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Behavioural and Acoustical Responses of Coastal Dolphins to Noisy Environments

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Declaration of authorship

I, **Sarah Anne Marley**, declare that to the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

The research presented and reported in this thesis was conducted in compliance with the National Health and Medical Research Council Australian code for the care and use of animals for scientific purposes 8th edition (2013). The proposed research study received animal ethics approval from the Curtin University Animal Ethics Committee, Approval Number AEC-2013-28 and AEC-2013-25.

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"You cannot begin to preserve any species of animal unless you preserve the habitat in which it dwells. Disturb or destroy that habitat and you will exterminate the species as surely as if you had shot it. So conservation means that we have to preserve forest and grassland, river and lake, even the sea itself. This is vital not only for the preservation of animal life generally, but for the future existence of man himself - a point that seems to escape many people."

– Gerald Durrell

"The world is full of wonders, but they become more wonderful, not less wonderful, when science looks at them"

– David Attenborough

Abstract

As human activities continue to expand across the marine environment, anthropogenic noise in the ocean is also rapidly increasing. The most ubiquitous source of noise pollution is from motorised vessels, which have the cumulative effect of reducing habitat quality by increasing underwater noise levels. This is of particular concern to dolphins due to their elaborate and extreme specialisations for auditory comprehension and sound production underwater. Coastal dolphin species are especially vulnerable to noise pollution, due to their high degree of habitat overlap with anthropogenic activities. There is a need for studies that describe the soundscape of coastal dolphin habitats and examine how prominent anthropogenic noise sources may impact these animals.

Western Australia provides an ideal location for such work. Dolphins are present along much of its coastline, from the urban Swan-Canning river system in the state capital of Perth to the relatively pristine waters of Roebuck Bay in the "last wilderness" Kimberley region. The overall aim of this thesis was to identify the behavioural and acoustical responses of coastal dolphins to environments rich in anthropogenic noise. To achieve this aim, a combination of visual and acoustic monitoring techniques were used. Autonomous underwater acoustic recorders collected data on dolphin acoustic habitats within the Swan River and Roebuck Bay. The soundscape of these areas was then described using a variety of techniques, including: weekly spectrograms, power spectrum density percentile plots and probability densities, octave-band levels, broadband noise levels, and generalised estimating equations . Land-based theodolite tracking at two sites within the Swan River provided information on vessel traffic whilst also recording dolphin occurrence, movement speeds, and behaviour. These data were then assessed using generalised additive models, Markov chains, and comparative statistics (e.g. Kruskall-Wallis) to investigate how dolphin behaviour varied in different vessel traffic contexts. Furthermore, modification to dolphin whistle characteristics as a result of underwater noise was also assessed using generalised additive models applied to data collected by the acoustic recorders.

Acoustic datasets collected at six Swan River sites from 2005 to 2015 indicated that some sites were 'noisier' than others, with the Fremantle Inner Harbour being noisiest due to anthropogenic activities. The most wide-spread anthropogenic sound source throughout the river system was vessel traffic, although port operations also considerably contributed to the Fremantle Inner Harbour acoustic environment. Theodolite observations from two Swan River sites – Perth Waters and the Fremantle Inner Harbour – showed differential site use by the resident dolphin community. Animals occupied the Fremantle Inner Harbour more frequently and for longer periods than Perth Waters, despite the heavier vessel traffic at the former site. This may reflect the importance of Fremantle Inner Harbour as a foraging site for these animals. To investigate whether a subtler response was occurring in the Fremantle Inner Harbour, additional analyses were conducted to examine dolphin behaviour at varying vessel densities and underwater noise levels. Results indicated significant alterations to dolphin movement speeds and activity states at high vessel densities. Furthermore, whistle characteristics varied with levels of broadband noise. Finally, the busy, noisy environment of the Fremantle Inner Harbour was compared with the relatively pristine acoustic habitat of Roebuck Bay. The potential consequences of hypothetical noise increases within Roebuck Bay were discussed with reference to knowledge gained from results from the Swan River component of the research.

Overall, this thesis categorises new soundscape recordings from the Western Australian coastline, quantifies the contribution of human activities to these soundscapes, identifies the response of coastal dolphins to anthropogenic activities and noise, and discusses potential consequences should 'quiet' dolphin habitats be altered. This work suggests that dolphins maintain occupancy at key foraging sites within the Swan River despite the presence of anthropogenic stressors. Short-term energy gains from foraging thus may outweigh energy costs of behavioural alterations by habituated dolphins during high traffic conditions. However, potential effects of long-term stress from disturbance to habituated dolphins have yet to be determined. In addition, more sensitive, inexperienced populations may respond differently, potentially dis-occupying former home ranges. A greater depth of knowledge of responses of multiple populations and species in a range of noise conditions is required to accurately inform management decisions.

This thesis is dedicated to my family;

Old and New,

Adopted and True.

And, of course, to the animals our lives inevitably revolve around.

So:

To my family,

and other animals.

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The Officials

This project was generously supported by the Swan River Trust, the Western Australian Marine Science Institute, the Holsworth Wildlife Research Endowment (Equity Trustees Charitable Foundation and the Ecological Society of Australia), and the Australian Acoustical Society. I would also like to thank the Department of Spatial Sciences at Curtin University for the generous use of their theodolite, and Dr Eric Kniest (University of Newcastle) for support during theodolite and Vadar software set-up. Fremantle Council and the Botanic Gardens and Parks Authority (BGPA) of Kings Park kindly allowed access to their sites for data collection, with Jake Tanner going above and beyond to provide assistance in accessing Cantonment Hill. The Fremantle and Broome Port Authorities, Swan River Trust, and Department of Parks and Wildlife provided assistance with logger deployment permissions and logistics.

The Unofficials

They say that "*All the talent in the world won't take you anywhere without your team mates.*" What I lack in talent I more than make up for in team mates. I am fortunate enough to have an amazing network of people – family, friends, colleagues, mentors, and supervisors – who have helped me through the past few years. I am truly indebted to many people, without whom this thesis would not have been possible. And so I make no apology for the lengthy list of appreciation that follows. After all, how often in life are you awarded the chance to thank the people who got you here?

The Professionals

All good students need a good teacher, and I was lucky to have not just one but two amazing teachers throughout this PhD. My heartfelt thanks extend to my main supervisor, Chandra Salgado Kent. At our inauspicious initial meeting, in a dank student kitchen in St Andrews, I'm sure neither of us foresaw the amazing journey that would follow. Several years later, I still have little idea what you saw in that quiet, inexperienced Scottish girl – but whatever it was, I'm sure glad you saw it! I admire your ability to always see the best in others, your patience in helping people develop both their skills and themselves, and your quiet confidence that things will work out. I have always said that one of the things I am most thankful for is the balance of our personal and professional relationship; it hasn't always been an easy line to tread, but I treasure our friendship. Other things I am thankful for include: weak lattes; coffee-shop meetings; the continual quest for that sweet combination of free wifi and electricity plugs; afternoon port; whales and wineries; late-night fieldwork chats; amateur psychology musings; and "special Chandra coffees". I hope to see more of these in our future! I feel privileged to have shared so many adventures with you.

Our fieldwork has taken us almost the full length of Western Australia, from small unassuming snubbies up north to tracking the beautiful blues down south. Through you I have learnt how to lead field teams, scare off snakes, critique statistical models, harness peoples' enthusiasm, and set up many, many damn theodolites. But I think the biggest lesson you have taught me is how to be strong yet compassionate, and the importance of looking after others. After a few rocky experiences as a volunteer myself, I appreciate your efforts to give volunteers an amazing experience. It is inspirational, and something I try to continue with my own volunteers. Over the past seven years we have trained hundreds of vollies together and undertaken many field seasons. I am honoured to have been by your side through it all. *Estoy orgullosa de trabajar contigo. Espero que nuestra amistad continúe.*

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As well as having two wonderful supervisors, I was fortunate enough to have two mentors through my PhD journey. Despite arguing from the start that they would be of limited assistance, Miles

Parsons and Iain Parnum have come through for me time and time again. Whether I am dredging up muddy river loggers, cursing Matlab code, or just having a general moment of despair, you have always been ready to jump in and help. Even if you didn't realise it, you've often come in with just the right words or encouragement just as I have needed it the most. I dread to think what state I (or this thesis) would be in without you both. Thank you so much for your time, energy, and support.

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The Friends

When I began the PhD, I did not fully realise what a lonely, isolated journey it would become. The cold, hard truth is that only so many people will ever be as deeply interested in your research as you are. Also, when most people ask "How are you?" or "How's it going?", they are not actually asking at all. So, it becomes increasingly difficult to be honest with people and say when you are not okay and things are not going well, especially as you sink deeper into the thesis. But I have been fortunate enough to have a core PhD Support Team to not only help keep me above water, but also join me in riding the waves.

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"Those sneaky dolphins!"
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Photo credit: Sarah Marley, Curtin University (2014)

Publications arising from this thesis

Marley, S.A., Erbe, C. and Salgado Kent, C.P. (2016). Underwater Sound in an Urban Estuarine River: Sound Sources, Soundscape Contribution, and Temporal Variability. *Acoustics Australia*, **44**(1): 171-186. DOI: 10.1007/s40857-015-0038-z.
(Chapter 2)

Marley, S.A., Salgado Kent, C.P. and Erbe, C. (2016) Occupancy of bottlenose dolphins (*Tursiops aduncus*) in relation to vessel traffic, dredging and environmental variables within a highly-urbanised estuary. *Hydrobiologia*, **792**: 243. DOI: 10.1007/s10750-016-3061-7.
(Chapter 3)

Marley, S.A., Erbe, C., Salgado Kent, C.P., Parsons, M.J.G. and Parnum, I.M. (2017) Spatial and temporal variation in the acoustic habitat of bottlenose dolphins (*Tursiops aduncus*) within a highly urbanised estuary. *Frontiers in Marine Science*, **4**: 197. DOI: 10.3389/fmars.2017.00197.
(Chapter 4)

Marley, S.A., Erbe, C. and Salgado Kent, C.P. (In Press) Underwater recordings of the whistles of bottlenose dolphins in the Fremantle Inner Harbour, Western Australia. *Scientific Data*.
(Chapter 5)

Marley, S.A., Salgado Kent, C.P., Erbe, C. and Parnum, I.M. (In Press) Effects of vessel traffic and underwater noise on the movement, behaviour and vocalisations of bottlenose dolphins (*Tursiops aduncus*) in a highly urbanised estuary. *Scientific Reports*.
(Chapter 5)

Marley, S.A., Salgado Kent, C.P., Erbe, C. and Thiele D. (In Press) A Tale of Two Soundscapes: Comparing the acoustic characteristics of urban versus pristine coastal dolphin habitats in Western Australia. *Acoustics Australia*.
(Chapter 6)

Related publications

Parsons, M.J.G., Erbe, C., McCauley, R.D., McWilliam, J., **Marley, S.A.**, Parnum, I.M., Salgado Kent, C.P. and Gavrilov, A.N. (2016) Long-term monitoring of soundscapes and deciphering a usable index: Examples from Australia. *Proceedings of Meetings on Acoustics*, 27**(1)**: 010023. DOI: 10.1121/2.0000286.

Parsons, M.J.G., Salgado Kent, C.P., **Marley, S.A.**, Gavrilov, A.N. and McCauley, R.D. (2016) Characterising diversity and variation in fish choruses in Darwin Harbour. *ICES Journal of Marine Science*, 73**(8)**: 2058-2074. DOI: 10.1093/icesjms/fsw037.

Recalde Salas, A., Salgado Kent, C.P., Parsons, M.J.G., **Marley, S.A.** and McCauley, R.D. (2014) Non-song vocalizations of pygmy blue whales in Geographe Bay, Western Australia. *Journal of the Acoustical Society of America*, 135**(5)**: EL213-EL218. DOI: 10.1121/1.4871581.

Statement of candidate contributions

This thesis is presented as a series of five manuscripts in journal format, in addition to a general introduction and general discussion.

These papers were primarily developed from my own ideas and approaches, with the support and guidance from my supervisors and collaborators. I designed the methodology and constructed statistical models based on discussions with co-authors, and carried out the relevant data analyses.

Dr Chandra Salgado Kent assisted with the set-up of theodolite hill stations, advised on deployment sites within the Swan River, and assisted with acoustic deployments in Roebuck Bay. I worked with Dr Christine Erbe to develop code for acoustic analyses, and she also assisted with the Heirisson Island (Swan River) acoustic deployments. Dr Miles Parsons assisted with the remaining deployments of acoustic recording equipment in the Swan River, and also made available the long-term Mosman Bay acoustic dataset. Dr Iain Parnum provided code to calculate broadband noise levels and gave feedback on analysis options for the Swan River and statistical results from modelling dolphin whistles. Other contributors to fieldwork or logistics are acknowledged in the relevant chapters.

I wrote all chapters, with feedback from Dr Chandra Salgado Kent, Dr Christine Erbe, Dr Miles Parsons, and Dr Iain Parnum.

Sarah A. Marley

(Student)

Dr Chandra Salgado Kent

(Primary Supervisor)

Contents

List of Tables

List of Figures

Chapter 1

General introduction

Despite the advancements of acoustic and visual monitoring techniques in marine environments over past decades, many fundamental questions regarding marine mammals, their acoustic habitats, and animal responses to changes in these habitats remain unanswered. Cetaceans are an excellent example of marine mammals highly specialised to depend upon sound for life functions. Due to the high attenuation of light in water and relatively low visibility in marine environments, many marine organisms rely on sound to investigate their environment (Nybakken & Bertness, 2005). Sound travels efficiently through water, at approximately four times the speed it travels through air. Cetaceans have evolved the most elaborate and extreme adaptations of marine organisms to sense and produce sound. Their auditory sensitivity and produced sounds include some of the widest frequency bands in the animal kingdom (Southall *et al.*, 2007; Tyack & Miller, 2002). These acoustic specialisations allow cetaceans to overcome the challenges of limited vision and instead use sound for vital processes, such as orientation, communication, and foraging (Tyack & Miller, 2002). However, these auditory adaptations also make cetaceans particularly susceptible to the impacts of anthropogenic noise.

One of the most widely discussed questions regarding cetaceans and their acoustic habitats is the impact of anthropogenic activities and associated noise on their populations. Like most fundamental issues, the lack of knowledge leads to many challenges. The core questions are what impacts does anthropogenic noise have on individuals and their populations, and what are the implications for their survival. To answer these questions, baseline information on cetacean acoustic habitats and how animals utilise these areas is required. Acoustic habitat (or soundscape) variation in space and time on broad scales in many underwater soundscapes remain unknown. Where soundscapes have been measured, the methods for characterisation vary in their detail and accuracy. Many coastal and marine habitats are already subjected to high levels of anthropogenic activity and noise, making it difficult to know what baseline levels were originally when the habitat was 'pristine'. Although man-made underwater noise in marine habitats has undoubtedly increased over the past few decades (McCarthy, 2004; McIntyre, 1999), there is little at most locations to formally document this.

In locations with high human activity, there is uncertainty regarding whether these activities and their associated underwater noise elicit responses in cetaceans by changing their behaviours (e.g. Pirotta *et al.*, 2013), including acoustic behaviours. In addition, the question of habituation arises:

Do we see no behavioural response to noise in some contexts because the population is already used to the presence of such sounds? If so, did behavioural responses ever occur or have animals developed strategies to deal with these noisy environments? And, if such strategies exist, do they evoke an energetic or reproductive cost to the animals involved? Many studies monitoring marine mammal behaviour are by necessity boat-based, thus introducing possible bias from the presence of observers (and their boat). These biases have the potential to confound results, and responses may go undetected. While the experimental design of impact studies is challenged by logistical constraints, the application of knowledge gained to management decisions is challenged by the variability in results obtained from studies. This variability results because the same species may respond differently in different environments and times, depending upon their previous experience with man-made noise and the importance of the habitat they are occupying for life functions. Moreover, results vary widely among different species, due to species-specific hearing abilities and sensitivities to sound.

My thesis examines the soundscape experienced by coastal dolphins at two locations within Western Australia, and investigates whether these animals display behavioural (including acoustical) responses to human activity and its associated anthropogenic noise. This first chapter introduces the background and framework for the research reported on in this thesis. First, the background concepts behind marine soundscapes are described, including the contribution of anthropogenic noise to the marine environment. Current knowledge on potential impacts of such noise on cetaceans is then discussed, with a particular focus on responses of dolphins to vessel traffic. Existing knowledge gaps and research challenges are then illustrated, including the need to consider dolphin habitats from an acoustic perspective. The introduction is concluded with the overall thesis aims and objectives, a brief overview of the study sites and research approach, a summary of the overall significance of the research, and an outline of the thesis chapters

1.1 Marine Soundscapes

Marine habitats are characterised by a unique combination of topographic structures, environmental conditions, and species compositions. These features contribute either directly or indirectly to the acoustic conditions, or the 'soundscape', of a particular environment made up of abiotic (e.g. wind, waves, currents) and biotic (e.g. crustaceans, fish, marine mammals) sources of sound. The soundscape varies in space and time, depending on changes in the physical and biotic environment in each location (Harris & Radford, 2014; Krause, 2008; Pijanowski *et al.*, 2011). This gives habitats their unique acoustical signature (Pijanowski *et al.*, 2011).

Habitat-specific acoustic signatures are becoming increasingly valuable in ecological assessments. Positive correlations have been found between the acoustic characteristics of an area and the density, diversity and biomass of marine organisms present (Kennedy *et al.*, 2010). Acoustic monitoring has also revealed relationships between acoustic characteristics and seafloor or reef structures (Kennedy *et al.*, 2010; Lillis *et al.*, 2014). A study of ten sites along approximately 1,890 km of the U.S. east coast found high levels of variability in ambient noise, highlighting geographical differences in the acoustic environment (Rice *et al.*, 2014). Even within a relatively small area, site-specific acoustic signatures and temporal patterns can exist. Soundscape studies in New Zealand, Pacific Panama, Ireland and Taiwan have noted site-specific sound fields at locations only a few kilometres apart (Guan *et al.*, 2015; Kennedy *et al.*, 2010; McWilliam & Hawkins, 2013; Radford *et al.*, 2010). There is some evidence that larval fish and invertebrates may rely on these habitat-specific acoustic characteristics to assist with their navigation and/or settlement (Montgomery *et al.*, 2006; Radford *et al.*, 2011, 2007; Simpson *et al.*, 2008; Stanley *et al.*, 2010; Vermeij *et al.*, 2010). In addition to spatial patterns, there can also be temporal variation in marine soundscapes. For example, many fish choruses show temporal patterns at hourly, lunar and/or seasonal time scales (McCauley, 2012; Parsons *et al.*, 2016b,c, 2013a). Snapping shrimp show diurnal and seasonal patterns in their snapping rates (Bohnenstiehl *et al.*, 2016). Many baleen whale species have diurnal and seasonal patterns in their singing behaviour (e.g. humpback whales, *Megaptera novaeangliae*; Au *et al.*, 2000). Knowledge of these spatio-temporal patterns in marine soundscapes can be used to monitor species presence, biodiversity and habitat quality (Farina & James, 2016; Harris & Radford, 2014). Whilst there is still much work to be done in understanding how to interpret acoustic data, these studies highlight the fact that soundscapes are important in the lives of marine fauna and are not naturally static, often varying considerably from adjacent areas and time periods.

