20} \times f_c(n)
\end{align*}
\]

and \( f_c \) is the centre frequency, using standard third octave centre frequencies (ANSI S1.11-2004) detailed in Table 25 below.

2) The bandwidth (BW) of each filter is calculated \( BW = f_{\text{up}} - f_{\text{low}} \)

3) Then the band level (BL) is calculated using \( BL = \text{PSD}_{\text{avg}} + 10 \log(BW) \) where \( \text{PSD}_{\text{avg}} \) is the average level within each band determined from the calculation of the upper and lower limits.

The TOLs can then be plotted against generalised marine mammal audiograms for comparison (generalised from porpoise, bottlenose dolphin and harbour seal data from Nedwell et al. (2004); Figure 87).

6.2.1.2 RESULTS AND INTERPRETATION

In order to compare the background-noise levels to the marine mammal audiograms, the minimum, average and maximum third octave levels (TOLs) for all three case study areas, Fall of Warness, Kyle Rhea and the Sound of Islay (Chapter Three) were plotted. The TOLs are calculated from the sound levels measured during each survey (Figure 93).
The ranges of these values are therefore indicative of spatial variation rather than temporal. It is relevant to recall that the background noise measurements were no more than a snapshot of the case study area characterisation (Chapter Three).

However, the TOLs illustrate the comparative range of levels in each case study area, and it can be seen there is a greater range of TOLs in the Sound of Islay particularly in the lower frequency range in comparison to the other areas.

Figure 93: Comparison between third octave (TOL) background noise levels and generalised marine mammals audiograms (dB re 1 µPa) (a) Kyle Rhea (KR) (b) Fall of Warness (FoW) & (c) Sound of Islay (SOI). Minimum, average and maximum TOLs illustrate the range of background noise levels in each area.
In all case study locations there is a raised profile in the higher frequencies, approximately the same frequencies as the marine mammals' peak hearing band (Figure 93) suggesting that in these tidal-stream case study areas, it will be the background noise levels that will limit device detection rather than species hearing ability. Background-noise limitation rather than hearing threshold limitation has also been suggested by other authors (Götz et al., 2011; Quintana-Rizzo et al., 2006) and is plausible when one considers human hearing in a noisy environment, if for example in a bar, if the music is sufficiently loud, people with good hearing will still be as impaired as those with poorer hearing.

6.2.2 ZONE OF AUDIBILITY

One aim of this thesis was to assess the potential audibility of marine renewable devices and marine mammals. Hearing has been proposed as the most likely sense by which the animals are alerted to the devices’ presence. Here a general model is presented that considers the detection distance to these devices. Figure 92 illustrated that audibility is dependent on the balance between the background noise levels and the device received level and the animal's hearing abilities. The comparison between third octave levels and marine mammal audiograms (section 6.2.1.2) suggests that the hearing abilities of the animal may have less of an influence than background-noise levels in determining audibility (Götz et al., 2011; Quintana-Rizzo et al., 2006).

The received level of noise is often estimated using propagation models, sometimes based on empirical data and sometimes estimated purely using a theoretical model. There are varying levels of complexity that can be coded into different transmission loss models, which can consider as many variables as there is available information, (including: depth, seabed type, water temperature, and salinity). The particular model used has a great influence in the resulting received levels estimated. In addition, the estimation of received levels is particularly challenging in shallow water areas as there are rapid changes in depth and the greater potential for multiple reflections off the sea surface, the sea bed and the shoreline (Shapiro et al., 2009).

Complex modelling of transmission loss (Section 1.6.4) requires comprehensive environmental variable parameters, such as water depth and temperature, seabed types, and salinity profile, involving either a thorough measurement programme, or the use of existing environmental data at suitable resolution. This is not always achievable or available, therefore, a commonly employed method is to measure a known source
level, at increasing distances away from the source, and then fit an $N \log(r)$ type model to the data (Chapter One). This is relatively straightforward and is a general ‘rule of thumb’ method as it does not capture the variability, temporally or spatially, of the propagation loss in the area (Cato, 2008). Transmission loss determinations and the resulting received levels should always be treated with caution as the actual model used can have a significant effect on the levels predicted. However, the use of a model can be invaluable when trying to assess a complex scenario and can allow trends and generalities to be unravelled.

“All models are wrong; but some are useful”

George Box

Figure 94 illustrates the variability in the level of transmission loss for the same sound source level and water depth depending on the transmission loss model used.

![Diagram of Transmission Loss levels in dB with distance from source for basic TL expressions, calculated at the water depth of 40m. This illustrates the dBs that are deducted from the source level in order to estimate the received level of sound at distance from source. Spherical (20 log R) and cylindrical (10 Log R), plus combination expressions 1 (Koschinski et al, 2003 - 20 log$_{10}$R + 15 log$_{10}$(R/R$_1$) combination 2 (15 log R) & combination 3 (Richardson et al, 1995 - 20 log$_{10}$R + 10 log$_{10}$(R/R$_1$)).](image)

Other factors affecting received levels of sound include the frequency dependence of transmission loss, higher frequency components do not transmit as well as low frequencies. However, in shallow water, the depth itself limits low frequency transmission. As sound propagates the frequency characteristics of the device sound signal are likely to change with distance away from source.
In Strangford Lough, the low frequency tonal components of the tidal-stream device were found to not propagate as well as the broadband levels (Chapter Five; Götz et al., 2011) and that the frequency components of the source are likely to change with distance. This evidence together with the uncertainty regarding our ability to predict a biological response to anthropogenic sound, led me to the decision to use a basic transmission loss model based on the sonar equations (Chapter One). In this project, the models’ usefulness is to explore the scenario, so it seems logical to apply a generic model in this case because of the limited data available to be included in a more complex model.

A further complexity is that background noise levels increase in inclement weather, plus there is a temporal component to the background noise ‘sound-scape’. Background noise levels can vary by 20-30dB and over relatively short timescales (Section 4.4.1; Cato, 2008). Zones of audibility will depend on the environmental conditions at the time and therefore, any predictions of the zones of influence must be treated with caution.