Many marine soundscapes are changing because of the increasing presence of anthropogenic sound sources. Such sources described in detail in Nowacek *et al.* (2007) include aircrafts, tourism activities, ice-breakers, marine construction, dredging, underwater explosions, marine geophysical surveys, military sonar, acoustic thermometry, acoustic deterrents or harassment devices, and general vessel traffic. The noise produced by these activities can be intentional (e.g. military sonar, seismic exploration) or incidental (e.g. noise from vessels, dredging, pile-driving). Whilst anthropogenic sounds may not always occur as frequently as those from abiotic or biotic sources, when present they have the potential to overwhelm the local soundscape (Spence & Houser, 2015). As a result, in recent years there has been increasing concern regarding the impact of anthropogenic sounds on marine areas and species (Boyd *et al.*, 2011; Holles *et al.*, 2013; Tyack, 2008). For instance, underwater noise can mask important acoustic signals produced by a number of marine animals, consequently disrupting vital life functions (Clark *et al.*, 2009). Anthropogenic noise may therefore act as a form of habitat fragmentation, artificially creating ‘quiet’ and ‘noisy’ areas (Rice *et al.*, 2014). However, these qualitative terms will of course be relative measures, varying not only by context but also according to the species or population in question.

The non-acoustic impacts of anthropogenic activity (such as habitat destruction, introduced species and diseases, animal population depletions, and chemical pollution) may also alter soundscapes indirectly by triggering shifts in the composition, and thus acoustic signature, of natural ecosystems (Harris & Radford, 2014; Laiolo, 2010). Consequently, acoustic sampling is increasingly being considered as a means of environmental monitoring, providing early warning of habitat disturbance or deterioration (Laiolo, 2010; Pijanowski *et al.*, 2011). The natural spatio-temporal variability of marine soundscapes combined with increasing anthropogenic acoustic pressures means that more research describing changes in acoustic habitat quality through long-term monitoring is needed. Implications to the life functions of marine fauna within those habitats can then be assessed – particularly for species that are acoustically specialised.

1.2 Cetacean Acoustic Habitats

Improved knowledge of the acoustic habitats cetaceans live in is vital if we are to understand the potential impacts of man-made noise exposure. Baseline information on the soundscape through space and time is the first component to assessing impacts from noise exposure. Baseline soundscape studies involve describing the habitat in terms of prominent sound sources, levels of acoustic energy in particular frequency bands, and patterns of ambient and anthropogenic noise. Such research has been conducted for some cetacean populations. Continuous seasonal recordings made over several years at three sites in the North Atlantic revealed consistent inter-annual trends and inter-site variations in noise parameters of North Atlantic right whale acoustic habitats (Parks *et al.*, 2009). In another study, shipping noise in beluga whale habitat determined that ferry traffic added 30 – 35 dB to ambient noise levels above 1 kHz, which contributed to a significant decrease in beluga communication range (Gervaise *et al.*, 2012). These studies are examples of those that have focused on soundscape categorisation to assess impacts.

In studies on dolphins, most have investigated the immediate response of dolphins to particular sounds, while relatively few have considered the soundscape. This knowledge gap is the result of a range of issues, including a lack of suitable datasets, inconsistent use of methodologies, and a paucity of pristine baseline habitat measurements for comparison purposes. Consequently the existing dolphin soundscape literature provides snapshots of acoustic habitats over short time periods, generally focusing on only one or two sites within the animals' range. For example, Spence & Houser (2015) described the presence of soundscape contributors at a site off Quintana Roo, Mexico where bottlenose dolphins (*Tursiops truncatus*) are known to frequent. Similarly, Guan *et al.* (2015) described the soundscape of two sites in Taiwan (23.7 km apart) by focusing on three octave bands, and related these characteristics to the local Indo-Pacific humpback dolphin (*Sousa chinensis*) population. Many areas are already heavily affected by anthropogenic sound sources. This can be a challenge for scientific comparisons and for management decisions. For example, whether conservation efforts ought to be directed towards reducing noise in habitats rich in anthropogenic sources (anthropogenically 'noisy' habitats) or preserving the remaining areas relatively free of anthropogenic noise (anthropogenically 'quiet' habitats) is the focus of an ongoing debate (Williams *et al.*, 2014b, 2015a). The long-term monitoring of both 'noisy' and 'quiet' areas may offer a solution by enabling meaningful comparisons and enable predictions of the consequences of changing soundscapes.

To fully understand dolphin behaviour and habitat use, dolphin habitats must be described from an acoustic perspective. In particular, given the overlap between coastal dolphins and recreational vessel traffic, consideration of the contribution of vessels to dolphin acoustic habitats is needed. Furthermore, as soundscapes are not static in their composition, marine habitats will display spatial and temporal variability. Thus, to understand the role acoustic characteristics may play in driving dolphin habitat-use and behaviour, there is a need to quantify the marine soundscape over large areas and over long periods of time. Once soundscape characteristics have been described and anthropogenic contributors quantified, scientists can begin to assess the influence of these on dolphin life functions.

1.3 Impacts of Underwater Noise on Cetaceans

Exposure to underwater sound has been found to impose a range of impacts on cetaceans, from minimal short-term effects to severe long-term consequences, with previous studies finding evidence of behavioural, acoustical, and physiological responses (Erbe *et al.*, 2015a; Nowacek *et al.*, 2007; NRC, 2003, 2005; Richardson *et al.*, 1995; Tyack, 2008; Weilgart, 2007; Williams *et al.*, 2015b, 2014a). At low levels, anthropogenic noise may be merely detectable to cetaceans. Increased noise levels can invoke changes in animal activity states, vocal effort or other fine-scale behaviours (Aguilar Soto *et al.*, 2006; Castellote *et al.*, 2012; Foote *et al.*, 2004; Holt *et al.*, 2009; Melcón *et al.*, 2012). Noise exposure can also cause changes in occurrence and site occupancy (Cosens & Dueck, 1988; Morton & Symonds, 2002; Muir *et al.*, 2016; Rako *et al.*, 2013). High noise levels may interfere with animal communication and acoustic signal detection. If prolonged exposure occurs, effects on the auditory system can occur and, if noise is sufficiently intense and at close range, physical damage to hearing structures or rupturing of organ tissues can occur (Clark *et al.*, 2009; Erbe, 2012; Erbe *et al.*, 2015a; Kujawa & Liberman, 2009).

Behavioural changes such as displacement are the most easily discernible animal responses to noise. Belugas (*Delphinapterus leucas*) have been found to react strongly to noise from ships and icebreakers in deep channels of the Canadian High Arctic, with animals rapidly swimming away (and consequently vacating the area) when a ship approached within 50 km (Cosens & Dueck, 1988). In British Columbia, killer whales (*Orcinus orca*) have been displaced by high-amplitude sound from acoustic harassment devices (Morton & Symonds, 2002), whilst fin whales (*Balaenoptera physalus*) in the Mediterranean were displaced in response to seismic airgun activity (Castellote *et al.*, 2012). Short-term behavioural changes, such as avoidance, may initially seem to induce only minor impacts on cetaceans. However, if animals are forced to abandon key areas (e.g. feeding sites, breeding grounds, resting areas), detrimental effects may occur at individual and/or population levels (NRC, 2003). Shifts in an animal's behavioural budgets due to activity changes could lead to similar consequences. For example, southern resident killer whales in British Columbia have been observed to spend less time foraging in response to vessel traffic (Lusseau *et al.*, 2009). Lost feeding opportunities, in particular, have been hypothesised to result in a substantial (18%) decrease in energy intake for northern resident killer whales (Williams *et al.*, 2006). Other behavioural responses can be far more subtle, for example changes in dive duration or respiration rates (Weilgart, 2007). Unusual foraging dives from Cuvier's beaked whales (*Ziphius cavirostris*) have been recorded in the presence of large ships (Aguilar Soto *et al.*, 2006). In this study, insight into animal movements underwater at high spatial resolution was gained by attaching D-tags to the animals (Aguilar Soto *et al.*, 2006). Evidence of behavioural changes occurring at the surface and underwater points to the need to consider cetacean responses both above and below the ocean surface.

'Masking' effects have also been shown to occur in the presence of underwater noise. Masking occurs when anthropogenic sounds interfere with cetacean acoustic signals (Erbe *et al.*, 2015a). In situations of collective noise from many sources, an animal's ability to perceive sounds may be impeded. In British Columbia, median noise levels were deemed high enough to reduce the communication space for fin and humpback whales by 1 and 52% respectively, increasing to 30 and 94% under noisy conditions (Williams *et al.*, 2014b). At this site, the communication space for killer whales was also reduced by up to 97%, with noise levels highest in legally-designated killer whale critical habitats (Williams *et al.*, 2014b). This type of acoustic interference may result in the reduction of an individual's fitness (Clark *et al.*, 2009). Animals either need to expend more energy to mitigate acoustic interference, or their performance in activities such as foraging may be affected. Studies investigating marine mammal acoustic responses to underwater noise have found evidence of altered call rates, durations, amplitudes, and frequency ranges. For instance, wild bottlenose dolphins (*T. truncatus*) were observed to have higher whistle rates at the onset of recreational vessel noise, compared to during and after exposure (Buckstaff, 2004). When exposed to low-frequency active sonar, humpback whales lengthened their song by an average of 29% (Miller *et al.*, 2000). Similarly, killer whale pods were found to increase their call durations in the presence of boats, but only following an extended period of increasing boat traffic (Foote *et al.*, 2004). Other killer whale studies have found evidence of increased call amplitude by 1 dB for every 1 dB increase in background noise levels (Holt *et al.*, 2009). Individual North Atlantic right whales (*Eubalaena glacialis*) also responded to periods of increased background noise by increasing the amplitude of their calls (Parks *et al.*, 2011). A shift in frequency band has been reported for belugas, with vocalising animals increasing their mean frequency from 3.6 kHz prior to noise exposure to frequencies of 5.2 – 8.8 kHz during exposure (Lesage *et al.*, 1999). Such noise-dependent call modifications may help maintain communication with conspecifics despite increased background noise levels, thus counter-acting the effects of acoustic masking. However, little is known of the threshold levels of noise required to evoke such 'anti-masking' strategies from different species. Nor are the long-term effects of such communication modification fully understood. By identifying the effects of masking, including energy expended by animals to mitigate the effects, the impacts in cetacean critical habitats with high levels of man-made noise can be managed effectively.

There has been little research into physiological changes occurring as a result of exposure to high noise levels. When the mammalian auditory system is exposed to prolonged or a high level sound, the cochlear hair cells begin to fatigue, resulting in reduced hearing sensitivity (NRC, 2005). If the exposure is below a critical level, the hair cells will eventually return to their normal shape and the hearing loss will be short-term, known as a temporary threshold shift (TTS; Kastak *et al.*, 1999; Nachtigall *et al.*, 2003; NRC, 2005; Schlundt *et al.*, 2000). That said, although the effect of acoustic overexposure on auditory hair cells is reversible, the cochlear nerve fibres can still experience long-term damage substantial enough to affect signal detection (Kujawa & Liberman, 2009). Exposure to sounds exceeding a higher threshold can result in a permanent threshold shift (PTS) that will leave the auditory system irrevocably damaged and cause permanent hearing loss (Finneran *et al.*, 2005; NRC, 2005; Schlundt *et al.*, 2000). However, for animals such as cetaceans who are reliant on sound for vital life processes, any reduction in hearing sensitivity could cause a significant disadvantage to survival.

1.4 Behavioural Responses of Dolphins to Vessel Traffic and Noise

Coastal areas are among marine habitats most at risk of degradation from human activities (McIntyre, 1999; Moore, 1999). As a result, coastal species such as bottlenose dolphins (*Tursiops* sp.) are among marine fauna most exposed to anthropogenic threats (DeMaster *et al.*, 2001; Thompson *et al.*, 2000). Furthermore, because dolphins are acoustically-specialised animals whose survival is strongly reliant on their ability to detect and produce sound underwater, they are not only vulnerable to anthropogenic activities but also to associated underwater noise. In coastal habitats, the most ubiquitous source of anthropogenic ocean noise is vessel traffic, which has been reported at 'chronic' levels in some locations (Andrew *et al.*, 2011; Frisk, 2012).

As a result, many dolphin behavioural response studies have focused on vessel-related impacts. In particular, vessels specifically targeting dolphins for tourism have been the subject of much investigation (e.g. Arcangeli & Crosti, 2009; Bejder *et al.*, 2006; May-Collado & Quiñones-Lebrón, 2014; Pérez-Jorge *et al.*, 2016; Scarpaci *et al.*, 2000; Steckenreuter *et al.*, 2012; Stensland &

Berggren, 2007; Symons *et al.*, 2014; Christiansen *et al.*, 2010; Constantine *et al.*, 2004; Guerra *et al.*, 2014; Heiler *et al.*, 2016; Lusseau, 2003a, 2005, 2006; Lusseau & Higham, 2004). These studies have reported many of the behavioural and acoustical responses mentioned in the previous section. Animals have been displaced or changed their occurrence/site occupancy in response to vessel traffic and underwater noise (Bejder *et al.*, 2006; Lusseau, 2005; Pérez-Jorge *et al.*, 2016; Pirotta *et al.*, 2015; Rako *et al.*, 2013). Dolphins have also been observed to alter their movement patterns within an area in response to vessel traffic, with animals changing their direction of travel, beginning to travel erratically, or significantly increasing travelling speeds when approached by vessels (Au & Perryman, 1982; Christiansen *et al.*, 2010; Lemon *et al.*, 2006; Lusseau, 2006; Mattson *et al.*, 2005; Nowacek *et al.*, 2001). Tourism vessels can cause a shift in dolphin behavioural budgets, generally increasing time spent travelling whilst decreasing resting and socialising behaviours (Arcangeli & Crosti, 2009; Constantine *et al.*, 2004; Lusseau, 2003a; Steckenreuter *et al.*, 2012; Stensland & Berggren, 2007). Other changes in behaviour can include alterations to dive patterns, displays of breathing synchrony, and changes in inter-animal distances (Hastie *et al.*, 2003; Janik & Thompson, 1996; Nowacek *et al.*, 2001; Stensland & Berggren, 2007). Tourism vessels not only cause potential disturbance from their presence, but also from their noise. Dolphins have been observed to alter their whistle characteristics such as their frequency range in elevated noise conditions or in the presence of tourism boats (Guerra *et al.*, 2014; Heiler *et al.*, 2016; May-Collado & Quiñones-Lebrón, 2014; May-Collado & Wartzok, 2008; Morisaka *et al.*, 2005; Rako Gospić & Picciulin, 2016). Changes to whistle duration have also been reported (Guerra *et al.*, 2014; May-Collado & Quiñones-Lebrón, 2014; May-Collado & Wartzok, 2008), as have increases in whistle production rates (Buckstaff, 2004; Guerra *et al.*, 2014; Scarpaci *et al.*, 2000).

These behavioural and acoustical changes may affect dolphin energetics. Energy expenditure can increase as a result of more time spent travelling, moving at speed, avoiding vessels, or leaving impacted areas. Disturbance can also affect individual health through lost foraging or resting time (New *et al.*, 2013). Dolphin metabolic rates increase during periods of vocal effort and sound production, with energy requirements varying according to the type of sound produced (Holt *et al.*, 2015, 2016; Noren *et al.*, 2013). Although some responses may be relatively minor over a short period, prolonged exposure to vessel traffic and noise may have cumulative health effects on individual dolphins, which have the potential to lead to changes at a population level (New *et al.*, 2013).

There are a range of possible behavioural responses to disturbance dolphins may display, ranging from relatively subtle (e.g. changing whistle characteristics) to more obvious behavioural changes (e.g. all animals leaving the affected area). Many previous studies have considered these behaviours independently of each other – that is, studies investigating physical changes in visually-observed behaviour may not necessarily consider concurrent changes in acoustic behaviour, or vice versa. This leaves a distinct knowledge gap, and a need for capturing a broader understanding of responses through studies utilising simultaneous visual and acoustic monitoring techniques. Additionally, comparatively little attention has been paid to potential impacts from recreational vessels in coastal areas. Recreational and other non-tourism vessels have the potential to impact dolphins despite not being actively engaged in wildlife-watching activities. Such vessels often occur in high densities around coastal areas, with vessel traffic predicted to increase over coming years (Buckstaff, 2004; Davenport & Davenport, 2006; Lloret *et al.*, 2008; Mattson *et al.*, 2005; McCarthy, 2004). Hence, there is a need to monitor vessel traffic in dolphin habitats from both a physical and acoustical perspective, and assess their impacts on coastal dolphins.

1.5 Knowledge Gaps and Research Challenges

As human activities continue to expand across the marine environment, anthropogenic noise in the ocean is rapidly increasing. The most ubiquitous source of noise pollution is from motorised vessels, which have the cumulative effect of reducing habitat quality by increasing underwater noise levels. This is of particular relevance to dolphins' abilities to carry out daily life processes due to their elaborate and extreme auditory and sound production specialisations and dependencies. Coastal dolphin species are especially vulnerable to noise pollution, due to their high degree of habitat overlap with anthropogenic activities. To examine how prominent anthropogenic noise sources may impact these animals, there is a need to characterise their soundscapes and assess their responses as these soundscapes change in the presence of man-made noise.

Dolphin research has historically been, and continues to be, challenged by logistical and economic constraints. These constraints result in inconsistent analytical approaches, biases and knowledge gaps. Key limitations include the following:

- **Consistent analytical approaches:** Underwater acoustics is a broad subject with dozens of potential measurements that can be made for any particular sound source. Each measurement results in unique information regarding the sounds measured. Most studies report certain measurements, and often these are not consistent with other studies making comparisons difficult. In addition, different metrics may describe the characteristics of certain sounds better than others. When considering numerous sound sources and their contribution to the overall soundscape, selection of appropriate measures is more complex. Many soundscape studies are descriptive and do not attempt to examine variation or potential patterns statistically. Underwater soundscape characterisation would benefit from appropriate and consistent metrics used, as well as inclusion of statistical modelling to ascertain patterns in space and time.

- **Bias from observer presence:** Impact assessment studies are often confounded by the fact that the majority of marine mammal studies are boat-based. This introduces a potential source of bias from the presence of the research vessel and the noise it creates. Such bias is unavoidable in many situations. In coastal settings, land-based observations are more readily implementable and may help reduce (or totally exclude) any influence from observer presence.

- **Behavioural responses measured:** Animal behavioural responses can take many forms. However, the majority of marine mammal behavioural response studies in the wild concentrate on visible changes to physical behaviour, such as changes in occurrence or cessation of certain activities. Far fewer consider a combination of behavioural changes, including acoustical behaviours. Obtaining a broader picture of behavioural changes through measurement of a range of behaviours reduces the risk of not detecting alterations in behaviour. For example, animals may maintain 'typical' physical behaviours in the area but alter their acoustic behaviour in response to noise exposure. Thus, it is important to consider a range of potential responses when attempting to identify evidence of disturbance.

- **Lack of 'Pristine' Habitats:** It is not only critical to work on reducing human impact in anthropogenically 'noisy' marine areas, but also to preserve the pristine nature of remaining 'quiet' areas. These quiet areas also serve for baseline and comparative purposes. Previous studies have not been able to quantify exactly how severely anthropogenic activities have altered marine soundscapes due to a lack of baseline data or pristine habitats to serve as controls. Also, knowledge of anthropogenically-noisy habitats allows predictions to be made for future scenarios of development of pristine areas to improve management outcomes.

1.6 Aims and Objectives

The overall aim of this thesis is to fill some of the gaps in knowledge resulting from limitations in previous studies on behavioural and acoustic responses of coastal dolphins to environments rich in anthropogenic noise. To achieve this aim, a combination of visual and acoustic monitoring techniques were used to fulfil the following objectives:

1. Within the Swan River:
    (a) Quantify prominent underwater sound sources
    (b) Identify temporal and spatial patterns in the underwater soundscape
    (c) Investigate bottlenose dolphin occupancy in relation to vessel traffic in key habitats

   (d) Examine bottlenose dolphin behavioural and acoustical responses to vessel traffic and associated underwater noise, and

2. Compare urban Swan River and pristine Roebuck Bay underwater soundscapes in relation to coastal dolphin communication

To achieve the objectives above, an anthropogenically 'noisy' and an anthropogenically 'quiet' location along the western Australian coast were selected. The coast of Western Australia provides a range of soundscapes and environments in which to examine responses of coastal dolphins to noisy environments. Dolphins are present within a range of coastline habitats. These dolphins occupy a diversity of habitat types and consequently many communities have become specialised to their unique environments, and range from coastal transients to river residents. This study was conducted in an urban river system (the Swan-Canning River estuary) in the state capital of Perth and a relatively pristine bay (Roebuck Bay) in the "last wilderness" Kimberley region for comparative purposes.

The Swan-Canning River estuary is home to a resident community of around 18 adult Indo-Pacific bottlenose dolphins (Chabanne *et al.*, 2012; Lo, 2009). The Swan and Canning Rivers flow through the centre of metropolitan Perth, a city of over 1.4 million people. The rivers are 72 km and 110 km long respectively, and together form an extensive river system composed of narrow channels, large shallow basins, and riverine upper reaches. Despite this urban setting, the resident community of Indo-Pacific bottlenose dolphins (*T. aduncus*) use this river system on a daily basis, with hotspots of dolphin sightings in particular areas (Beidatsch, 2012; Chabanne *et al.*, 2012; Moiler, 2008). However, the rivers are also exposed to numerous anthropogenic activities: a commercial port; vessel channel dredging and maintenance; transport ferries; jetski and powerboat races; recreational boating and fishing; and shoreline construction.

Although the species itself is widely distributed, small community sizes and limited genetic exchange rates make bottlenose dolphin communities vulnerable to environmental changes and anthropogenic pressures (Ross, 2006; Wilson *et al.*, 1999). An example of this was seen in 2009, when six dolphin deaths occurred in the Swan-Canning River system dolphin community (Holyoake *et al.*, 2010). Subsequent investigations into the 2009 dolphin deaths suggested that an increase in viral, bacterial and/or fungal infections played a role in some of these cases. These likely resulted from a lowered immune system due to multiple pressures, such as contaminant exposure or human activities (Beazley, 2010; Holyoake *et al.*, 2010). Human-induced injuries also represent a significant health challenge for dolphins inhabiting the river system in the form of entanglement or vessel-strike (Holyoake *et al.*, 2010). Thus, the Swan River dolphin deaths of 2009 are reflective of the stressful environment that these animals inhabit. Whilst the number of deaths was relatively small, it represented a significant proportion of the Swan River population (at that time, 20 – 25 adults; Holyoake *et al.*, 2010). Furthermore, there are high seasonal sighting rates and long mean residency times for dolphins in the Swan River community, indicating year-round residency in this area (Chabanne *et al.*, 2012). High degrees of site fidelity to small, defined areas (such as for the Swan River dolphin community) also make some dolphin populations particularly vulnerable to anthropogenic pressures, as they are exposed to repeated and cumulative effects of such stressors (Finn, 2005). Such responses to intense noise have been observed in this community. Paiva *et al.* (2015) found that detections of dolphins decreased during impact and vibratory pile-driving activity within the Fremantle Inner Harbour near the mouth of the Swan River. While the area experiences heavy vessel traffic, prior to the start of this thesis no work had been undertaken to investigate its potential effects on the Swan River dolphin community or their acoustic habitat.

In contrast to this busy, noisy river system, Roebuck Bay in the far north of Western Australia in the Kimberley region provides relatively pristine habitat to coastal dolphins. The largest town in this region is Broome, with a permanent population of approximately 15,000 people. However, in the austral-winter tourism season, the population can swell to around 45,000 people. Broome sits on the shores of Roebuck Bay which is regularly visited by bottlenose dolphins (*T. aduncus*; D. Thiele, pers. comm.; Brown *et al.*, 2016). Roebuck Bay is also home to a resident population of snubfin dolphins (*Orcaella heinsohni*). This recently described species is endemic to northern Australia, and is thought to prefer shallow, coastal areas around river mouths and estuaries (Beasley *et al.*, 2005; Parra & Jedensjö, 2009; Parra *et al.*, 2006b). Although listed as 'near threatened' by the International Union for the Conservation of Nature (IUCN; http://www.iucnredlist.org/details/136315/0), there is currently insufficient data to assess how snubfin dolphins in Western Australia should be listed under the Wildlife Conservation Act (1950) (Bejder *et al.*, 2006). Coastal development in north-western Australia has been booming following the expansion of the petroleum and mining industries, leading to increasing human population, industrial port developments, dredging activities, habitat modification, and increased vessel traffic (Bejder *et al.*, 2006). Existing data from boat-based surveys and photo-identification indicate that Roebuck Bay is an important area for snubfin dolphins. With a population of approximately 130 – 161 individuals, Roebuck Bay represents the location with the largest reported abundance of snubfins in Australia (Brown *et al.*, 2014a; Thiele, 2010). Given the near-shore distribution of this species, it is likely to be particularly vulnerable to impacts from human activities (Cagnazzi *et al.*, 2013; Jefferson *et al.*, 2009). However, baseline data regarding snubfin distribution, behavioural ecology, population dynamics and acoustic habitat in Western Australia are lacking.

More generally, the Western Australian coastline is currently undergoing intense development in the form of port maintenance and construction, marine construction, pipeline creation, and tourism expansion. These activities are recognised to have detrimental effects on the marine environment and local fauna, through habitat degradation, chemical contamination, littering, and loss of food sources (Clark, 2001). Of particular relevance to coastal dolphin is the steady rise in underwater noise resulting from development and associated activities, such as pile-driving, dredging and vessel traffic. Despite the fact that similar anthropogenic activities are occurring in both the Swan River and Roebuck Bay, and these sites do not present significant logistical constraints for research, little is known about the soundscapes of these areas. The research conducted in this thesis is a stepping stone to understanding dolphin acoustic habitats and behavioural responses more broadly in Western Australia.

1.7 Overview of Research Approach

To "set the scene" of fieldwork methodology, a brief description of the main acoustic and visual monitoring techniques is provided here. Research methods and accompanying analyses relevant to each chapter are described in detail within the chapters themselves.

Soundscape and dolphin whistle characterisation was achieved by deploying autonomous underwater acoustic loggers. Within the Swan River, loggers were deployed at five sites from 2005 to 2015. In Roebuck Bay, loggers were deployed at one site during 2014 and 2015. In Roebuck Bay, additional vessel-based acoustic recordings were made opportunistically in the presence of dolphins during a separate study in July 2014. Dolphin behavioural responses to vessels were recorded using land-based theodolite tracking of dolphins and vessels at two sites in the Swan River – the Fremantle Inner Harbour and Perth Waters. These sites were known to have regular dolphin sightings (Swan River Trust, 2012) and had vantage points with the minimum recommended heights for theodolite stations (35 m for dolphins; E. Kniest). Both sites were anticipated to receive high levels of vessel traffic, with the addition of dredging works at the Perth Waters site. Theodolite tracking was conducted in the Fremantle Inner Harbour from 2012 – 2015 and in Perth Waters from 2014 – 2015. Five mutually-exclusive dolphin activity states were recorded during observations: foraging, milling, resting, socialising, and travelling. Vessels tracked were categorised according to type (small recreational vessel, sailboat, cargo ship, etc.), and their behaviour noted (either as stationary, milling, or travelling in the north, east, south, or west direction). A trial theodolite station was set up in Roebuck Bay but was deemed unsuitable. This was partly due to the low heights of surrounding cliff tops, but was also due to large tidal variations. Roebuck Bay experiences changes of tidal height > 7 m, which had the potential to keep animals at too great a distance from the theodolite station during low tidal periods.

1.8 Significance of Research

Although multiple studies have investigated either the effects of vessel traffic with its associated noise or elevated underwater noise levels on bottlenose dolphins (*Tursiops* sp.), few have considered both types of impact on the same dolphin community. Fewer still have explored multiple behavioural and acoustical responses to these impacts, or included contextual variables to provide key information on other influencing factors. Additionally, many behavioural response studies of marine mammals rely on boat-based data-collection techniques, potentially biasing the results. This study relies on autonomous underwater acoustic recordings and land-based visual observations for data collection. By using a combination of visual and acoustic monitoring techniques, this research provides a unique approach to assessing bottlenose dolphin behavioural responses to vessel traffic and elevated underwater noise without risking observer disturbance. Information on dolphin group size, composition, and environmental variables provided detailed context from which to investigate potential impacts from anthropogenic activities and noise.

As well as providing the first study of vessel disturbance on the Swan River dolphin community, this research also describes human-use at key locations within the river system. Currently, no records are kept regarding levels of vessel traffic in different parts of the river, and only one previous study (constrained to the Fremantle Inner Harbour; Salgado Kent *et al.*, 2012) has investigated aspects of the river soundscape. Similarly, little is known about human-use of Roebuck Bay or the underwater soundscape of this site. Without knowledge of how humans use these areas, it is difficult to suggest appropriate management of anthropogenic activities. This research provides information that supports the design of effective management strategies, and allows for more accurate impact assessment of new developments or areas of increasing boat traffic.

Finally, this project involved dozens of volunteers in fieldwork and data collection. Over 60 undergraduate and work experience students contributed their time to fieldwork, providing many with their first opportunity to participate in hands-on applied research. Volunteer involvement allowed for education, increased awareness and promotion of wildlife research to the next generation of researchers, many of whom have subsequently continued into research degrees or careers. This is of significant benefit to marine research, government, industry and conservation programs through the training and encouragement of future scientists.

1.9 Thesis Structure and Overview of Chapters

This thesis contains five data chapters, each addressing one of the objectives detailed above. As the data chapters are in the format of scientific papers, each comes complete with its own Introduction, Methods, Results and Discussion. Every effort has been made to provide a comprehensive yet non-repetitive literature review; however it is inevitable that some overlap occurs given the preparation of chapters as 'papers'. The content of the data chapters is detailed below:

Chapter 2: Underwater Sound in an Urban Estuarine River: Sound Sources, Soundscape Contribution, and Temporal Variability

As underwater noise levels increasingly become considered as an indicator of habitat quality, there is a need to characterise aquatic soundscapes. The purpose of this chapter was to provide a baseline description of underwater sound sources at one site within the Swan River. The methods used here set the protocol for acoustic analyses in the rest of the thesis, in terms of sound source identification, soundscape contribution, and assessment of acoustic variability at a range of temporal scales. Indeed, this chapter illustrates how different analytical techniques can be used complimentarily to assess the acoustic environment, from broad overviews to fine-scale descriptions.

Chapter 3: Occupancy of bottlenose dolphins (*Tursiops aduncus*) in relation to vessel traffic, dredging and environmental variables within a highly-urbanised estuary

This chapter investigates the occupancy of dolphins with regard to vessel traffic, dredging activities, and environmental conditions at two sites within the Swan River. The inclusion of environmental variables allowed alternative reasons for occupancy patterns beyond anthropogenic activities to be considered.

Chapter 4: Spatial and temporal variation in the acoustic habitat of bottlenose dolphins (*Tursiops aduncus*) within a highly-urbanised estuary

This chapter aimed to expand on the initial sound source characterisation provided in Chapter 3 by examining spatial and temporal variability throughout the Swan River soundscape. Acoustic data were collected from five locations across eight years. These were first analysed following the acoustic protocol set out in Chapter 3, and the methods supplemented by including measurements of broadband noise levels. The relevance of sound sources and soundscape patterns were then related back to the requirements of dolphin acoustic habitat for communication.

Chapter 5: Effects of vessel traffic and underwater noise on the movement, behaviour and vocalisations of bottlenose dolphins (*Tursiops aduncus*) in a highly-urbanised estuary

Previous chapters characterised the Swan River soundscape, anthropogenic noise components within, and at two locations investigated dolphin occupancy in response to vessel traffic and noise. To investigate whether behavioural responses occurred at finer scales, this chapter measured surface behaviours and whistle characteristics, using a combination of non-invasive visual and acoustic monitoring with a theodolite and an autonomous underwater noise logger.

Chapter 6: A Tale of Two Soundscapes: Comparing the acoustic characteristics of urban versus pristine habitats for coastal dolphins in Western Australia

The final data chapter takes knowledge gained from the studies conducted in the noisy, urban Swan River system and relates it to a relatively quiet, pristine dolphin habitat. First, the soundscape of Roebuck Bay itself is characterised as per the acoustic analytical protocol utilised in Chapters 3 and 5, regarding sound source identification, soundscape variability, and temporal patterns in broadband noise levels. Whistles recorded from snubfin and bottlenose dolphins at this site are also characterised. The Roebuck Bay soundscape is then compared with that of the Fremantle Inner Harbour, with particular consideration for frequencies utilised for coastal dolphin whistle communication. The potential consequences on coastal dolphins within Roebuck Bay if noise increased in the future are discussed, based on observed behavioural and acoustical responses described in Chapter 5.

The thesis concludes with a general Discussion intended to reflect on the significant findings from the project, and identify limitations and future research directions.

Chapter 2

Underwater sound in an urban estuarine river: Sound sources, soundscape contribution, and temporal variability

Human waterborne activities emit noise into the marine environment. This is of particular concern with regards to the potential impact on marine fauna such as cetaceans due to their acoustic specialisations. The Swan-Canning River system in Western Australia is home to a resident community of Indo-Pacific bottlenose dolphins (*Tursiops aduncus*), but is also a site regularly used for various human activities. As underwater noise levels increasingly become considered as an indicator of habitat quality, there is a need to characterise the soundscapes of such areas with regards to their cetacean fauna. This study aimed to provide a description of a site within the river system known as "The Narrows". Acoustic data were collected over a six-week period with an autonomous underwater acoustic recorder. These data were analysed using a combination of weekly spectrograms, power spectral density percentile plots, 1/3 octave band levels, and generalised estimating equations to identify prominent soundscape contributors and investigate temporal patterns in their occurrence. The soundscape was found to be strongly influenced by wind, snapping shrimp and vessel traffic, with the sounds of bridge traffic, waves, fish, machinery, dolphins and precipitation also contributing to the acoustic environment. Furthermore, three of these sound sources (boats, waves, and fish) were found to vary at a range of temporal scales. These results take a vital step in characterising the acoustic habitat of this river system, highlighting the need to consider temporal patterns when assessing the composition of underwater soundscapes.

2.1 Introduction

The marine acoustic environment is composed of sounds of abiotic, biotic and anthropogenic origin (Hildebrand, 2009). The term 'soundscape' describes the physical combination of such sounds, which prevails at a particular place and time (Harris & Radford, 2014; Pijanowski *et al.*, 2011). Previous studies on the occurrence of marine species have primarily considered geographical features (e.g. depth, slope, proximity to shore) and environmental variables (e.g. temperature, salinity, chlorophyll concentration) to explain animal distribution (Friedlaender *et al.*, 2006; Maxwell *et al.*, 2009; Panigada *et al.*, 2008; De Stephanis *et al.*, 2008; Wiley *et al.*, 2003). Yet, few consider the acoustic characteristics of marine habitats. In recent years there has been increasing concern regarding the impact of anthropogenic activities on marine soundscapes (Boyd *et al.*, 2011; Holles *et al.*, 2013; Tyack, 2008). However, much remains to be learned about the nature of soundscapes rich in anthropogenic noise and how marine organisms respond to them. This is of particular concern with regard to acoustically-specialised fauna, such as whales and dolphins, due to their reliance on sound for vital life-functions and their consequential susceptibility to the impacts of anthropogenic noise (Richardson *et al.*, 1995).

The most ubiquitous source of anthropogenic ocean noise is vessel traffic, an increasingly 'chronic' source in some parts of the world (Andrew *et al.*, 2011; Frisk, 2012). The potential for such noise to mask important acoustic signals is a growing cause for concern with regard to effective conservation of cetacean populations and management of environmental quality (Clark *et al.*, 2009; Erbe *et al.*, 2012; Hatch *et al.*, 2012; Parks *et al.*, 2009; Tyack, 2008; Williams *et al.*, 2014b). Additionally, non-acoustic consequences of anthropogenic activity can indirectly alter the soundscape of an area by changing the composition of the ecosystem (Harris & Radford, 2014; Laiolo, 2010). Thus, there is a need for more research describing the acoustic quality of marine environments, particularly with regard to defining cetacean critical habitats.

The Swan-Canning River system is an estuarine river system flowing through Perth, the Western Australian state capital, a major metropolitan area of more than 1.4 million people. This system consists of an area where the Swan and Canning Rivers meet, and is a frequently-used commodity by humans for transportation, industrial, commercial and recreational purposes. As a result, high levels of underwater noise have been reported within the Fremantle Inner Harbour, located at the mouth of the river system (Salgado Kent *et al.*, 2012). Sources of man-made noise included: vessel traffic; train and vehicle traffic passing over a nearby bridge; machinery noise; and wharf construction. On average, noise levels within the Fremantle Inner Harbour were at their highest between 10:00 and 15:00 hrs, which was most likely due to anthropogenic activity (Salgado Kent *et al.*, 2012).