In this thesis, the assumption is made that the signal from the tidal-stream device is detectable where the broadband received level is greater than the broadband background noise levels in the area. This may be reasonable where the noise is broadband (Madsen et al., 2006) however, if the noise has tonal qualities (as tidal-devices are likely to) then the signal may be detected at a few dB below the background noise levels (Madsen et al., 2006) depending on the frequency of the tone. Thus, the ranges estimated using broadband levels may be conservative.

It is likely tidal devices may have low frequency tonal components (Chapter 5) and although it was shown for frequencies above ~1 kHz that it was the background noise limiting the detectability (section 6.2.1.2), for frequencies below 1 kHz the limiting factor may be the animals hearing threshold (Figure 93). It is therefore possible that by estimating the signal-to-noise ratio using broadband levels, a detectable component of the tidal device output may be missed. However, hearing ability in this frequency range is reduced, meaning the level of sound would need to be quite loud in order to be detected, therefore in this preliminary exploration, the signal to noise approach was developed further.
6.2.2.1 METHODS

Due to various constraints, it was not possible within this project to empirically measure the propagation loss in the three case study locations. Therefore the propagation or transmission loss was estimated using a basic sonar equation of the form $TL = N \log R$ where $N$ represents the spreading loss and $R$ represents the range. There are many examples in the literature of the use of these generic equations. For example Götz et al (2001) fitted a log regression curve to measured data, and the resulting best fit equation was $TL = 14 \log (R)$ in relation to the propagation loss of the broadband signal. Madsen et al (2006) used $16 \log (R)$ and Koschinski et al (2003) used a combination of spherical and cylindrical spreading equations and used $20 \log (R_1) + 15 \log (R/R_1)$ where $R_1$ represents the distance at which spherical spreading loss changes to cylindrical spreading. There are many other examples of this equation with various versions of $N$ (section 1.6.4). For the purposes of this thesis, the equation of the form $TL = 15 \log (R)$ was used here, this is a generic representation and is comparable to the equation that was used for a similar purpose in Strangford Lough (Götz et al, 2001).

Each case study area was considered independently and for the purposes of this exploration, a single device acoustic output was considered rather than an array. The received level of device noise was estimated at every background noise level sample segment location (Chapter Three). Source levels relevant to the case study areas were used where possible. The OpenHydro source level was used in the Fall of Warness as this is where the device is being tested, and the MCT SeaGen source level was used in Kyle Rhea as this is a proposed location for MCT, and it was also used for the Sound of Islay. The Hammerfest Strøm device is planned for the Sound of Islay, however there is no source level available for the HS1000 as yet, therefore the MCT source level was used in preference to the smaller HS300 device, because it is likely that the bigger device will be louder than the HS300 (Chapter Five) with potential spectral differences also.

The signal-to-noise ratio, or difference between the background noise level and the received level was determined. The modelled received level was deducted from the broadband Sound Pressure Levels (plotted in Chapter Four) the resulting number was the measure of audibility. A negative number therefore represents device inaudibility at that location. The signal-to-noise ratio was then plotted on a map of the case study area using ArcGIS.
6.2.2.2 RESULTS AND INTERPRETATION

6.2.2.2.1 FALL OF WARNES

According to the signal-to-noise map (Figure 95) the OpenHydro device is predicted to be inaudible in this location. This is a paradox because the measurements of the device were made in the Fall of Warnes and the device acoustic output could be heard on the recordings albeit in close proximity to the device (within 500 m). However, the OpenHydro survey was conducted on a day where there was significant vessel noise in the area and as such the majority of the recordings were unusable as the device acoustic output could not be isolated against the vessel noise. The recordings that were used to estimate the device acoustic output were made at the end of the survey period, when all vessel activity had ceased and the local flow speed was less than 2 m/s. Conversely, the background noise level maps are a composite of recordings that include vessel noise.

The OpenHydro device was the quietest of the available tidal-device acoustic characteristics, and this example suggests that there could be occasions were a tidal-device is not audible depending on the environmental conditions at the time.

Figure 95 – Map illustrating the signal-to-noise of the OpenHydro device in the Fall of Warnes. The black triangle denotes the location of the device. The colour contours range from -8 (red) to -39 (green) (Negative numbers relate to levels below background noise levels). Based on this model the tidal-stream device is inaudible.
6.2.2.2.2 Kyle Rhea

The Kyle Rhea scenario is very different to the Fall of Warness (Figure 96). The MCT SeaGen device has a louder acoustic signature in comparison to the OpenHydro (Chapter Five) and based on this model, is predicted to be above background noise levels up to a distance of 1.2 km away from the device.

However, the levels are predicted to be only a few dB louder than background from a distance of approximately 500m from the device; the device dB level ranged from 0.5 to 9 dB. This difference also does not decrease linearly with distance from the device; there are increases and decreases, suggesting patchiness of the signal-to-noise ratio.

![Figure 96 - Map illustrating the signal-to noise ratio in Kyle Rhea. The device location denoted by the black triangle. The device acoustic output falls below background noise levels at a distance of 1.2 km from the device. The signal-to-noise ranges from 23 dB above background (dark purple) to 17 dB under background levels (Yellow). The levels denoted by the red contour are between 0.5 dB and 9 dB above background. The contour map illustrates patchiness of the acoustic detectability.](image)

6.2.2.2.3 Sound of Islay

The source level from MCT SeaGen was also used for the Sound of Islay as a proxy for the larger HS1000 device proposed at this location. The device acoustic output is approximately 30 dB louder than background noise levels close to the device locations.
(up to about 200 – 500 m distance) and drops below background at a distance of about 1 km (Figure 97). From these data, the device acoustic output can be seen to increase and decrease in level in patches away from the sound source.