Despite this, biotic sounds were also recorded within the Fremantle Inner Harbour, including snapping shrimp, fish grunts and choruses, and the whistles of Indo-Pacific bottlenose dolphins

(*Tursiops aduncus*; Salgado Kent *et al.*, 2012; Ward, 2013). Dolphins are known to occur throughout the Swan and Canning Rivers, where a community of approximately 18 individuals (excluding calves) show daily use of the river system and high site-fidelity, indicating year-round residency (Chabanne *et al.*, 2012). However, despite the use of this area by such an acoustically-specialised species, no further sections of the Swan or Canning Rivers have been assessed in terms of their acoustic components.

This work aims to provide a baseline description of underwater sound sources at a site of acoustic interest within the Swan River. The focus of this paper is an area of the river known as "The Narrows", which is the only gateway to the upper reaches of the Swan River and is thus presumed to be a commonly-used location by both humans and dolphins travelling through the area. Thus, this study has the specific objectives of identifying: (1) prominent sound sources within the soundscape; (2) their contribution to the soundscape in different frequency bands; and, (3) significant temporal patterns in the occurrence of soundscape contributors at a time of busy and expected increasing anthropogenic recreational use of the river (commencing three weeks prior to the Austral summer school holidays and ending after New Year).

2.2 Methods

2.2.1 Study Site

Acoustic data were collected using an autonomous underwater acoustic recorder, which was set on the riverbed near the Narrows Bridge, close to Perth City in the Swan River (Figure 2.1). This area is primarily shallow (< 1 – 6 m), with a mud or weedy substrate, and forms part of the Perth Waters region of the Swan River. It is characterised by two ferry lanes, allowing the transit of transport and tourist ferries between the main jetty on the Perth CBD foreshore (Barrack Street Jetty) and other locations in the river. The logger location was south of one of the main ferry lanes, and adjacent to a traffic bridge supporting one of the major routes through the city centre. At the time of this study, construction work was underway on the north Perth foreshore as part of the Elizabeth Quay development. This involved construction activities on the north riverbank, and the placement of a large silt-net for future dredging works.

2.2.2 Acoustic Data Collection

The underwater recorder was built by Curtin University's Centre for Marine Science and Technology (CMST) and equipped with an external hydrophone (HTI 90U, sensitivity -197.9 dB re 1 µPa/V), entering the housing via a bulkhead connector to an impedance-matching pre-amplifier with a total gain of 40 dB. Digitised recordings were written on a flash card and regularly transferred to a hard disk whenever the flash card was full. The recorder was calibrated by applying white noise of known power spectral density. An 8 Hz high-pass filter was employed

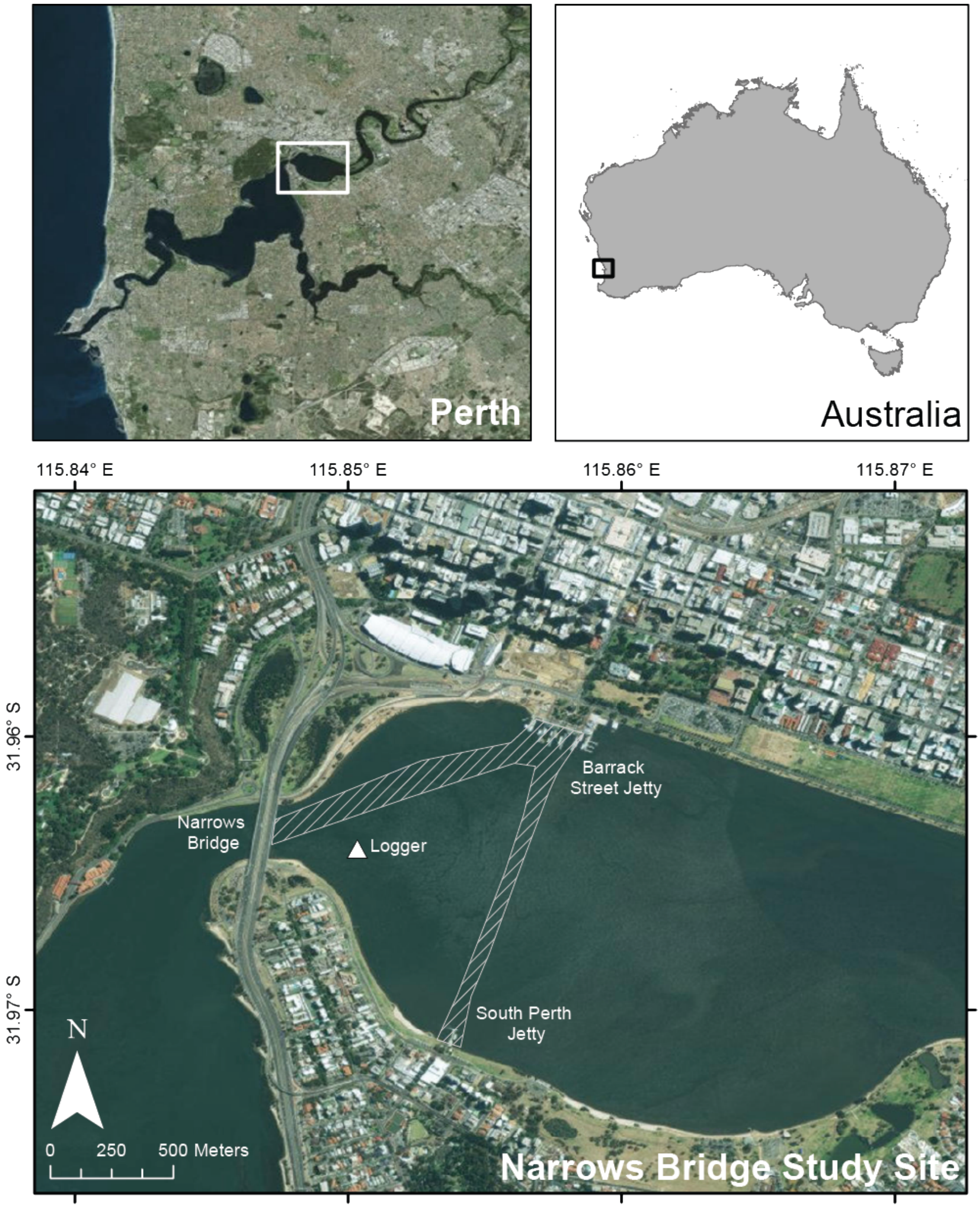

Figure 2.1: The logger (Δ) was deployed near the Narrows Bridge, located in the Swan River, Perth. Neighbouring ferry channels are cross-hatched and the Perth CBD can be clearly seen to the north. This site is the only access point to the upper reaches of the Swan River.
Map Source: ESRI (2015)

to filter out high levels of low-frequency noise, enhancing the dynamic range of the recorder at the frequencies of interest. It recorded at a duty cycle of 10 min every 15 min at a sampling frequency of 22 kHz. This sampling frequency allowed data collection of low-frequency anthropogenic noise, whilst still providing overlap with dolphin whistles and snapping shrimp clicks.

The recorder was deployed from the 27th November 2013 to the 4th January 2014. This six-week period was selected as it occurred immediately prior to the commencement of dredging works for the Elizabeth Quay development. Additionally, this period represented the build-up to Austral summer holidays, a time when greater availability of recreational time was assumed to gradually increase vessel traffic using the river. Thus, this data set was intended to provide a baseline for the Perth Waters area prior to dredging, across several weeks with varying intensities of human activity.

2.2.3 Data Analysis

Recordings were analysed in Matlab (Version R2013a, The MathWorks Inc.). As a first step, the data were Fourier transformed in 1 s windows producing a time series of power spectral density (PSD). Cable noise from hydrophone movement was identified as brief broadband spikes, and the corresponding 1 s windows were discarded from further analysis.

2.2.3.1 Weekly Spectrograms

Next, the PSD of underwater sound was averaged into 10 s windows. The first 10 s PSD average of every minute of recording was plotted in a weekly spectrogram (Mon – Sun). Spectrograms of all six weeks were inspected and compared to identify prominent sound sources. To identify sound sources related to human activity, two of the authors (S.M. and C.E.) conducted opportunistic visual observations, noting the presence of ferry traffic and train crossings.

2.2.3.2 PSD Percentile Plot

The statistical variability of underwater sound across the study period was computed and illustrated as a PSD percentile plot. In such plots, the nth percentile gives the level that was exceeded n% of the time, with the 50th percentile representing the median. All of the PSDs (one 10 s PSD average for each minute of recording) of the full six-week recording period were used to compute the PSD percentiles. To reduce computational effort, we further averaged the PSD into a series of adjacent frequency bands, each 10 Hz wide.

2.2.3.3 1/3 Octave Band Levels and Wind Correlation

The acoustic data were further assessed to investigate the contribution of wind to the local soundscape. Average wind speed (km/h) for the study site was provided at one-minute resolution by the Bureau of Meteorology (BOM) from their Perth CBD Weather Station. Wind speed was averaged into 10 min blocks to correspond with the duty cycle of the underwater recorder. Wind data for the last 5 min of every quarter hour (i.e. when the recorder was "off") was discarded. The 1 Hz PSDs of underwater sound were converted to linear units, averaged over every 10 min acoustic recording and integrated into adjacent 1/3 octave band levels (1/3 OBL). This resulted in time series of noise levels in each 1/3 octave band, with one sample every 15 min.

The existence of an association between average wind speed and 1/3 OBLs was tested using a Spearman's rank correlation coefficient. This non-parametric rank statistic is a measure of the strength of a monotonic association between variables, which does not impose assumptions about the frequency distribution of the data nor that the relationship between variables is linear (Hauke & Kossowski, 2011). Thus, it is appropriate to use when the distribution of the variables makes parametric tests misleading (such as Pearson's correlation coefficient), as was the case here. All correlations were conducted in R with the aid of the package *stats* (R Core Team, 2015).

2.2.3.4 Noise Levels Over Time

The 1/3 OBLs were further used to investigate variation in noise levels over time. Firstly, the whole study period of six weeks was considered in entirety, with 1/3 OBLs plotted as a function of time. Centre frequencies of interest were then extracted for closer examination. Additionally, the broadband noise level was computed by summing all the 1/3 OBLs on a linear scale (i.e. over the bandwidth 9 Hz to 9 kHz), with one sample every 15 min (i.e. a 15 min average band level). All plots were produced in R (R Core Team, 2015) with the aid of the package *ggplot2* (Wickham, 2009).

2.2.3.5 Sound Source Presence and Temporal Patterns

To assess the occurrence of various sound sources at the Narrows Bridge site, the data were manually inspected. The dataset was sub-sampled to select hourly recordings of 10 min duration (n = 901). These were inspected using Audacity (Version 2.0.6) to identify the presence of sound sources: abiotic (rain, waves); biotic (snapping shrimp, fish, dolphins); and anthropogenic (boats, machinery). The occurrence of these sound sources was recorded in a binary fashion (0 = absent; 1 = present) for each sound file.

In order to adequately model temporal patterns in sound source presence, a summary of each sound source was produced to identify and remove those sources with fewer than 20 occurrences. As a result, two sound sources were excluded from further analysis of temporal patterns: rain and dolphins. Furthermore, one sound source (snapping shrimp) was present in all manually-inspected files and, consequently, was also removed from further analysis. Thus, the final sound sources to be included in temporal pattern analysis were: waves, fish, boats and machinery.

Temporal variation in the probability of these four sound sources being present was examined for: hour of day ("Hour"); day type (whether it was a weekday or weekend; "DayType"); and week number ("Week"). All levels had greater than 20 samples each. These associations were assessed using Generalised Estimating Equations (GEEs). As multiple temporal scales were being considered and as it was possible that sound sources remained within the study area for several hours, it was necessary to use an analytical technique which can disentangle such temporal variation whilst accounting for temporal autocorrelation. GEEs are extensions of generalised linear models (GLMs) but relax the GLM assumption of independence between observations, thus allowing for temporal autocorrelation in the data to be modelled (Photopoulou *et al.*, 2011). They do this by using within-cluster correlations to increase the efficiency of estimation, thus allowing maximum use of sequential or repeated measures data (Bailey *et al.*, 2013). Furthermore, GEEs can be used with data having non-normal response variables, such as presence/absence data (Zuur *et al.*, 2009). As a result, GEEs were the preferred method for this scenario.

The response variable was binary and the presence of a sound source within an hour was likely to be affected by its presence in the previous hour. Therefore, a GEE with a binomial error distribution and a logit-link function was used. With regard to the model terms, Week and DayType were included as factors. The variable Hour (h) was converted to a cyclical covariate using sine and cosine vectors, termed H_s and H_c respectively (Bailey *et al.*, 2013; Zar, 1984):

$$H_s = \sin(\frac{2\pi \times h}{24})$$

$$H_c = \cos(\frac{2\pi \times h}{24})$$

Since time of day forms part of a cycle, this allowed hours at the start and end of the day to be considered close to each other (e.g. 23:00 hrs and 01:00 hrs). A similar approach has been used by other studies when dealing with circular variables such as Julian date, tidal state, lunar phase, and season (Bailey *et al.*, 2013, 2009, 2010; De Boer *et al.*, 2014; Griffin & Griffin, 2003; Pirotta *et al.*, 2013).

GEE models were fit to data for each sound source type separately. Variance Inflation Factors (VIFs) were calculated for each model, but revealed no collinear variables. A Runs Test indicated that there was an issue with correlation in the residuals for all models ($p < 0.0001$), therefore a blocking structure was selected to model this correlation. To select the clusters used in the model blocks (ID), the autocorrelation of the model residuals by ID was plotted to check for a decline in correlation over time. During each separate "Date" (a sequential value beginning on Day 1 of sampling and ending on the final day of sampling), the correlation of observations made hourly declined to approximately zero within a day (24 h). Thus, separate days were treated as independent, and so "Date" was used to define clusters of data points within which residuals were allowed to be autocorrelated.

The GEEs were initially fit with multiple correlation structures (AR-1, independent, unstructured, and exchangeable) and a quasi-likelihood information criterion (QIC; Pan, 2001) was used to manually investigate the most suitable correlation structure for each particular sound source. The QIC scores were very similar for competing models with different correlation structures. Therefore, given that the data are serially correlated and that GEEs are robust in providing consistent estimates of mean parameters even when the correlation structure is mis-specified, an AR-1 was selected as the most logical correlation structure for all models.

Model fit was further explored by plotting observed versus fitted values, and plotting fitted values versus scaled Pearson's residuals. Once the final model was selected, repeated Wald's tests were used to assess the significance of each temporal variable and partial residual plots of significant terms were created. No variable was excluded on the basis of its significance as this study only aimed to identify whether temporal variation existed, not to model the cause of any such variation.

All GEEs were produced in R (R Core Team, 2015) with the aid of *geepack* (Højsgaard *et al.*, 2006; Yan, 2002; Yan & Fine, 2004), *MESS* (Ekstrom, 2014) and the *MRSea* (Scott-Hayward *et al.*, 2014) packages.

2.3 Results

The logger recorded approximately 608 h of acoustic data over a 39-day period between November 2013 and January 2014. Sound sources recorded included: wind, precipitation, waves (from boat wake/surface buoy movement), snapping shrimp, fish, dolphins, vessel traffic, machinery, and trains/vehicles crossing the Narrows Bridge.

2.3.1 Weekly Spectrograms

Note that two weeks were not recorded in full: Week 1 started mid-week, and in Week 6 the recordings ceased on Saturday. An example of the weekly spectrograms for the study period can be seen in Figure 2.2, with the prominent sound sources highlighted. From these weekly

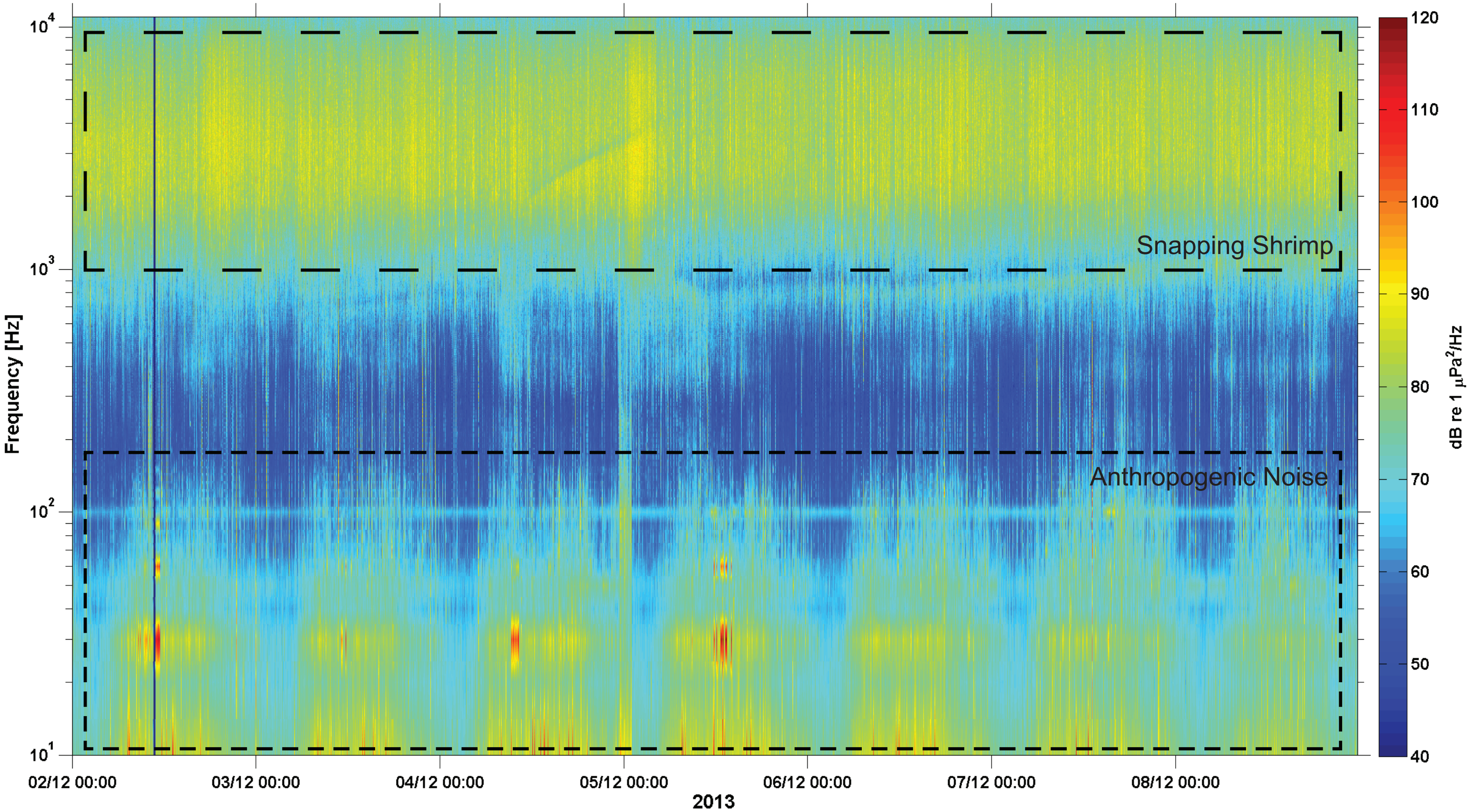

Figure 2.2: Spectrogram of underwater noise recorded at the Narrows Bridge site over a week (Mon – Sun) during passive acoustic monitoring in December 2013, showing examples of prominent sound sources. The term "Anthropogenic Noise" includes overlapping bridge noise (trains and vehicles) and vessel transits. An unidentified 100 Hz tone was present for the entire duration at this site.

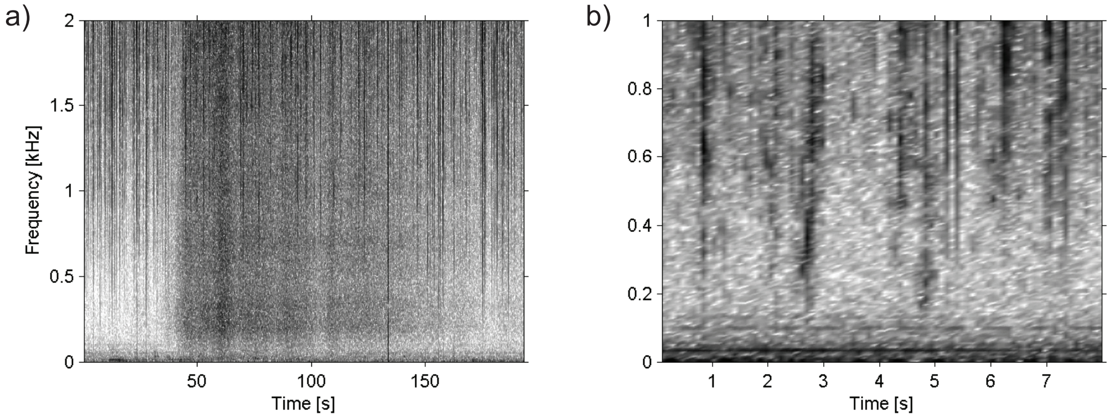

Figure 2.3: Abiotic sound sources at the Narrows Bridge site included: (a) rain and (b) wave noise. Rain was confirmed as such by weather data provided by the Bureau of Meteorology. Note that "waves" were most likely the result of boat wake or objects moving at the water surface (e.g. mooring buoys) rather than wind-driven waves.

spectrograms, it was possible to identify three broad categories of sound sources: abiotic, biotic and anthropogenic noise.

2.3.1.1 Abiotic Noise

No strong patterns of abiotic noise were observed in the weekly spectrograms. However, this is not to say that such noise was absent. Manual data review identified a period of precipitation noise (Figure 2.3a), which was confirmed via rainfall data available in the Bureau of Meteorology records.

Although wind is capable of generating prominent levels of broadband noise (Wenz, 1962), no periods of this stood out in the weekly spectrograms. During finer-scale data review, wave noise was heard (Figure 2.3b); but its occurrence did not match periods of increased wind speed. Due to this and the nature of the sound source, it was thus inferred that the category 'waves' included sounds from surface objects moving at the water surface (e.g. boat wake, movement of mooring buoys or crabpot floats). However, wind is still likely a contributor to the underwater soundscape at the Narrows Bridge, as discussed below.

2.3.1.2 Biotic Noise

Snapping shrimp were the most prevalent sound source at the Narrows Bridge site, present continuously throughout the six-week study period, covering the 1 – 10 kHz frequency range (Figure 2.4). There did not appear to be any fluctuating patterns of occurrence in snapping shrimp sounds at this site; however, a general increase in intensity was observed over the study period, likely due to increasing settlement of these animals on the equipment and mooring.

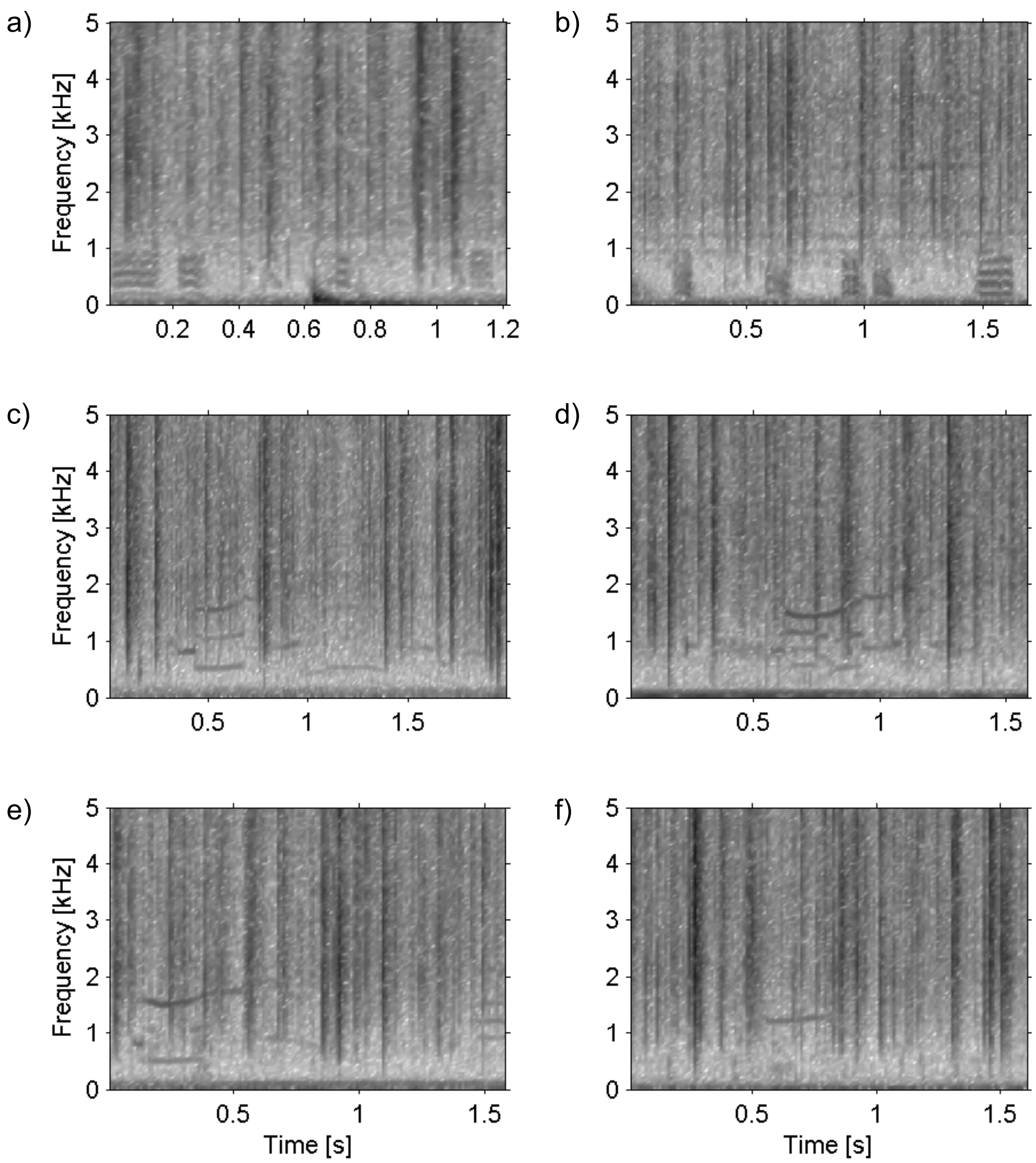

Figure 2.4: Biotic noise sources at the Narrows Bridge site included: (a – b) fish calls and (c – f) potential bottlenose dolphin whistles. Note also the presence of snapping shrimp clicks in all spectrograms.

Although fish choruses have been recorded in other parts of the Swan River (Parsons *et al.*, 2013b, 2006) none were observed during this study. A chorus is characterised by the presence of many simultaneously calling fish at some distance, such that individual calls cannot be identified in the cacophony of calls. In the absence of fish choruses at the Narrows Bridge site, individual fish calls were still recorded; however, due to their transient nature, were difficult to identify in weekly spectrograms alone. The fish calls typically ranged in frequency from 200 to 700 Hz (Figure 2.4a and Figure 2.4b). But, unfortunately, it was not possible to identify these to species-level.

A number of frequency-modulated tones were recorded at the Narrows Bridge site. These ranged from 0.5 – 2 kHz, often with harmonics (Figure 2.4c – Figure 2.4f). Although lower than the average frequency for bottlenose dolphin whistles, these tones were presumed to originate from dolphins as they were similar to whistles recorded elsewhere in the river system (Ward, 2013). In the Fremantle Port, bottlenose dolphins were recorded to produce whistles ranging from 1 – 19 kHz (Ward, 2013). Given the low signal-to-noise ratio, it is likely that dolphins were not close enough to the acoustic recorder for a good sample of whistles to be obtained. Again, as a result of their transient nature, it was not possible to identify whistles from the weekly spectrograms alone.

2.3.1.3 Anthropogenic Noise

Anthropogenic sources of noise at the Narrows Bridge site included: vessel traffic; general revelry; machinery; bridge traffic; singing propellers of transiting ferries; and some unidentified sounds (Figure 2.2 and Figure 2.5). Due to the transient nature of passing vessel traffic, individual vessel transits were relatively difficult to identify in the weekly spectrograms, as each vessel transit lasted a matter of seconds (Figure 2.5a). Upon finer-scale investigation, there were periods of substantial vessel traffic. In some instances, these were accompanied by a number of miscellaneous sounds, such as noise from mobile phones, general revelry (people talking, singing and listening to pop music; Figure 2.5b). Machinery noise was relatively infrequent and sporadic, and thus was also poorly visualised in the weekly spectrograms. When it was present, machinery noise generally occurred between 50 – 200 Hz (Figure 2.5c).

The weekly spectrograms showed clear periods of anthropogenic noise following distinct patterns. Low-frequency anthropogenic noise was present from 10 – 250 Hz, following a diel pattern of occurrence from approximately 8:00 – 17:00 hrs which was particularly pronounced on weekends (Figure 2.2). Several signals were observed to contribute to this band. Firstly, a 20 – 30 s duration sound occurred from 50 – 250 Hz, with tones every 10 Hz (Figure 2.5d). These sounds were observed to occur immediately prior to north-bound trains and immediately subsequent to south-bound trains crossing the Narrows Bridge. Secondly, a frequency-modulated tone undulating around 35 Hz with a weak harmonic around 70 Hz was recorded (Figure 2.5e). This tone was observed to occur in the presence of ferries transiting the study area, and was attributed to a singing propeller. Two transport ferries regularly cross between Barrack Street Jetty and South Perth throughout the day, in addition to several tourism companies which run river cruises passing through the Narrows to reach other parts of the river. Finally, a very low-frequency sound occurred as a series of four pulses separated by 20 – 30 s intervals, centred around 10 Hz (Figure 2.5f). The exact origin of this noise could not be identified, but was potentially the result of vehicle traffic crossing the dividing sections of the Narrows Bridge.

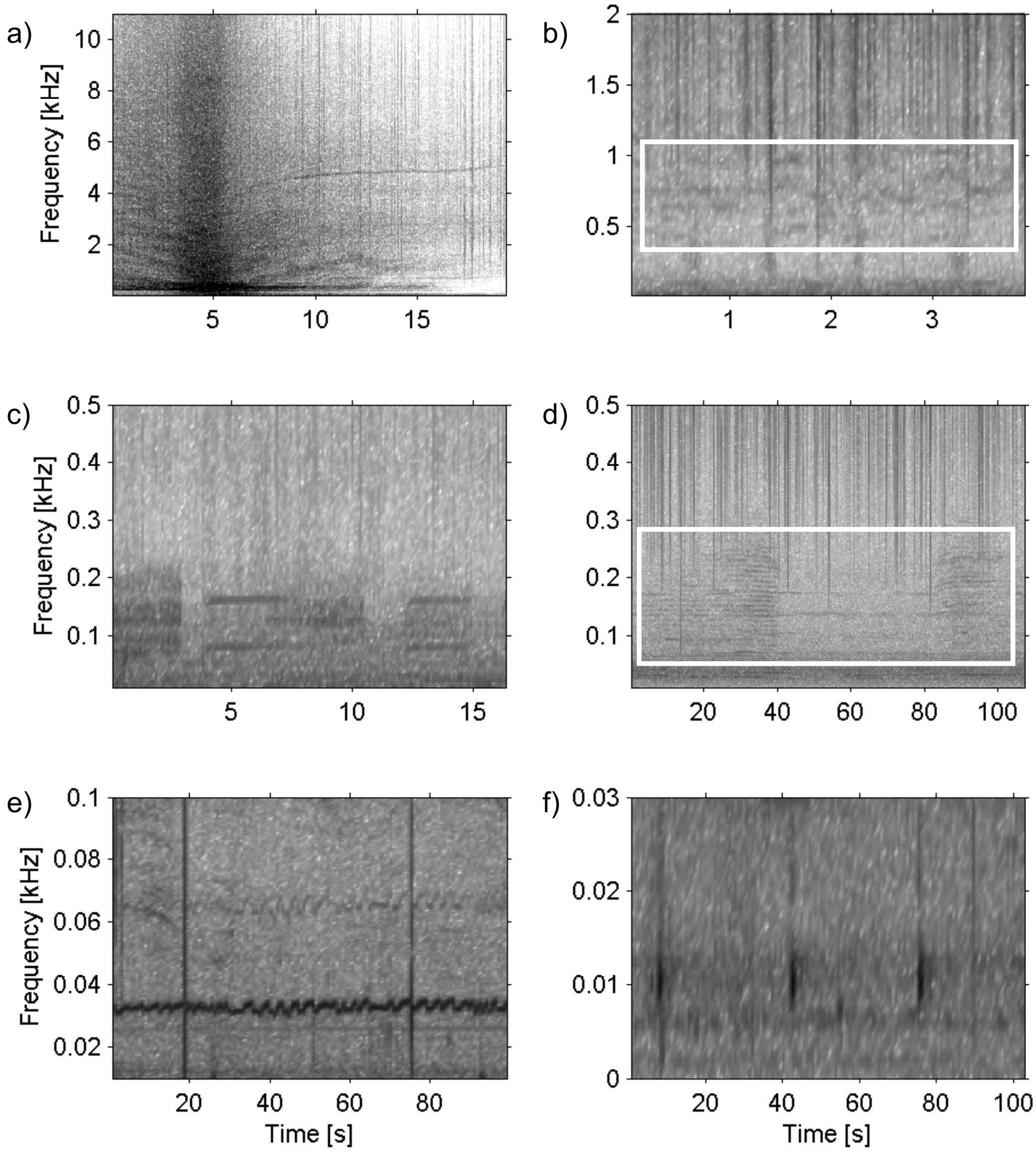

Figure 2.5: Anthropogenic noise sources at the Narrows Bridge site included: (a) vessel transits; (b) human socialising noise such as pop music (in white box); (c) machinery noise; (d) trains crossing the Narrows Bridge (in white box); (e) singing propellers of ferries using the adjacent shipping lanes; and (f) unknown low-frequency impulses presumed to be from bridge traffic.

2.3.2 PSD Percentile Plot

The PSD percentile plot (Figure 2.6) shows acoustic power versus frequency as a statistical function of time. The lower frequency range (10 – 100 Hz) of the Narrows Bridge site soundscape was influenced by anthropogenic sounds (vessel traffic, machinery noise and bridge traffic) and likely wind noise in shallow water. The peaks at 40 and 70 Hz seen in the 1^{st} – 75^{th} percentiles correspond to the singing ferry propeller emitting a 35 Hz tone with 70 Hz harmonic. Note that the PSD percentiles in Figure 2.6 are averaged into 10 Hz bands, which is why there is no peak at

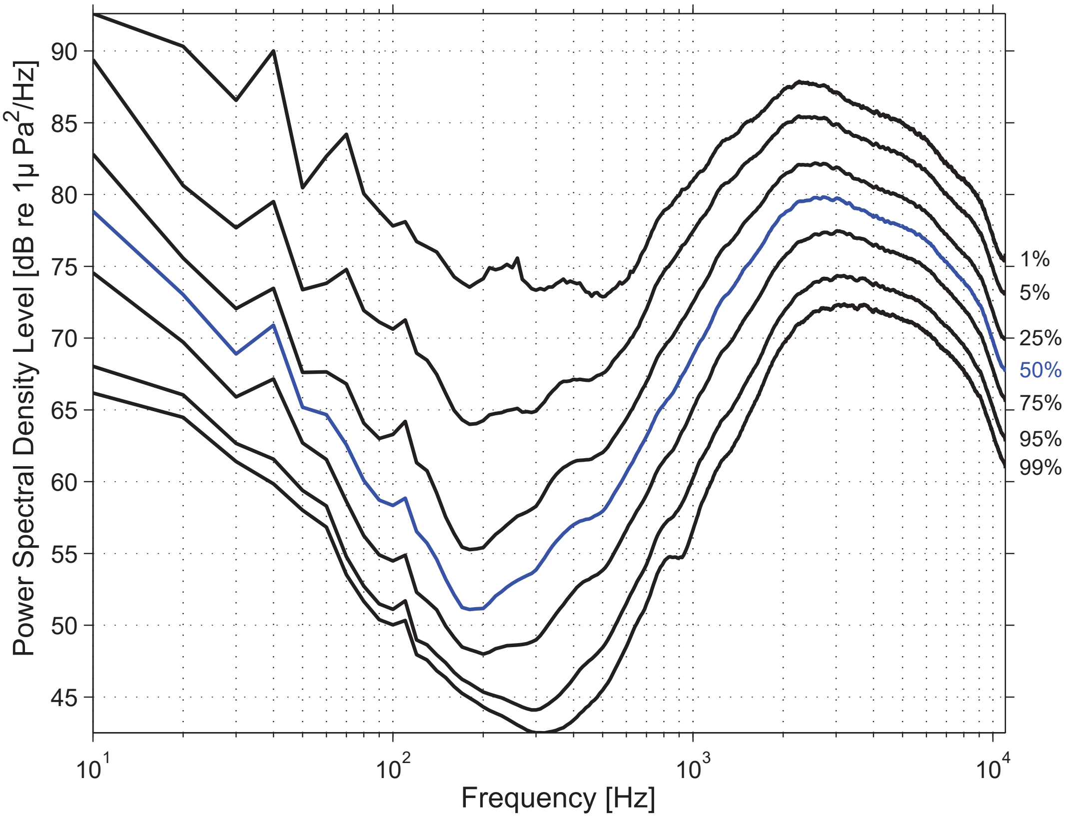

Figure 2.6: Power spectrum density (PSD) percentiles (averaged into 10 Hz bands) over the six-week study period at the Narrows Bridge site. The nth percentile gives the level that was exceeded n% of the time. The 50th percentile is the median.