The distance that the device acoustic output is greater than background presented here, is similar to the detection distances presented in in Götz et al (2011). Based on the broadband signal of the MCT device, their model suggested that in high tidal conditions the device would be audible to both harbour porpoise and harbour seals up to a distance of 1.4km. This is perhaps unsurprising as this study has used the same source level and a similar propagation model. In quiet background noise conditions they predict a much greater range of audibility, up to 3-5 km range.

Figure 97 - Map illustrating the signal-to-noise ratio in the Sound of Islay. Black triangle denotes location of device. The device acoustic output falls below background noise levels at approximately 1 km from the device. Purple contour denotes the device acoustic output at 30 dB louder than background, yellow denotes 8 dB lower than background.
6.3 SUMMARY AND DISCUSSION

This chapter has considered the potential signal-to-noise ratio of tidal-stream devices in the three case study locations. Marine mammal hearing was discussed, and the uncertainty was highlighted in our understanding of how and what they hear, and in particular the uncertainty with regard to marine mammal audiograms. However, this is the current state of knowledge, and as time moves forward, technology and techniques will improve to investigate these difficult-to-study animals and the degree of uncertainty surrounding audiograms and perhaps behavioural responses should decrease.

The criteria currently being used to assess the impact of anthropogenic noise on marine mammals were also discussed. The degree of uncertainty regarding criteria in general was highlighted, as was the controversy surrounding which metric should be used for assessment. There are undoubtedly issues with all metrics proposed to assess noise impact, but at this stage, there is nothing more certain to use instead. Again as research and time moves forward, these criteria may become more refined.

The range of device acoustic output presented here was from completely below background to above background out to a distance of 1.2 km. The maximum audible zone estimated here may not afford marine mammals a lot of acoustic warning. If one assumes an average swimming time of 1.5 m/s within a flow speed of 2 m/s, then it would only take this animal approximately 5 minutes to get to the device. It is apparent from the behavioural data available that it is not straightforward to predict what an animal may do if/when it hears the tidal-stream device with any certainty. Especially when the evidence suggests that marine mammals are more than capable of detecting vessel and pingers and fishing nets, but that they do not always do so and collisions occur. The activity the animal is engaged in and their behavioural motivation (e.g. feeding) appear to be of key importance for an animal to pay attention to a sound source.

Data available on tidal-device acoustic output in general suggests that it is closest in sound level and characteristics to vessel noise (Table 11 – Section 4.1.1 & Table 18 – Section 5.3) and thus should be audible, but the higher levels of background noise levels in tidal-stream locations needs to be accounted for. It is likely that in these areas the background noise levels will be the limiting factor in determining audibility. Based on the device source levels and subsequent received levels in comparison to the Southall criteria, tidal-stream devices operational sound levels are certainly not loud enough to
cause auditory injury, indeed this chapter suggests that the devices may not be easily audible depending on the levels of background noise.

Determining audibility is not necessarily straightforward; there is a complex mix of variables, the interaction of which is not yet fully understood. Even when a source is audible over a large distance (e.g. shipping examples) the behavioural reactions have been observed over a much smaller radius in the order of hundreds of meters. As was mentioned earlier, this distance in a tidal flow environment may not allow for a lot of warning time. It is also important to highlight that based on the OpenHydro work presented in Chapter Five; it is likely that vessel noise will mask the sound signal from tidal-devices.

Broadband sound pressure levels were used as the background noise levels, rather than trying to disentangle frequency specific criteria, because the low frequency tones generated by the device were suggested to propagate poorly, plus spectral characteristics will travel differently over distance, therefore a straightforward assessment was used in this exploration. There was no adjustment for hearing capabilities (e.g. using M-weightings) as this study has suggested that it is the background noise levels rather than the hearing abilities that are the limiting factor (at peak hearing sensitivities), plus the majority of the broadband signal falls within the ‘flat’ area of the filter therefore it could be argued that no adjustment is necessary (Götz et al, 2011). There may be an issue with recording device noise in situ as the recording will include the background noise levels present at the time. It was suggested that windfarm noise was only measurable below 500 Hz (Section 6.1.3.3) in the future with further investigation, we determine that this is the same for tidal-stream devices, then this could mean that the signal-to-noise ranges are lessened from currently predicted as 500 Hz is within the low frequency tail of marine mammal hearing and therefore will be more difficult to hear.

The propagation model used here is very basic, and is not likely to accurately represent the transmission loss. For a specific, rather than this conceptual study, it would have been useful to have introduced a sound source to the area and then measured the transmission loss. Or had time allowed, been able to investigate the use of a more sophisticated model. However the results presented here in this generic study highlight some important characteristics. It would also be interesting to compare the results of a
complex propagation model with a more generic one to see if there is a difference in the interpretation.

The signal-to-noise maps presented here are non-symmetrical due to the ‘patchiness’ of the background noise levels. These patterns are likely to be further complicated due to any directionality of the device sound signatures, and due to any variability in the propagation loss characteristics due to site specific parameters. Transmission loss in shallow water areas is not as simple as a decrease in intensity as distance from source increases (Shapiro et al, 2009). Also these maps have been computed using a point source; it is not yet known how this may change with the emplacement of multiple devices.

It is clear that the radii of the zones of influence will not be circular in nature spreading out from the tidal-device(s) and may have patches that are inaudible closer to the device than a patch where the device may be audible. What is not understood is how a patch of greater background noise intensity might affect the propagation of the device sound signal, might there be a scattering effect therefore the propagating sound does not make it through the patch. Also how does this patchy background noise environment change over time? The ranges illustrated here must be treated with caution due to the reasons detailed in the discussion section 6.2.2.