35 Hz. Small boats passing at close range contributed to a broader range of frequencies, up to 10 kHz (Figure 2.5a) but their high-frequency energy did not dominate the soundscape. Above 1 kHz, the spectra follow the typical shape and levels of snapping shrimp clicks. As no fish choruses were observed at the Narrows Bridge site, it appears that the contributions of individual fish calls (200 – 600 Hz) were not substantial enough to feature distinctly in the PSD percentile plot.

2.3.3 1/3 Octave Band Levels and Wind Correlation

Spearman's rank correlation tests revealed a statistically significant, moderate-strength relationship (with most correlation coefficients of 0.4 – 0.5) between average wind speed and 1/3 OBLs from 10 Hz to 630 Hz (Figure 2.7). However, for 1/3 OBLs between 800 Hz and 8000 Hz, the correlation coefficients indicated a very weak relationship (sometimes negative) which in some cases was not statistically significant ($p > 0.05$; 1/3 OBLs at 1000 Hz, 2500 Hz, and 3150 Hz).

Although strong correlations with wind speed have previously been reported for frequencies up to 10 or 20 kHz (Wenz, 1962), in this case there is no obvious correlation above 1 kHz. This is the result of snapping shrimp dominating the higher frequencies from 1 kHz upwards (Figure 2.6),

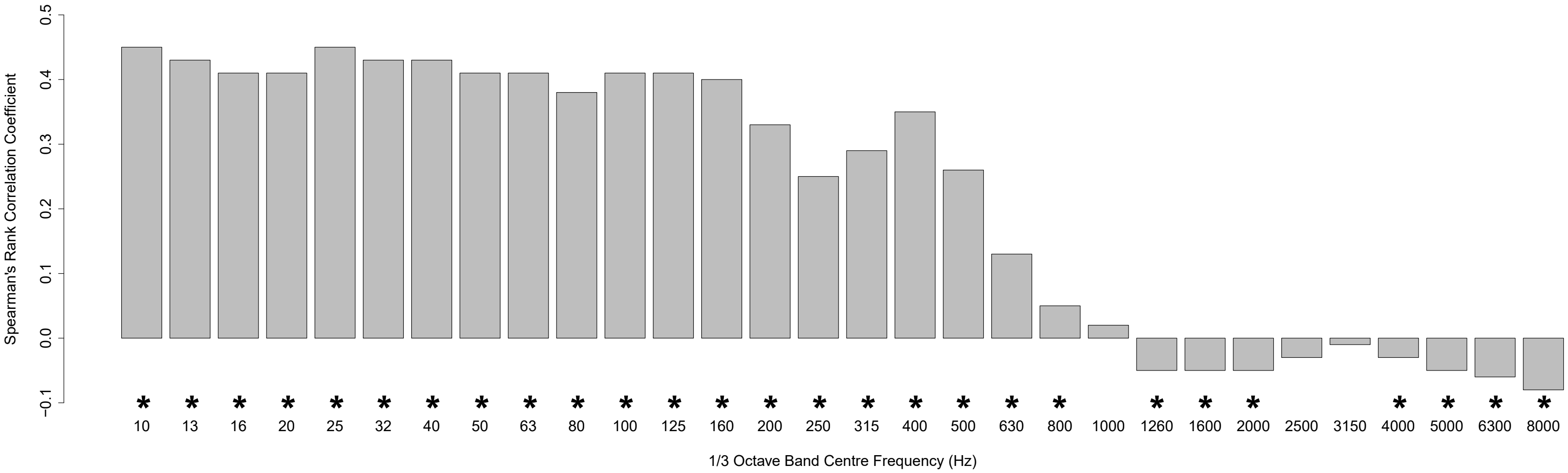

Figure 2.7: Spearman's rank correlation coefficients for each 1/3 octave band when correlated with average wind speed. Statistically significant relationships ($p < 0.05$) are indicated with "*".

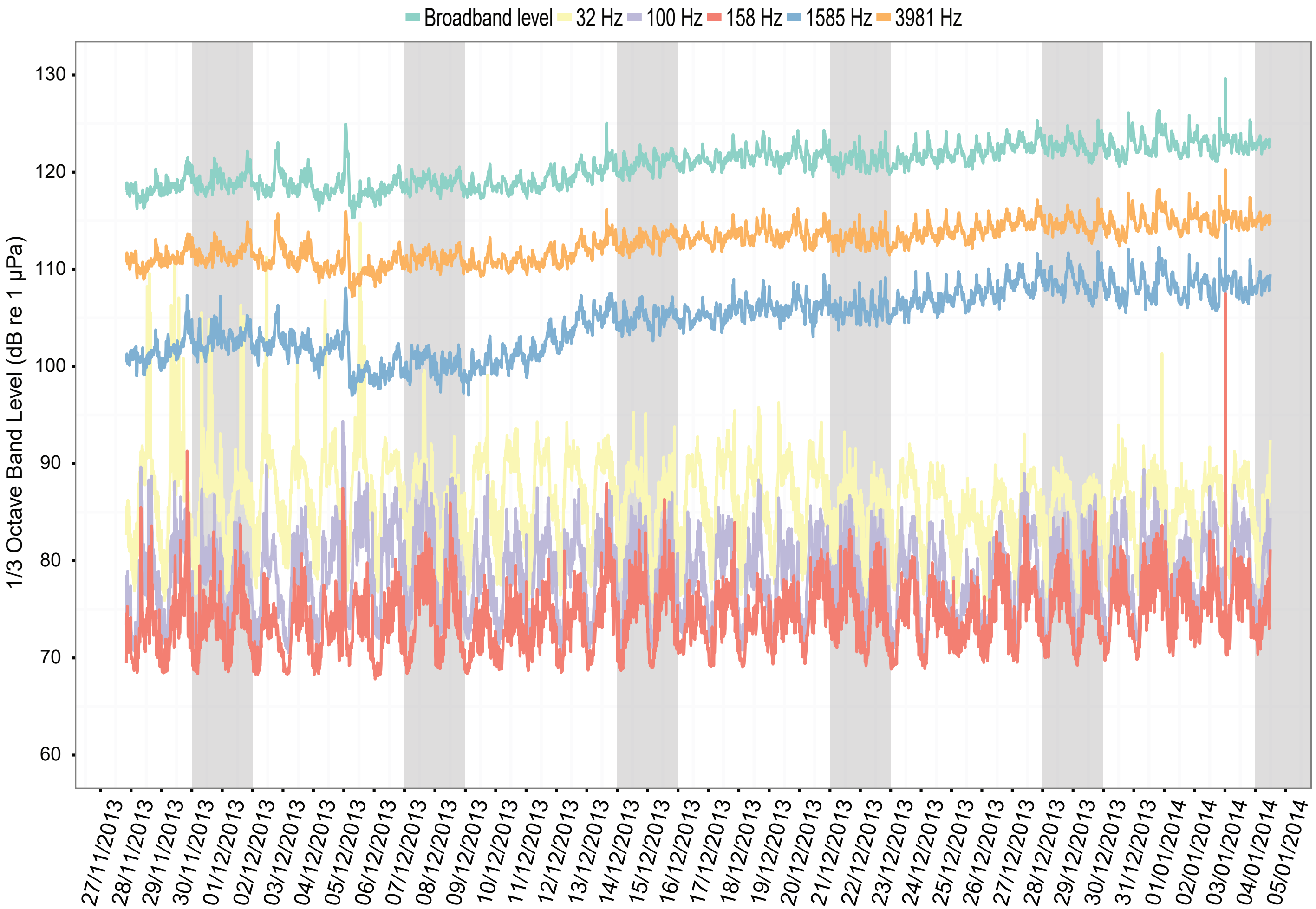

Figure 2.8: Variation in broadband (9 Hz – 9 kHz) and selected 1/3 octave band noise levels across the six-week study period. Weekends are indicated by greyed-out blocks. Notice the diel pattern in all frequency bands, with higher levels recorded during daytime, and a steady increase in high-frequency noise (> 1 kHz) over the study period due to the increasing settlement of crustaceans on the mooring.

thus confounding the pattern of correlation between wind and 1/3 OBLs at those frequencies. Similarly, it is likely that the correlation is further confounded by boat transits, which consequently would be limiting the maximum correlation coefficient achievable.

2.3.4 Noise Levels Over Time

To investigate noise levels over the entire study period, five 1/3 OBLs were selected (32 Hz, 100 Hz, 160 Hz, 1600 Hz, and 4000 Hz) in addition to the broadband levels (Figure 2.8). The 1/3 OBL centred on 32 Hz showed high variation in the first two weeks, which declined across the study period. This range included the singing ferry propeller mentioned above, suggesting a change in the presence of this vessel. The 100 Hz centre frequency included the unknown tone which was consistently present throughout the study period in the weekly spectrograms. Although Figure 8 shows level variation in this 1/3 OBL, this variation reflects diel changes in anthropogenic noise overlapping the unknown tone. The 1/3 OBL centred at 160 Hz was one of the quietest bands (see also Figure 2.6), which nonetheless also showed daily cycles. The 1/3 OBLs above 1 kHz gradually increased across the study period, reflecting the increasing presence of snapping shrimp, as also indicated in the weekly spectrograms.

2.3.5 Sound Source Presence and Temporal Patterns

In the 901 hourly acoustic files manually inspected, seven sound sources were recorded: rain, waves (from boat wake or movement of surface buoys), dolphins, fish, snapping shrimp, boats, and machinery. The proportion of files which contained each sound source can be seen in Figure 2.9. Snapping shrimp were the primary contributor to the soundscape of the Narrows Bridge site, being present in 100% of files. A high number of files also contained evidence of boat traffic (56%), wave noise (27%) and fish calls (25%), whilst machinery noise was present in a relatively low proportion of files (3%). The remaining sound sources occurred in less than 2.5% of inspected files and, due to their infrequent occurrence, were excluded from further analyses.

The results of the GEEs indicated that there were significant temporal variations in the presence of four prominent sound sources at a range of scales (Figure 2.10, Figure 2.11, and Table 2.1). Wave noise was found to vary by week number (X^2 = 33.6, df = 5, p < 0.0001) and hour of day (X^2 = 14.2, df = 1, p = 0.00017), with the final two weeks of the study period showing a significantly lower proportion of files with wave noise than other weeks. The presence of fish calls in the acoustic data was also found to vary significantly by week number (X^2 = 105.8, df = 5, p < 0.0001) and hour of day (X^2 = 24.1, df = 1, p < 0.0001). Fish calls appeared particularly prevalent in Week 3, and also showed two distinct peaks by hour of day around 05:00 – 08:00 hrs and 16:00 – 19:00 hrs. Significant patterns in the presence of boat noise were found by week (X^2 = 34.9, df = 5, p < 0.0001), day type (X^2 = 13.3, df = 1, p = 0.00027), and hour of day (X^2 = 94.8, df = 1, p < 0.0001). Boats were more prevalent as the study period continued, and were present in greater abundance during the weekend. Boat traffic peaked daily around 07:00 hrs, 10:00 hrs – 14:00 hrs, and 16:00 – 19:00 hrs. Machinery noise did not show significant variation at any temporal scale. However, as machinery only appeared in 29 of the 901 recordings manually inspected (which was borderline for inclusion in modelling), this lack of significance could be due to this small sample size.

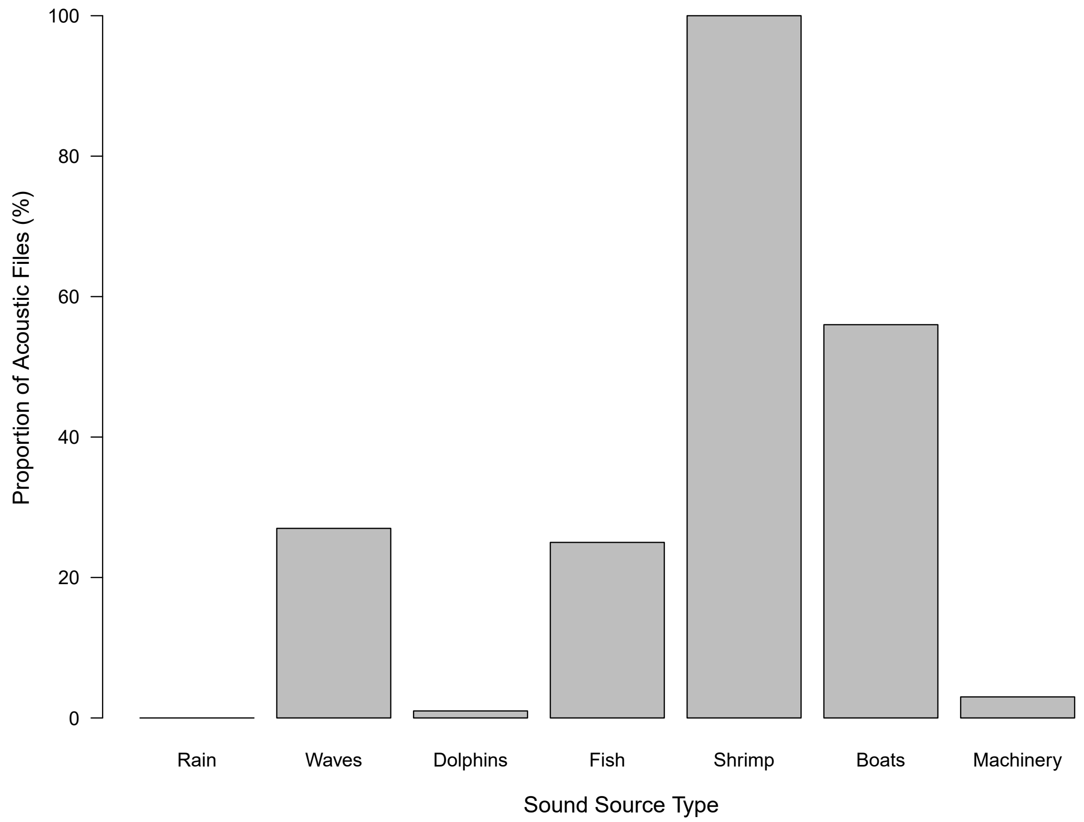

Figure 2.9: Presence of several abiotic, biotic and anthropogenic sound sources in the Narrows Bridge soundscape, showing the proportion of manually-reviewed hourly recordings (n = 901) containing each sound source.

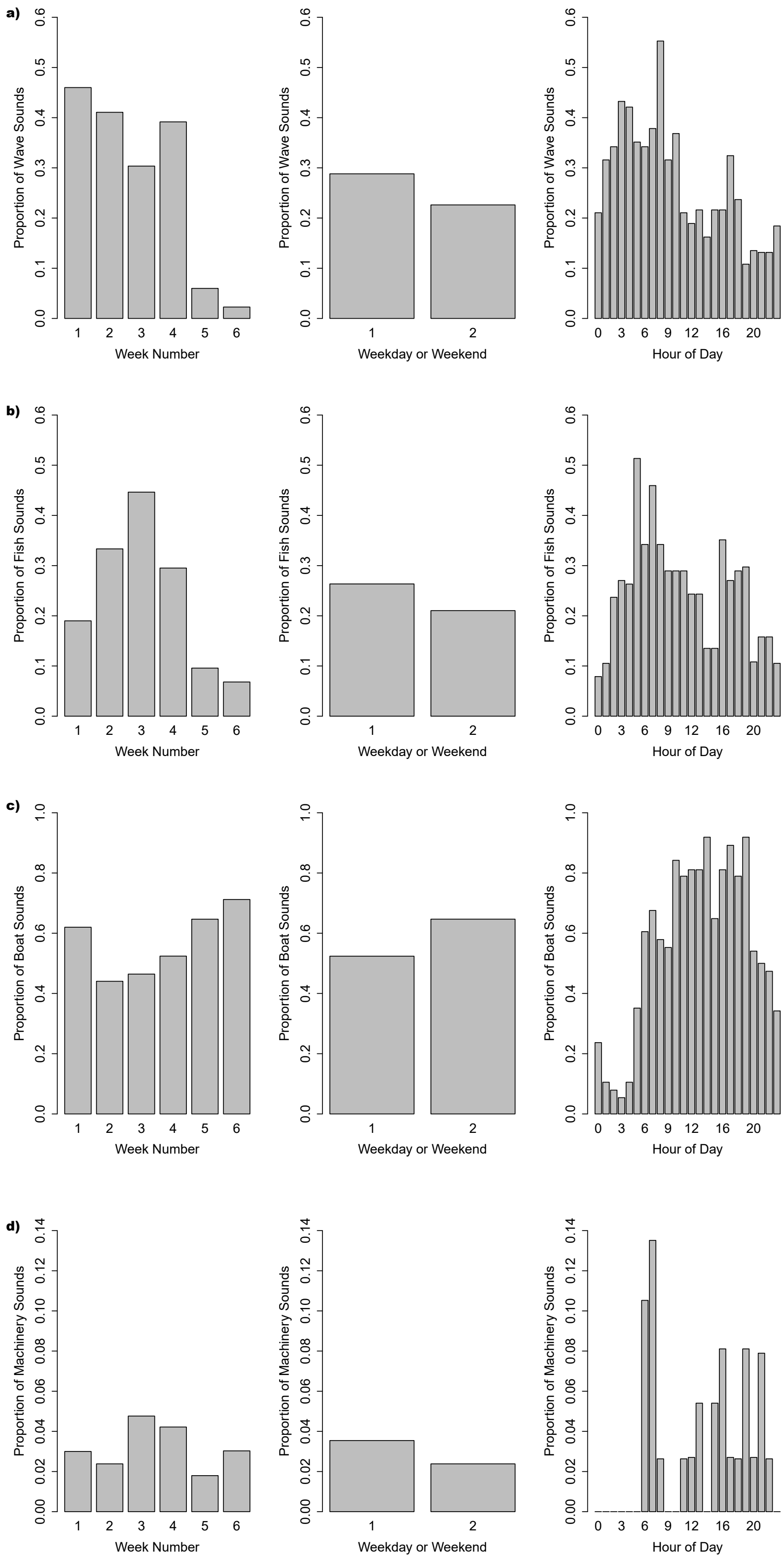

Figure 2.10: Temporal patterns of four prominent abiotic, biotic and anthropogenic sound sources in the Narrows Bridge soundscape (excluding snapping shrimp), as identified from manual data review: (a) Wave sounds; (b) Fish calls; (c) Boat traffic; and (d) Machinery noise. Note dates for each week: (1) 28 Nov – 01 Dec 2013, (2) 02 – 08 Dec 2013, (3) 09 – 15 Dec 2013, (4) 16 – 22 Dec 2013, (5) 23 – 29 Dec 2013, and (6) 30 Dec 2013 – 04 Jan 2014.