This chapter has highlighted the uncertainty in making audibility predictions, and has presented snapshot audibility scenarios for the three case study areas. In these examples the range over which the device noise is greater than background noise varies from inaudible to a distance of approximately 1.2 km away from source. Importantly, these types of predictions are site, device and temporally specific.
CHAPTER SEVEN - GENERAL DISCUSSION

7.1 INTRODUCTION

My thesis has explored the underwater background noise levels present in tidal-stream locations in Scottish coastal waters. This thesis adds data to the little studied underwater acoustic characteristics of these challenging locations (Bailey et al, 2010). The ultimate aim was to add information to the discussion regarding the audibility of tidal-stream devices to marine mammals using the background noise levels in tidal-stream areas together with the acoustic output of tidal devices. This thesis is timely with the current development of the marine renewable industry rapidly moving forward to deployment of multiple devices in the near future in locations were the environmental effects are poorly understood (Chapter One), with collision risk for marine mammals being a key concern.

To investigate my thesis hypotheses and research questions (Chapter One) a drifting hydrophone methodology was employed (Chapter Two).

My thesis hypotheses were that;

1) Tidal stream areas are currently loud environments.
2) The acoustic output of tidal devices may therefore be masked by the environment and thus not easily detected acoustically.

Consequently, my research questions for this thesis were as follows;

1) What are the noise levels in areas suitable for tidal energy extraction and how varied is the underwater noise field?
2) How does this compare to better quantified deep-water sound levels?
3) What effect does the tidal flow have on the background noise?
4) What is the likely acoustic output from tidal-stream devices?
5) Is it the case that when the turbines turn at their optimum revolutions per minute, the background noise in the area is at its noisiest?
6) Over what range might the signal of tidal devices be greater than the background noise?
Chapter Seven

General discussion

The noise levels measured were then mapped (Chapter Three) and the spectral content was explored (Chapter Four). Available information relating to the acoustic output from tidal devices (sound levels and frequency content) were reviewed (Chapter Five). Marine mammals hearing abilities and behavioural reactions were reviewed (Chapter Six) and the relative uncertainties were highlighted, so that predictions can be viewed in context. Information from the preceding chapters were then combined to generate a basic model that generated signal-to-noise maps to explore the potential range of audibility of these devices to marine mammals (Chapter Six).

The structure of this discussion chapter is as follows; the choice of case study areas is contemplated, followed by a discussion regarding the drifting hydrophone and mapping methodology. Then, cross-chapter information is drawn on to consider my thesis hypotheses. Firstly – whether tidal streams are currently loud environments followed by whether tidal devices may be masked by the environment and thus not easily detected by marine mammals. This chapter will conclude with a consideration of the lessons learnt from this work.

7.2 Case study locations

The three case study locations presented in my thesis are all tidal-stream locations of interest to tidal device developers (Chapter Three). The most northerly site is the Fall of Warness (59° 8’ N 02° 49’W) and is the location of the European Marine Energy Centre (EMEC) tidal-stream test facility. Moving southwest, Kyle Rhea (57° 14’N 05° 39’W) is a narrow strait between mainland Scotland and the island of Skye, and has been identified by Marine Current Turbines as a potential development site. The Sound of Islay (55° 50’ N 06° 06’ W) is the strait between the islands of Islay and Jura on the west coast of Scotland and Scottish Power Renewables has consent to develop this area (Chapter Three).

In effect these case study locations were chosen for me by necessity because the project was funded without scope for field work. All data were collected for the dual purpose of commercial work obtained by SAMS and SAMS Research Services Ltd and for this thesis. I was fundamentally involved in the field work for these projects and was solely responsible for the data analysis. The data was fully reworked for my thesis. This presented a considerable challenge to the process of this thesis in that my time was not totally devoted to the PhD project, I had to be flexible in approach and meet commercial deadlines as a priority. This was an essential strategy for the data collection. The
negative aspects of the time required (which limited my opportunity to fully explore analysis methodologies), were balanced by the positive, in that it gave me the opportunity to be involved in the first projects of this kind with developers, thus being at the cutting edge of this area of research.

**7.3 METHODOLOGY**

**7.3.1 DRIFTING HYDROPHONES**

The merits of using drifting hydrophones as opposed to statically moored equipment were discussed in Chapter Two. The main advantage of using mobile platforms, as opposed to static units, is that drifting hydrophones drift with the tidal flow thus avoiding the input of unwanted sound from the passage of water past the sensor. A further advantage is that the deployment of multiple devices means that a greater area can be covered during a survey. The drifting hydrophones used for these surveys were prototypes and developed for a proof-of-concept study conducted by the Scottish Association for Marine Science for the European Marine Energy Centre (EMEC) in Orkney (Wilson & Carter, 2008).

The drifters were comprised of off-the-shelf hydrophone and digital recorder components and housed in a water-proof pod (see Chapter Two). The GPS etrex unit was also an off-the-shelf handheld unit that was housed in a Peli-case on top of the pod (see yellow case in Figure 98). These mark I units were a challenge to use, they were temperamental and the collection of .WAV files were not guaranteed.

![Figure 98](image)

Figure 98 - Photo of the SAMS/EMEC drifting hydrophone equipment on the deployment vessel, showing the drogue, float, connecting ropes and electronics pod.

The drifters also had the tendency to introduce self-noise from the recording platform. In turbulent situations, the hydrophone transducer ‘hit’ the drogue assembly resulting in
a ‘knocking’ sound. This was clearly observable both visually as a significantly larger spike in the recording and audible as a low frequency knocking sound. These occurrences of self-noise were either cut out of the audio file prior to analysis, or if extensive, the file was discarded. I am aware that SAMS have designed ‘drifting ears mark II’ improving the robustness and ease of use of the design. Unfortunately, this development was post my thesis and therefore not available to me for this work. However, it should be noted that when the drifters mark I were treated with care, they worked well in tidal-stream conditions and good quality data was recorded.

A further issue with the drifters used for my thesis was that these drifters were resident in Orkney, and therefore whenever they were required for a project they had to be requested from EMEC. This limited my ability to conduct repeat measurements and testing. Having more data is always helpful, notwithstanding this, I feel that there was enough data for the purposes of this thesis, and in any-case it could be argued that the manual nature of the data analysis may not have been able to cope with a greater amount of data.

The equipment used for this study had the capability of recording and analysing acoustic data up to the frequency of 48 kHz. This range does not cover the full range of the marine mammals likely to be found in the areas suitable for marine renewable development. But, the focus here was to consider marine renewable tidal-stream device input in the context of existing underwater background noise levels, both of these contributors have the majority of sound energy at lower frequencies, therefore this frequency range was considered to be reasonable. It is conceivable though that there may be a higher frequency input from these devices that has not been highlighted using this frequency range. However Kongsberg (2010) when assessing the input of the Marine Current Turbine device SeaGen, presented power spectrum data for the frequency range 10 Hz to 250 kHz and the output from the device was found to be mainly tonal (below 2 kHz) and with some broadband output. This supports the paradigm that the majority of noise from man-made contributors into the marine environment is low frequency (Richardson et al, 1995). Therefore the frequency range presented here is not unreasonable.
7.3.2 Data analysis

The analysis method used for this project (Chapter Two) was time consuming and inelegant. Better programming would make this process easier in the future, particularly for batch runs. However, the manual nature of my analysis meant that I looked at all sound files and therefore there was a better chance of picking up issues with the files that might affect the results (such as the hydrophone knocking on the drogue). The main disadvantage was the time involved in processing the data, and the potential for human error. An automatic method will ensure consistency, but perhaps would miss the problems I detected with individual files.

This methods as used in my study, had the major advantage in that it was a relatively inexpensive method of gathering data, thus making this research possible on a lower budget. Standard methodology for acoustic data collection and reporting is not currently in existence (de Jong et al, 2011). Standard methodology would make comparisons between areas and studies easier, which will in turn assist conclusions to be drawn and therefore help to better understand the acoustic environment in our shallow coastal seas. However, it may not be practical to be too detailed in prescribing in-field methods as there is such variability in the capabilities of the acoustic equipment. It is perhaps more appropriate to ensure that the reporting of such data is consistent. Methods and equipment will be evolving all the time and it is necessary that for continual development that the data acquisition methods are not too closely constrained.

One vital component of underwater acoustic analysis is the equipment calibration as this sets the scale for the absolute measurements. This is not straightforward without specialised equipment. Calibration was not possible in-house at SAMS, therefore for this study a reference hydrophone was calibrated professionally by the National Physical Laboratory (NPL) in London and the drifters were calibrated by comparison. We also conducted a check of the entire measurement chain at NPL so that the performance from hydrophone to software analysis could be understood and accounted for. The major advantage with the calibration by comparison method employed here was that a relatively low budget project could calibrate the drifters as many times as required and this proved invaluable as during the lifetime of this project there were a few hydrophone casualties, therefore the calibration of the replacement sensors could be accommodated.
7.3.3 Spatial versus Temporal Characteristic of Mapping Acoustic Data

The acoustic landscape can vary in very small timespans (Cato, 2008; Richardson et al., 1995) and this is most likely the basis of the view that mapping acoustic measurement data is not possible as the measurements cannot be made at suitable timescales (de Jong et al., 2011) particularly in the case of mapping the propagation of an impulse sound. However, because the mapping method described in this thesis, uses continuous background noise data from the entire survey period, the temporal signal is blurred, therefore provided there is enough data, this mapping methodology works to illustrate the spatial heterogeneity of background noise. This is relevant because it highlights that a point measurement in one location, for instance, may not be entirely representative of the area. The patchy characteristic of the noise field as presented in this study could be used to inform modelling studies in the variability of underwater background noise spatially within the survey area, as well as temporally.

The spatial – temporal balance could be further investigated in a study using drifting hydrophones, by deploying them in a single file formation rather than across the area of interest. This intention would be to cover the same spatial area, but at different times. This survey would be useful to explore the temporal variation in a tidal stream location.

Vessel movement has both a spatial and temporal component, and depending on the degree and location of the vessel movement, could have the ability to skew the background noise-maps depending upon the intensity and duration of the noise. If the input was an individual occurrence at one point during the survey period, then the effect on the maps would be blurred and potentially not observable. However, if vessel noise was persistent, in the same area (for example a frequent ferry crossing) then this would influence the noise-maps. But for the purpose of this study, this noise is a characteristic of the area against which acoustic signals from tidal devices would need to be detected against and therefore should be represented in this case.

The background noise-mapping presented here is a visual snapshot of the survey period itself. It would be informative to repeat surveys in the same locations to investigate seasonal differences; however the drifters would not be able to gather data in rough weather scenarios, the Kyle Rhea survey for example had to be ceased when the weather deteriorated to Beaufort wind scale force 5/6 for personal safety reasons as well as the drifters ability to record and save the acoustic files. There is however a body...
of work in the literature that describes how the noise-fields change due to increasing rain and wind (discussed further in section 7.4 below).

7.4 **HYPOTHESIS 1)** - TIDAL STREAMS ARE CURRENTLY LOUD ENVIRONMENTS

Chapter Three considered the broadband SPL levels and Chapter Four looked in more detail into the frequency content of these recordings to address research questions 1 and 2. Table 26 below details broadband SPL levels from this thesis and from available literature, and it is clear that it is very difficult to assess from a comparison of these figures alone whether tidal-stream areas are a ‘loud’ environment in comparison to other areas. All levels quoted here though are from shallow water areas, and it is generally accepted that shallow water locations can be both louder and quieter than deep water levels (Richards et al, 2007). These studies all used different methods of measurement and analysis and as stated before this makes comparison problematic. However, all levels quoted in Table 26 appear to be in a similar numerical range. Although based on these few examples, we can see that in most cases the SPL levels in tidal-stream areas are louder than the offshore wind data, particularly at the upper limits of SPL, suggesting that tidal-stream areas are ‘noisier’ than less energetic coastal areas.

Table 26- Broadband SPL levels measured from this study in comparison to published levels from the tidal-stream areas and offshore wind locations (ns) – not specified in report.