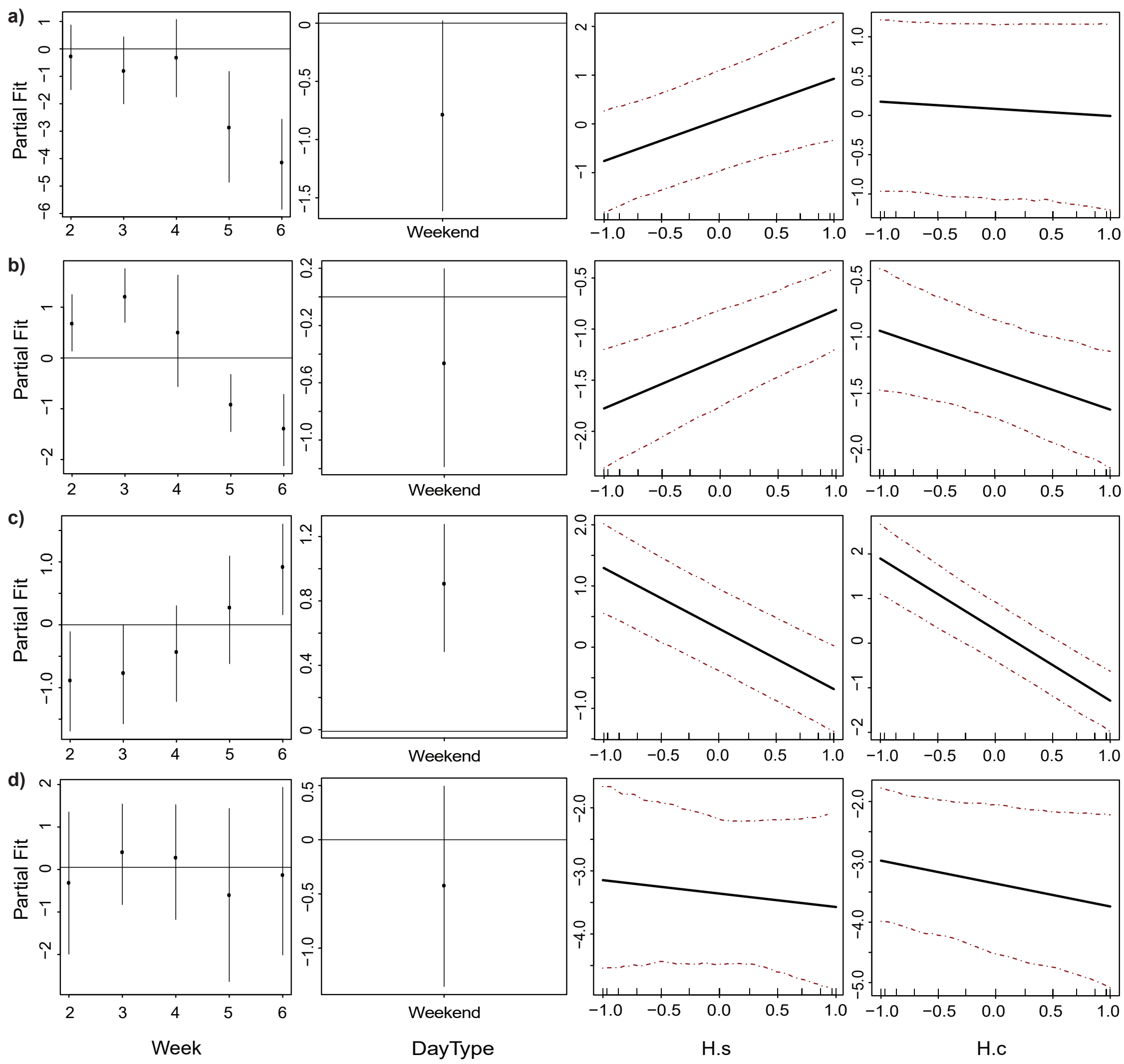

Figure 2.11: Partial residual plots showing temporal modelling of four prominent sound sources in the Narrows Bridge soundscape, as identified from manual data review: (a) Wave sounds; (b) Fish calls; and (c) Boat traffic; and (d) Machinery noise. Lines around data points indicate 95% confidence intervals. Note that Hour was included as a cyclical variable (Hs and Hc), whereas Week and DayType (weekday or weekend) were included as factors.

Table 2.1: Results from the generalised estimating equation (GEE) models, using AR1 autoregressive correlation structures (for waves and machinery) and exchangeable correlation structures (for fish and boats). Separate days were treated as independent. Note that, as hour was incorporated as a cyclical variable, it is represented by H_s and H_c.
Significance level: ≤0.001 ***; ≤0.01 **; ≤0.05 *

Parameter	Coefficient Estimate	Standard Error	Wald	p value	
Waves					
Intercept	0.0830	0.5472	0.02	0.87949	
Week 2	-0.2745	0.5829	0.22	0.63767	
Week 3	-0.8033	0.6223	1.67	0.19676	
Week 4	-0.3199	0.7426	0.19	0.66658	
Week 5	-2.8678	1.0487	7.48	0.00624	**
Week 6	-4.1419	0.8768	22.31	2.3e-06	***
Weekend	-0.7862	0.4533	3.01	0.08281	
H_s	0.8437	0.2254	14.01	0.00018	***
H_c	-0.0908	0.1436	0.40	0.52726	
Fish					
Intercept	-1.2944	0.2297	31.76	1.7e-08	***
Week 2	0.6768	0.2881	5.52	0.0188	*
Week 3	1.2059	0.2891	17.40	3.0e-05	***
Week 4	0.5004	0.5758	0.76	0.3848	
Week 5	-0.9187	0.2812	10.67	0.0011	**
Week 6	-1.3904	0.3445	16.29	5.4e-05	***
Weekend	-0.4640	0.3362	1.90	0.1676	
H_s	0.4817	0.0987	23.80	1.1e-06	***
H_s	-0.3497	0.1557	5.05	0.0247	*
Boats					
Intercept	0.305	0.345	0.78	0.377	
Week 2	-0.885	0.408	4.71	0.030	*
Week 3	-0.768	0.423	3.30	0.069	
Week 4	-0.433	0.397	1.19	0.276	
Week 5	0.273	0.420	0.42	0.515	

Week 6	0.919	0.379	5.89	0.015	*
Weekend	0.907	0.207	19.16	1.2e-05	***
H_s	-0.990	0.126	61.67	4.1e-15	***
H_c	-1.593	0.164	94.75	<2e-16	***
Machinery					
Intercept	-3.360	0.602	31.10	2.4e-08	***
Week 2	-0.313	0.882	0.13	0.72	
Week 3	0.406	0.642	0.40	0.53	
Week 4	0.278	0.717	0.15	0.70	
Week 5	-0.603	1.068	0.32	0.57	
Week 6	-0.131	1.067	0.02	0.90	
Weekend	-0.424	0.467	0.82	0.36	
H_s	-0.212	0.401	0.28	0.60	
H_c	-0.380	0.237	2.57	0.11	

2.4 Discussion

The soundscape of the Swan River near the Narrows Bridge was found to vary in its composition over a range of temporal scales. The acoustic characteristics of marine habitats are increasingly being considered as key environmental variables, particularly for acoustically-specialised fauna such as dolphins. Thus, there is a need to consider how marine soundscapes vary both spatially and temporally in their composition. This study takes a crucial step in characterising the soundscape of an urban, estuarine river system in Western Australia.

The Narrows Bridge site soundscape was found to consist of several sound sources, including abiotic, biotic and anthropogenic sources. Weekly spectrograms illustrated that the most prominent sound sources included sounds from snapping shrimp, vessel traffic, and bridge traffic noise from vehicles and trains traversing the Narrows Bridge. Percentile plots revealed the extent to which the soundscape was influenced by these different sound sources, in particular highlighting vessel traffic and snapping shrimp as principal contributors to the Narrows Bridge site noise budget. The combination of these two sound sources covered the majority of the frequency range recorded by the noise logger, suggesting that statistical variability of contributors to the noise budget of this area could be mostly explained by these two sources. However, by considering the soundscape in different frequency bands, wind was also identified as a significant contributor to the noise budget. In a sense, the sounds from vessels and snapping shrimp "sit on top" of wind noise, with all three significantly contributing to the composition of the acoustic habitat. Broadband (9 Hz – 9kHz) noise levels and 1/3 OBLs indicated a diel pattern with higher levels during day- rather than night-time. To determine if further statistical variability existed in the temporal occurrence of sound sources, the data were manually inspected at hourly intervals and modelled using GEEs across three temporal scales: weeks ("Week"), weekdays vs. weekends ("DayType"), and hours of day ("Hour"). These showed that the Narrows Bridge site soundscape does indeed display temporal patterns in the presence of particular types of sound.

By way of these four methods (weekly spectrograms; PSD percentile plots; 1/3 OBLs; and GEEs), this study also illustrates how different analytical techniques can be used to assess the acoustic environment. Weekly spectrograms provide a broad overview of prominent sound sources and may illustrate patterns in occurrence if acoustic events are of sufficient duration, but lack the resolution to easily identify transient acoustic events. This can lead to under-representation of such events when assessing the characteristics of a particular soundscape, such as could have occurred with vessel transits in this study. Complimentarily, PSD percentile plots, which give a statistical distribution of recorded levels as a function of frequency, can highlight brief, transient events, if they are of significant power (sound level), in addition to consistent, long-duration events. However, different sound sources with overlapping frequencies and levels may be poorly illustrated. This is somewhat abetted by breaking the acoustic data into 1/3 octave band levels, which can then be investigated for statistical correlation with different sources (such as wind speed or other environmental drivers). Manual inspection of acoustic recordings allows detection of transient and long-duration events, identification of different sound sources with similar acoustic characteristics, and statistical modelling of the presence/absence of sound sources at varying scales. Unfortunately, this method requires a considerable amount of effort for dedicated data review, and so generally requires sub-sampling of the dataset rather than a census of all recordings. While all methods identified vessel traffic and snapping shrimp as the dominant sound sources in their respective frequency bands, a combination of methods is needed for soundscape characterisation in order to also quantify sounds which are weaker, briefer, or difficult to identify via manual data review (such as animal calls or wind-driven noise).

Although the Narrows Bridge site soundscape consists of several sound sources, only five were observed in sufficient proportions to warrant statistical modelling to investigate temporal variability: waves, snapping shrimp, fish, boats and machinery noise. While snapping shrimp showed the greatest prevalence (being present in all recordings inspected), their constant presence made modelling unnecessary at the temporal scale. By considering the 1/3 OBLs containing snapping shrimp noise, it was shown that noise from these animals increased over the study period, likely due to more and more animals settling on the mooring. However, in future work an assessment of longer-term changes in noise levels from snapping shrimp would identify whether there are seasonal changes at this site or if this is merely the result of settlement. In this study, only the presence or absence of sound sources were considered. It was not possible to record counts of individual sound producers, due to a lack of visual data for confirmation – thus leaving it questionable as to whether certain sounds, for example fish calls or boat transits, were being produced on multiple occasions by one individual or if multiple individuals were contributing to the total number of sounds recorded. For this reason, count data is often problematic in acoustic analyses, and consideration of presence/absence allows a more conservative approach to acoustic assessment. Development of noise level indices could allow incorporation of a relative abundance measurement in the future.

Regardless, the presence of boat traffic in over half of the hourly recordings inspected across the study period clearly shows the strong contribution of anthropogenic noise in this environment. Interestingly, though perhaps unsurprisingly, anthropogenic sound sources showed clear temporal variation which parallel human routines. For example, the observed increase in boat noise during weekends as opposed to weekdays matches the general patterns of human recreational time on weekends. Whereas the fact that machinery noise was primarily observed during weekdays – i.e. during normal working hours – corresponds with the use of machinery in a professional capacity. This is substantiated by the hourly patterns of anthropogenic sound occurrence, where machinery noise is not observed overnight (23:00 hrs – 06:00 hrs) and vessel traffic shows peaks which mimic the typical 'rush-hour' of boat-users heading out mid-morning and returning early evening. The weekly increase in vessel traffic towards the end of the study period may also reflect the onset of the summer holiday period in Perth, as more people enjoyed increased recreational time due to the Christmas holidays. It is worth noting at this point that the apparent high in vessel traffic during Week 1 may be skewed due to the recordings starting mid-week (thus resulting in Week 1 having only four sampling days, two of which were the weekend). Similarly, Week 6 recordings ended mid-week and did not include the weekend, suggesting that had the recordings run full-week then even higher levels of vessel traffic would have been detected. The main observation from these results is the strength to which human lifestyle patterns appear to influence the underwater soundscape.

Fish also showed considerable variability in the presence of their calls, with a significant peak in the third week of the study period. Yet there were still observable peaks in fish call presence by hour, occurring around 05:00 – 08:00 hrs and 16:00 – 19:00 hrs. Although there were no fish choruses occurring during this deployment, they have been observed in the Swan River (Parsons *et al.*, 2013b, 2006). Fish choruses in other locations have been shown to be synchronised with environmental variables, particularly in relation to sunrise/sunset or lunar phase (McCauley, 2012). Given the relatively short duration of this deployment, it was not possible to incorporate monthly variation as a factor or fully investigate the range of potentially contributing environmental factors. However, the inclusion of additional acoustic data could provide further insight to the drivers of such temporal patterns.

It is worth noting that only correlations within a single cluster stratum can be accommodated by a GEE (Bailey *et al.*, 2013). Therefore, only correlations between consecutive hours were included in this analysis. Investigation of the soundscape at this site over greater temporal scales would allow further investigation of this, whilst also greatly improving the baseline knowledge of temporal patterns in sound source contribution to the acoustic environment. In terms of spatial comparison within the Swan River, it is interesting to note that this study recorded many of the same sound sources as have been observed in the Fremantle Port (snapping shrimp, fish, dolphins, boats, machinery, bridge traffic; Salgado Kent *et al.*, 2012). This illustrates how human activities contribute to the soundscape in both the lower and middle reaches of the Swan River. It is suggested that the inclusion of multiple sites to further examine spatial variation within the overall soundscape of the entire Swan-Canning River system could provide several interesting comparisons and illustrate a greater degree of soundscape complexity.

It has been clearly demonstrated that the Narrows Bridge site soundscape is a variable acoustic environment. Information regarding the use of underwater acoustics as an environmental variable, with the ability to influence the presence or behaviour of aquatic species, would be of use to industry, government departments, research bodies, the general public, and other stakeholders of natural areas such as the Swan-Canning River system. This is particularly relevant given many marine species rely on their ability to detect abiotic and biotic cues in the natural environment for their survival and reproduction. For example, further work incorporating data from dolphin "hotspots" throughout the Swan-Canning River system would provide an evaluation of the occurrence of these animals with regard to different acoustic habitats within the river system. Overlaying maps of dolphin distribution with noise maps can identify both areas of risk (where strong overlap exists and effective dolphin communication could be diminished) and areas of opportunity (where the probability of dolphin presence is high yet noise is low), both of which are important areas to be considered in conservation management and marine spatial planning (Williams *et al.*, 2015a). Unfortunately, insufficient information was available to allow such comparisons in this study, but they are strongly recommended in the future through integration of additional acoustic data collection sites and visual observations of dolphin presence.

This study indicated that variation in the probability of different sound sources contributing to the Narrows Bridge site soundscape occurred at a range of temporal scales. In particular, anthropogenic sound sources exerted strong temporal patterns across the lower frequencies, showing the extent to which anthropogenic activities can influence the underwater soundscape. Understanding the factors that drive such temporal patterns remains a key challenge for describing the soundscape of the Swan-Canning River system. Furthermore, determining the influence of such patterns on the aquatic fauna who utilise the acoustic environment of this site would provide vital information for the managers and users of this urban estuarine river system.

2.5 Acknowledgements

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Chapter 3

Occupancy of bottlenose dolphins (*Tursiops aduncus*) in relation to vessel traffic, dredging and environmental variables within a highly urbanised estuary

Coastal areas, and thus coastal species, are at increasing risk from human activities. Sections of the coastline of Western Australia are undergoing intense coastal development to fulfil commercial, industrial and recreational requirements. Multiple populations of bottlenose dolphins (*Tursiops aduncus*) occur around this coastline; however, small community sizes and limited genetic exchange rates make them susceptible to anthropogenic pressure. This study investigated the occupancy of dolphins within the Swan-Canning Rivers, an urbanised estuary, with regard to: (1) presence/absence; (2) abundance; and (3) duration in terms of time spent in the area. These response variables were related back to environmental conditions (tidal state, tidal height, salinity, temperature), vessel traffic, and dredging activities using generalised additive modelling (GAM). Theodolite-tracking data revealed high levels of boat traffic at the two sites considered; however, dolphin occurrence was only negatively affected by vessel density at one of these sites. Dolphin occupancy was also significantly influenced by temperature, with possible seasonal effects. No dolphins were sighted on days when backhoe dredging was present, however low sample sizes limited statistical interpretation. These results highlight the need to consider context in behavioural response studies, in terms of habitat type studied, explanatory variables considered, and response variables selected.

3.1 Introduction

Coastal habitats are among marine areas most at risk from the impacts of human activities (McIntyre, 1999; Moore, 1999). As a result, threats to coastal species, such as Indo-Pacific bottlenose dolphins (*Tursiops aduncus*; Ehrenberg, 1832), are among those in need of management to reduce their impacts (Allen *et al.*, 2012; DeMaster *et al.*, 2001; Ross, 2006; Thompson *et al.*, 2000). Due to their acoustic specialisations, bottlenose dolphins are vulnerable to noise and disturbance from human activities, which are widespread throughout their coastal range (Bejder *et al.*, 2006; Buckstaff, 2004; Nowacek *et al.*, 2007; Pirotta *et al.*, 2015; Steckenreuter *et al.*, 2012; Tyack, 2008; Guerra *et al.*, 2014; Hastie *et al.*, 2003; Heiler *et al.*, 2016; Jensen *et al.*, 2009; Lusseau, 2003a, 2005; May-Collado & Quiñones-Lebrón, 2014; Morisaka *et al.*, 2005).

Sections of the Western Australian coastline are currently undergoing intense development in the form of port maintenance and expansion, marine construction, and increasing tourism (Bejder *et al.*, 2012; Davenport & Davenport, 2006; Allen *et al.*, 2012; Beazley, 2010; Hanf *et al.*, 2016). These activities can have detrimental effects on the marine environment (e.g. habitat destruction, chemical contamination, littering, underwater noise, loss of food sources; Clark, 2001) which can lead to impacts on local fauna. Multiple local populations of Indo-Pacific bottlenose dolphins occur around the coast of Western Australia. These dolphins occupy a diversity of habitat types, having adapted to unique environments such as inshore bays, riverine and semi-enclosed estuaries. Although the species itself is widely distributed, many live in small communities with limited genetic exchange outside of their social network (Holyoake *et al.*, 2010). These attributes, in combination with their near-shore distribution, make bottlenose dolphin communities vulnerable to environmental changes and anthropogenic pressures (Chabanne *et al.*, 2012; Ross, 2006; Wilson *et al.*, 1999). Additionally, strong site fidelity to small, defined areas makes some dolphin communities particularly vulnerable to anthropogenic pressures, as they are exposed to the repeated and cumulative effects of such stressors (Finn, 2005; Ross, 2006).