<table>
<thead>
<tr>
<th>Tidal-stream</th>
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<th>Average SPL</th>
<th>High SPL</th>
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<td>114</td>
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<td>Willis et al (2012)</td>
<td>72</td>
<td>(ns)</td>
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<td>Nedwell &amp; Brooker (2008)</td>
<td>115</td>
<td>(ns)</td>
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<table>
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<th>Offshore wind farms</th>
<th>Reference</th>
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<td>Tougaard et al (2009)</td>
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<tr>
<td>Bailey et al (2010)</td>
<td>104</td>
<td>(ns)</td>
<td>119</td>
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</table>

Additionally, when the spectral levels measured from this study were compared to the Wenz curves (accepted deep water levels) (Figure 71 - Chapter Four) the levels for three of the case study areas presented are higher than the upper Wenz curve across all frequencies. The Sound of Islay initial survey was below the upper Wenz curve for frequencies below 10 kHz then, for higher frequencies, above the Wenz curve for the (in keeping with the other case study locations). This would suggest that tidal-stream areas tend towards the upper Wenz curve levels or above and are therefore louder.
environments than deeper waters. The flatter profile suggests more sound input in the higher frequencies (above 10 kHz) probably due to the tidal flow lifting and moving sediment. Although all these areas are tidally swept environments (rock) there is evidence that there are pockets of gravel and sediment present in all locations (Chapter Four – Section 4.3). Another contributing source raising the background noise spectral profile is the influence of local vessel/boat noise (especially ferries), raising the profiles in the mid frequency ranges (100 – 2000 Hz).

Data presented here suggests that there is variability between the sites, but that there is as much variability within a site. The relative limited variability between sites may be because these locations are similar in physical characteristics (Chapter Three – Table 11), they are tidal-stream locations affected by the coastal oceanography and therefore the seabed characteristics are similar, so although there will be differences between sites, the weather and anthropogenic activity, are probably the dominant drivers of backgrounds noise measurements in these areas. The spread of sound level measurements (Chapter Three – Figure 32) highlights the variability within the same survey. But these measurements were made at different locations throughout the study site, and the mapping highlights the patchy nature of the sound levels, this variability is a reflection of both spatial and temporal elements. So many factors influence the sound levels at any one point in time and space; it is therefore perhaps unsurprising that the data does not have a clear trend.

In Chapter Six, a selection of marine mammal audiograms were compared with the background noise levels measured in tidal-stream case study locations. In general the marine mammal audiograms used in this study, tend to follow the slope of the Wenz curve, suggesting that these animals have not adapted to hearing the low frequencies necessarily well because that is where the majority if the background noise is, instead they have a lower hearing threshold at higher frequencies where the background noise levels are reduced (compare Wenz (Chapter Four – Figure 51 and marine mammals audiogram (Chapter Six – Figure 87)). However, these measurements from tidal-stream areas show elevated levels in the higher frequency range, so for any one of the selected marine mammal species, these areas may in fact be noisy environments.

Chapter Three considered the effect of flow speed on noise levels (Research Question 3) and found through statistical analysis that there was an average increase of 1.24 dB for every 1 m/s flow speed increase. Therefore assuming a maximum flow speed of 3.5
m/s, this would relate to an increase in sound levels by a little over 4 dB. This increase is slight in comparison to the increase in noise levels due to wind or rain and therefore may be the reason why the normalised background noise-maps (appendix one) were not very different from the raw data maps.

In contrast, there is a 10 dB increase in noise levels due to a tripling of the wind speed (or an increase from sea state 0 to sea state 5) (Ingenito & Wolf, 1988). Richardson et al (1995) spectral graphs illustrate an increase of about 20dB from sea state 0 to sea state 6. Rain can raise the underwater background levels by up to 35 dB (NRC, 2003). Therefore, although an increase in tidal flow speed does increase the underwater background noise levels, the increase can be masked by variability in underwater noise levels from other sources (particularly weather and vessel movement).

Based on these data, tidal-stream areas can be considered to be ‘loud’ areas before including consideration of the acoustic input of tidal-stream devices.

7.4.1 What is background/ambient noise?

We know that background noise is a mixture of sound waves from multiple sources all intermingled. Many of the recordings made for this study when listened to, sounded just like varying levels of static, but with some signals being discernible such as the crackling sound likely to be sediment transport, but that also could be snapping shrimp. Also, within the background noise recordings there were other clearly identifiable sounds, such as vessel/boat noise, chains can be heard clanking and, on one occasion in the Falls of Warness, the power-washing of a pile mounted device structure was easily audible and sounded exactly the same as the sound of power- washing a car. Fish farm acoustic warning devices can also be heard clearly. All these sounds are in the background noise-field to a marine mammal, and it is against this background that an animal needs operate, to hear communication signals from conspecifics, to locate prey and avoid predators, and to navigate their environment and avoid obstacles. Therefore for the purposes of assessing background noise, all these contributors should be considered bearing in mind some contributors are more transitory than others.

All animals are used to living in an environment with background noise nevertheless, and based on human experience - an environment without sound would be disconcerting. For humans, standing in an anechoic chamber - sound feels muffled and uncomfortable (an anechoic chamber is one where the reverberation or echoes are
prevented by foam wedges on the walls, ceiling and floor). The brain is used to
background noise and filters out what is not needed, but a lot of information is
unconsciously gained by the background noise, therefore sensing the environment using
auditory cues. Background noise, by implication, is necessary.

Marine mammals are used to the variability of background noise (Cato, 2008), and
because background noise levels can increase by around 30 dB due to increasing wave
noise due to wind speed (Chapter Three – Section 3.1.3; Tyack 2008) animals are likely
to modify their vocal behaviour in response to changing local acoustic conditions (Tyack,
2008; May-Collado & Wartzok, 2008; Morisaka et al, 2005) for example by waiting until
noise level decreases or by changing the source level of their vocalisation (Tyack, 2008)
or by increasing or changing the frequency of the vocalisation (Tyack, 2008).

The patchy nature of sound field in these tidal-stream areas as presented here, may be a
result of each location measured due to the physical characteristics of that location
(such as depth, or sediment composition, or biology) but the patches may also be
connected to the propagation of sound through the area. Ambient noise (the sound in
the background for a which the source cannot be located) is a combination of sound
from many sources (Chapter Four) but, sound will have emanated from a source location
and will therefore radiate away from that source and will consequently have a direction.
The combination of the propagation paths of these wave forms may add and cancel out
in a complex manner in these relatively narrow shallow coastal sites, thus adding to the
patchy noise-field observed. Background noise is not stationary level, but is constantly
changing.

7.5 HYPOTHESIS 2) – THE ACOUSTIC OUTPUT OF TIDAL DEVICES MAY
THEREFORE BE MASKED BY THE ENVIRONMENT AND THUS NOT EASILY DETECTED
ACOUSTICALLY.

Chapter Five reviewed available information regarding the acoustic output from tidal-
stream devices in considering research question 4. It is clear that currently there is
scarce information available. This is because of the relatively early stage in the
development of these devices and the associated industry. As such this lack of
information is likely to be because either; the acoustic output has not been investigated
as yet for individual devices or, for developers further down the development process,
that the data is commercially sensitive and so not freely available. The information
drawn upon for this thesis is based on only three developers, and as devices are likely to
be modified throughout the development process, and may be specifically tailored to
the particular site to make best use of the flow characteristics, the acoustic signatures
may vary more widely than the examples presented here.

There are similarities that can be drawn from these examples. The main acoustic energy
emitted from the devices seems to be low frequency tones (< 5000 Hz) and some
broadband energy (Chapter Five). However, there are specific characteristics linked to
the device type, for example the OpenHydro device and a particular clicking signal, not
reported for the other devices. One further caveat with regard to drawing conclusions
from these data, are that these relate to single devices, at this point in time it is difficult
to say how the environment may be modified by arrays of devices.

These data were collected in the field; therefore by default also include input from the
local background. It may not be straightforward to extrapolate all of the acoustic input
from the device against the background.

Device noise output is likely to be directional (Chapter Five) this will result in different
levels encountered by marine mammals depending on the direction and angle of
approach. Lloyd et al (2011) suggested that the least sound generated was in the plane
of the rotor, and hinted that this may be an issue for marine mammals detecting the
device. The plane of the rotor will be perpendicular to the tidal flow; therefore an
animal on direct approach may have less of an acoustic cue than animals on a more
oblique path. It would be interesting to make measurements of an operational device at
different depths and at different angles to the device to investigate this further.

The acoustic output studies for MCT SeaGen in Strangford Lough (Kongsberg, 2010)
Seaflow (Richards et al, 2007) and HS300 in Hammerfest (Akvaplan-niva, 2009) all noted
that the low frequency tonal components decayed more rapidly with range than the
broadband signal. This is interesting because low frequency sound is usually considered
to propagate better than high frequency sound through the water, except where the
water depth is too shallow to support the low frequency waveform. Therefore, this
finding is likely to be due to the bathymetry of the tidal-stream areas. This could also
mean that the frequencies containing the most energy emitted from these devices may
not propagate well over distance. This may minimise the acoustic input into the area
and thus potentially affect the audibility of these devices.
The propagation loss calculation used in Chapter Six was based on basic geometric spreading equations. The comparison of the range of equations (section 6.2.2) highlighted the variability of loss amounts depending on the equation used. The ‘absolute’ variability is potentially greater than is suggested here. More elegant propagation loss equations that consider the depth, seabed type and the seabed slope for instance are likely to generate different loss amounts again, especially when frequency dependency is factored into the estimations. It is important therefore that any ‘predictions’ using propagation loss equations are considered with these caveats in mind.

Research question 5) aimed to investigate whether when the turbines are turning at their optimum revolutions per minute that this would coincide with the noisiest background noise in the area. Based on the data presented in this thesis, I do not believe this will always be the case. Background noise levels appear to increase with tidal flow, but as discussed above this increase is not a large increase in comparison to weather or vessel effects; therefore the audibility is likely to depend on the local circumstances at the time.

![Diagram](image)

*Figure 99 - Schematic of non-concentric 'zones of influence' (Richardson et al, 1995) X - sound source (a) zone of hearing loss, discomfort or injury (b) the zone of masking (c) the zone of responsiveness and (d) the zone of audibility (not to scale).*

Research question 6) considered the potential audible range of tidal-stream devices to marine mammals. The measure of audibility maps (Chapter Six) illustrated that the
audibility radii are not concentric circles as interpreted from Richardson et al (1995). But the audibility radii presented are a result of the patchy characteristic in background noise levels, and have not considered any directionality of the device itself therefore the scenario could conceivably be more acoustically patchy than these maps suggest. See Figure 99 for a representative schematic of the acoustic ‘zones of influence’.

Based on the data presented in this thesis, tidal-stream devices are not likely to be noisy relative to the background noise. In certain circumstances they may not be audible at all (e.g. OpenHydro – Chapter Six) particularly when vessel traffic is in operation in the area.

The predominant energy from operational tidal devices is low frequency and as the selected marine mammals are not best suited to hearing lower frequencies; the tidal-stream device acoustic signature may not be an obvious acoustic cue to the devices presence for these species. This may not be the case for low frequency specialists such as the minke whale.

![Figure 100](image.png)

**Figure 100** Comparison between background noise levels in third octave levels and generalised audiograms for odontocetes and pinnipeds with boxed area highlighting the approximate frequency range of tidal-device acoustic input.

Figure 100 illustrates the comparison between the likely output from tidal devices, marine mammals’ audiogram and the third octave background noise levels. Tidal devices appear to be similar in sound to vessel noise (Chapter Five; Götz et al, 2011) and marine mammals are known to collide with ships (Laist et al, 2001) it is therefore conceivable that the collision risk is also there for tidal-stream devices. A tidal-stream
device acoustic signature will add acoustic energy to the background noise-field in a tidal stream development area, but it is likely that they will add energy similar to sound sources already in the area, and therefore not be easy to distinguish, but just raise local levels.

In relation to detectability, only passive hearing was considered in this study, but there are likely to be other cues available to marine mammals (including visual and echolocation) which may help with detectability. Also important to consider is that at the moment there is no clear understanding of marine mammals’ behavioural reactions when faced with these devices, therefore it may well be inappropriate to assume the nature of behavioural reactions at this stage.

7.6 Lessons learnt and conclusions

1. Drifting hydrophone methodology is suited to the challenge of tidal-stream locations and enables a greater spatial area to be covered during a survey and is therefore ideal for pre and post deployment surveys and monitoring surveys. This method however only provides snapshot data for the survey unless repeated deployed in one area. This would generate vast quantities of data, using the analysis methods employed in this study this would be time consuming, therefore an automated method of analysis would be necessary.

2. It is a challenge to operate the drifters in worsening weather conditions, and certainly would not practicable above Beaufort Force 5.

3. The direction of tidal flow (flood or ebb) or tidal cycle (springs or neaps) are not necessarily the parameters of relevance in the measurement of background noise levels in tidal-stream areas. The relevant parameters that have more influence in background noise levels in these areas are the location plus the weather and local anthropogenic activity and then the tidal-flow speed (to a lesser extent).

4. The variability of the acoustic noise-field and the main contributors as detailed in this thesis, are consistent with existing knowledge (Chapter Four) but this thesis has shown that the spatial background noise-field in these tidal-stream areas is very patchy, and that the levels tend to the upper Wenz curve or higher, suggesting these areas are already noisy environments.
5. During higher tidal flow-speeds, noise levels in the higher frequencies (1 kHz and above) are elevated, probably due to sediment transport leading to a flatter spectral profile than is observed in the deep water/low tidal-speed Wenz curves.

6. These patterns were consistent across all three areas in the west and north of Scotland and it would be rewarding to look elsewhere to establish how general these findings are.

7. Based on the data presented here, it is unlikely that the operational noise from tidal-stream devices will be a hazardous noise for marine mammal, or that they will present an acoustic barrier, rather that it is conceivable that tidal-devices may not be audible in all circumstances for marine mammals to detect them at distance against the background-noise environment using passive hearing alone.

7.7 Recommendations for Further Research

1. To further investigate the relationship between tidal flow speed and measured noise levels. Other drivers should be considered as well as depth and distance to shore, such as weather, vessel activity, sea bed type and sea bed slope.

2. To further investigate the causes of the patchy noise maps, and attempt to correlate parameters in a more detailed methodology. Suggestions include, the use of weather stations coincident with the survey runs of drifting hydrophones, the use of current meters, to better define the flow speed within which the drifter is travelling, the use of a drop down video to gain better detail on the sea bed composition and if available better resolution sea bed type spatial information.

3. To investigate the temporal stability of the discrete noise patches, to run drifters over multiple days and compare the spatial data. In this study, only the Sound of Islay work was conducted over multiple days.

4. These data were acquired during the day for operational reasons. The drifters had to be tracked visually to be retrieved at the end of the run. It would be interesting to collect data at night to assess what difference there might be. This would require a new method of deploying the drifters and then tracking.
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Sound Pressure Levels (dB re 1µPa)

H = High level
L = Low level

Figure 101 - Background noise-maps of the Kyle Rhea, normalised for flow speed. Sound pressure levels are colour contoured with the red representing areas of more intense sound (a) Locations of the sample points (b) All SPL – broadband frequencies up to 48 kHz (c) high band – broadband filter >10 kHz-48 kHz (d) mid band – broadband filter 1 – 10 kHz and (e) low band – broadband filter < 1kHz. Levels given in dB re 1 µPa.
Sound Pressure Levels (dB re 1 µPa)

H = High level
L = Low level

Figure 102 - Background noise-maps of the Fall of Warness normalised for flow speed. Sound pressure levels are colour contoured with the red representing areas of more intense sound (a) Locations of the sample points (b) All SPL – broadband frequencies up to 48 kHz (c) high band – broadband filter >10 kHz-48 kHz (d) mid band – broadband filter 1 – 10 kHz and (e) low band – broadband filter < 1kHz. Levels given in dB re 1 µPa.

These maps were then generated in ArcGIS using the normalised SPL.

Statistical analysis (detailed in Chapter Three) suggested that for every 1 m/s increase in flow speed – there was a corresponding increase in SPL by 1.2427 dB.

The normalised maps were therefore corrected for flow speed by;

\[ \text{Raw data SPL} - (1.2427 \times \text{flow speed}) = \text{Normalised SPL} \]
Sound Pressure Levels (dB re 1µPa)

H = High level
L = Low level

Figure 103 - Background noise-maps of the Sound of Islay, normalised for flow speed. Sound pressure levels are colour contoured with the red representing areas of more intense sound (a) Locations of the sample points (b) All SPL – broadband frequencies up to 48 kHz (c) high band – broadband filter >10 kHz-48 kHz (d) mid band – broadband filter 1 – 10 kHz and (e) low band – broadband filter < 1kHz. Levels given in dB re 1 µPa.
Sound Pressure Levels (dB re 1µPa)

H = High level
L = Low level

Figure 104 - Background noise-maps of the Fall of Warness - slack water normalised for flow speed. Sound pressure levels are colour contoured with the red representing areas of more intense sound (a) Locations of the sample points (b) All SPL – broadband frequencies up to 48 kHz (c) high band – broadband filter >10 kHz-48 kHz (d) mid band – broadband filter 1 – 10 kHz and (e) low band – broadband filter < 1kHz. Levels given in dB re 1 µPa.
Figure 105 - Rainy fieldwork in Kyle Rhea May 2011 (Photo J. Elliott)