The Swan-Canning River system, flowing through the Western Australian state capital of Perth, is an urban estuary subjected to several forms of human activity. Within this system are an industrial port, commercial ferry channels, jetski and powerboat race areas, shoreline construction works, and thousands of recreational vessels. As a result, sections of the river have been reported to experience considerable anthropogenic noise (Marley *et al.*, 2016a; Salgado Kent *et al.*, 2012). In spite of this, the river system is also home to a small, resident community of bottlenose dolphins (*T. aduncus*), composed of approximately 18 adults and several juveniles/calves (Chabanne *et al.*, 2012; Swan River Trust, 2015). These animals are distributed heterogeneously within the river system, with some particular areas acting as dolphin “hotspots”, based on nearest neighbour hierarchical clustering analyses to determine which areas have a higher number of dolphin sightings (Moiler, 2008).

Despite these animals inhabiting a noisy, urbanised environment, limited work has been done investigating any potential disturbance from human activities. The only existing behavioural response study involving this community of dolphins focused on pile-driving within the Fremantle Inner Harbour located at the mouth of the river system. The study found that visual detections of dolphins decreased during pile-driving activity associated with harbour-deepening (Paiva *et al.*, 2015; Salgado Kent *et al.*, 2012). Reduced detections may have reflected: increased absences of dolphin groups from the study area; reduced number of dolphins using the site; or decreased occupancy time within the harbour (Paiva *et al.*, 2015).

The most ubiquitous anthropogenic activity in the Swan-Canning River system (and indeed the majority of marine systems) is vessel traffic, which has been shown to induce a range of behavioural responses in cetaceans. These range from relatively subtle effects, such as changes to inter-breath intervals, inter-animal distances, breathing synchrony, travel heading and speed (Hastie *et al.*, 2003; Lusseau, 2006; Nowacek *et al.*, 2007; Weilgart, 2007; Williams *et al.*, 2002) to more obvious reactions, such as termination of activities or displacement from the impacted area (Bejder *et al.*, 2006; Christiansen *et al.*, 2010; Constantine *et al.*, 2004; Cosens & Dueck, 1988; Lusseau, 2003a,b; Morton & Symonds, 2002; Nowacek *et al.*, 2007). Over 97,000 recreational vessels are registered within Western Australia, approximately 53,000 of which are registered within the Perth metropolitan area (J. Nunn; personal communication, 21st January 2014). A study investigating underwater noise at a site within the Swan River found vessel noise to be present in 52% of hourly acoustic recordings (Marley *et al.*, 2016a). Furthermore, parts of the river system have also experienced dredging activities for the maintenance and expansion of vessel channels. Dredging has the potential to impact cetaceans through acoustic masking, behavioural changes, or changes to prey availability (Clark *et al.*, 2009; Erbe, 2002; Todd *et al.*, 2015). For example, both probability of occurrence and time spent in the area by bottlenose dolphins (*T. truncatus*) within Aberdeen Harbour (an urbanised foraging patch) declined during higher intensities of dredging, despite high baseline levels of disturbance from vessel traffic and the importance of the area as a foraging site (Pirotta *et al.*, 2013). The small size of the Swan-Canning River resident dolphin community makes it inherently vulnerable to human impacts (Chabanne *et al.*, 2012). Thus, vessel traffic and dredging (and their cumulative effects) are activities which warrant investigation with regard to their potential effects on this dolphin community.

Describing patterns of animal occurrence and occupancy in a particular area can provide important information on the status of mobile cetacean species in an area of interest (Durban *et al.*, 2000). "Occurrence" typically connotes frequency of an event, whereas "occupancy" connotes that the event occurs at least once (Lele *et al.*, 2013). Therefore, how a species occupies a particular area can be measured in various ways, such as presence/absence, relative abundance, or time spent in an area (Efford & Dawson, 2012; Latif *et al.*, 2016; Lele *et al.*, 2013; MacKenzie & Nichols, 2004). Although these are all assessing animal occupancy, such response variables each provide different levels of context to behavioural response studies. For example, an impact study may see no change in the overall daily presence/absence of a species in the impact area – but animals may still be spending less time in the area. Or perhaps the number of minutes with animals present in the study area may not change – but only because one individual is spending hours circling the area, when pre-impact there were multiple individuals passing through. Monitoring animal occupancy in a variety of forms can thus provide deeper perspective to behavioural response studies. Such information can also help identify critical areas within a population's range for conservation management strategies (Ingram & Rogan, 2002).

This study aims to investigate whether vessel density and dredging activities are related to dolphin occupancy. The study did not aim to test the effects of anthropogenic sources on behaviour, spatial distribution, or broad seasonal occurrence. To achieve the aims of this study, two sites were selected for monitoring: Perth Waters and the Fremantle Port. Land-based theodolite-tracking was used to ensure no disturbance from the presence of the research team. Patterns of vessel traffic were described for both sites and dolphin occupancy in these areas was assessed in terms of their: (1) presence/absence; (2) relative abundance; and (3) duration of time spent in the areas. Theodolite observations allowed continuous tracking of dolphin groups and calculation of duration of time spent in the study area by each group. These data were related back to environmental conditions, as well as the density of vessels and (in the case of the Perth Waters site) dredging activities. Environmental conditions were included to consider whether any observed changes to occupancy were indeed due to anthropogenic activities, rather than other environmental processes. Additionally, environmental variables could be related to key occupancy drivers such as prey availability.

3.2 Methods

3.2.1 Study Site

The Swan-Canning River system flows through the centre of metropolitan Perth, a city of over 1.4 million people. The Swan and Canning Rivers are 72 km and 110 km long respectively; together, these form an extensive river system composed of narrow channels, large shallow basins, and riverine upper reaches. The river system was originally partially closed, due to a large sand bar at the river mouth, making the river mostly fresh and brackish. The bar was dredged in the late 1800s to allow development of the Fremantle Port, which also allowed increased intrusion of oceanic water (Hodgkin & Hesp, 1998). This considerably altered the salinity of the river system and opened it to tidal influences. The estuary now experiences low-amplitude diurnal tides (Robson *et al.*, 2008). This area also shows larger water-level variations which coincide with the passage of atmospheric pressure systems; water levels rise in response to low barometric pressure, which is linked with variations in water column salinity (Hamilton *et al.*, 2001). Furthermore, there are seasonal changes to sea level as a result of the Leeuwin Current, which are reflected within the estuary (Thomsen *et al.*, 2001). The river system experiences a strongly seasonal inflow of freshwater with most rain (approximately 70%) falling in austral winter, when saline estuarine water is flushed from the upper estuary. Almost no river flows occur during the austral summer to autumn months (Hamilton *et al.*, 2001; Thomsen *et al.*, 2001). As a result of these features, estuarine salinity levels vary within and between years, depending on the balance of tidal diffusion and mean water flow (Thomsen *et al.*, 2001). However, typically salinity varies seasonally due to the low tidal amplitude and strong seasonal rainfall (Kurup *et al.*, 1998). The estuary can thus be described as a micro-tidal system with strong hydrological dependence on seasonal river inflows (Robson *et al.*, 2008).

The resident community of bottlenose dolphins use this river system on a daily basis, with hotspots of dolphin sightings in particular areas of the lower and upper reaches of the estuary (Beidatsch, 2012; Chabanne *et al.*, 2012; Moiler, 2008). However, the dolphins also range far into the upper reaches of both the Swan and Canning Rivers, using the entirety of the river including the two sites which were the focus of this study – Perth Waters and the Fremantle Inner Harbour.

Perth Waters is a 1 km wide bay in the upper reaches of the Swan River (Figure 3.1). It is a relatively shallow area, most of which is only 1 m deep, with several dredged ferry channels (approximately 5 m deep). Perth Waters is also the site of the Elizabeth Quay development, a new waterfront facility which was under construction at the time of this study, involving terrestrial landscaping, jetty reconstruction, and dredging to create deeper vessel-access channels. A high number of recreational boats use this area, in addition to transport and commercial ferries, contributing significantly to the underwater soundscape (Marley *et al.*, 2016a). This area appears to be used by dolphins moving between the upper and middle reaches of the Swan River (Beidatsch, 2012). The Fremantle Inner Harbour is situated at the mouth of the river system (Figure 3.1). The Fremantle Port is situated within the Inner Harbour and is the state's biggest general cargo port and Australia's fourth largest container port (http://www.fremantleports.com.au). The Fremantle Inner Harbour also experiences high use by recreational vessels, transiting the area between the Swan-Canning River and the Indian Ocean. As a result, it experiences high levels of anthropogenic noise from vessel traffic, wharf maintenance, and traffic passing over nearby train and traffic bridges (Salgado Kent *et al.*, 2012). Despite this, it appears to be a seasonal dolphin hotspot, primarily used for foraging (Moiler, 2008). The harbour depth is 13 m (dredged to accommodate ship movements), but at the eastern-most edge the river channel is 5 m deep, forming a sill known as the "Wangara Shoal".

These two sites were selected due partly to their use by dolphins (based on previous modelling works by Beidatsch, 2012; Moiler, 2008; Paiva *et al.*, 2015) and also due to their significance for anthropogenic activities. Furthermore, adjacent vantage points of significant height (> 30 m) allowed theodolite-tracking to be employed and reduced observational bias.

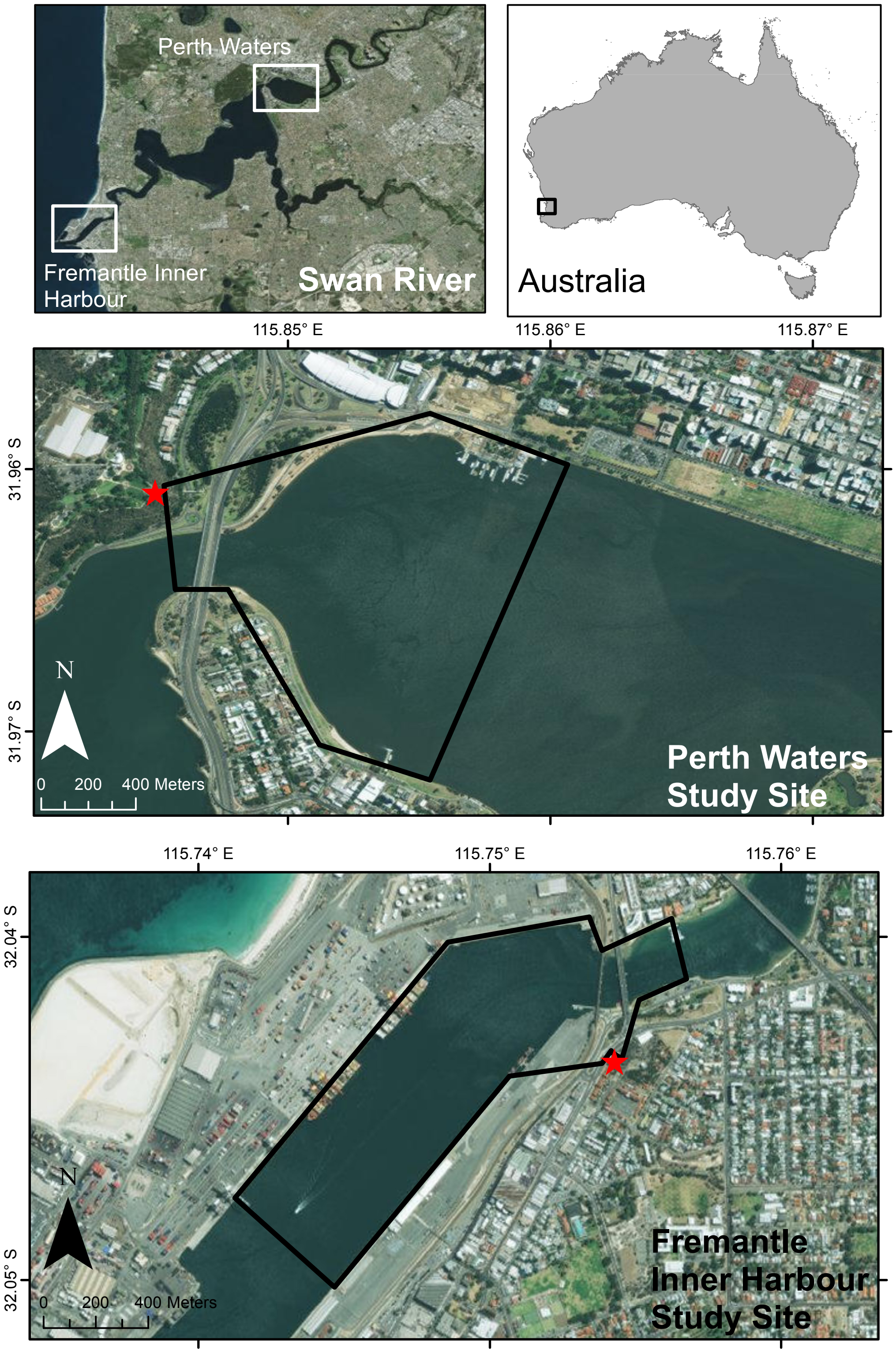

Figure 3.1: Theodolite tracking of dolphins, vessels and dredging occurred at Perth Waters and Fremantle Inner Harbour in the Swan-Canning Rivers. Theodolite stations are marked with a star. Map Source: ESRI (2015).

3.2.2 Theodolite-Tracking

Land-based observations were conducted from two elevated locations (Figure 3.1): one overlooking the western side of Perth Waters in the vicinity of Elizabeth Quay (31.960901°S, 115.844951°E; 63 m height) and another overlooking the east end of the Fremantle Inner Harbour (32.043634°S, 115.754284°E; 32 m height). Fieldwork occurred over two years between January and June (Table 3.1). A surveyor's theodolite (TopCon GTS-603 AF Electronic Total Station) was used to obtain the position of dolphin groups, vessels, and dredgers. Data were collected by a team of 3 – 4 trained observers and recorded in real-time using Vadar (vr 2.00.01b) software (E. Kniest, University of Newcastle). Fieldwork at each location was limited to single four-hour surveys per day conducted in good weather conditions (high visibility, Beaufort < 3, low glare, temperatures < 35°C) to ensure accurate data and avoid observer fatigue. Due to the Perth Waters location facing east and the Fremantle Inner Harbour location facing west, to avoid observers looking into the rising/setting sun the surveys were conducted during the afternoon and morning at these sites respectively.

Observers scanned the study area using 7x50mm binoculars. If dolphins were sighted, an initial position was taken with the theodolite and the group size was noted. For the purposes of this study, a 'group' was defined as 'dolphins observed in apparent association, moving in the same direction and often, but not always, engaged in the same activity' (Shane, 1990). The dolphins were tracked until they left the study area, were lost from sight, or until conditions deteriorated sufficiently to justify ending the survey. If multiple dolphin groups were present, they were simultaneously tracked by taking alternating theodolite positions during group surfacings. A 'track' was defined as a series of theodolite positions taken of the same dolphin group. Tracks were therefore assumed to be independent of each other.

Vessels were tracked continuously during their time in the study area via the same theodolite used for dolphin positioning. Vessels were tracked even if no dolphins were present in the study area. The identity of each vessel was noted based on either the name or a physical description of the vessel (colour, crew, distinguishing features, etc.). This enabled continual tracking of each vessel, regardless of how many vessels were present in the study area, with points taken in turn over a short period of time to reflect the entrance, exit and movement of vessels within the study area. Vessels were categorised according to type, as defined in Table 3.2. If a vessel was conducting a transit through the area, a minimum of three theodolite shots were deemed acceptable to determine average speed and course. However, if the vessel was milling or using the area for recreational activities (e.g. fishing), then theodolite shots were taken whenever the vessel appeared to have significantly changed its position. The vessel behaviour was also noted, either as stationary, milling, or travelling in one of four directions (north, east, south, or west).

Table 3.1: Overview of observation effort at the Perth Waters and Fremantle Inner Harbour field sites, with information on number of dolphin and vessel sightings, and surveys with dredging activity.

Survey Effort				Observations			
Year	Study Period	No. of Surveys	Effort (h)	Surveys with Dolphins	No. of Dolphin Sightings	No. of Vessel Sightings	Surveys with Dredging
Perth Waters							
2014	12 Jan - 14 Jun	46	130	10	24	1,547	12
2015	12 Jan - 03 April	32	100	8	28	1,297	0
Fremantle Inner Harbour							
2014	19 Feb - 13 Jun	35	106	32	229	1,820	0
2015	13 April - 23 Jun	23	71	23	180	1,192	0

Table 3.2: Vessel types and their descriptions.

Vessel Type	ID	Description
Barge	BA	Flat-bottomed vessels mainly used for transporting heavy material or goods. While some are self-propelled, those in this study were not self-propelled and needed to be towed
Cargo	CA	An ocean-going bulk carrier or tanker. Only observed within the Fremantle Inner Harbour
Charter	CH	Displacement hull with an inboard motor. Equipped with extensive deck space, fully-enclosed cabin, and entertainment facilities for tourism
Crayboat	CR	Large commercial fishing vessel with an inboard motor. Large rear deck space and an enclosed front cabin

Dredger	DR	Backhoe dredger mounted on a spud-stabilised pontoon. Uses a hydraulic excavator to dredge material, but is not selfpropelled
Ferry	FE	Commercial transport vessel, operating for both tourism and public transport within the Swan–Canning Rivers
Jetski	JE	Personal water craft which is jet-propelled
Kayak	KA	Light, canoe-like boat with a watertight frame in which a paddler sits with legs forward, using one paddle with two blades
Large Rec	LR	Fibreglass-hulled boat with either inboard or large outboard motor. Equipped with either partially or fully enclosed cabin; designed to stay on the water for days at a time
Motoryacht	MY	Typically 12 m or above with powerful inboard engines. Ample deck and cabin space; designed to stay on the water for days or weeks at a time
Pilot	PI	Work boat used to transport maritime pilots between land and in- or outbound ships. Medium to large vessels with inboard motors. Only observed within Fremantle Inner Harbour
Sailboat	SA	Small yacht with both sail and inboard engine capabilities. At the two study sites considered, they were always under motor
Small Rec	SR	Small, fibreglass or aluminium hulled boat with an outboard motor. Open top with forward controls or a centre console; designed to stay on the water for short periods of time (i.e. day trips)
SUP	SU	Stand-up paddleboard. Propelled by paddling by rider using one paddle with one blade
Tinny	TI	Small, aluminium hulled boat with a tiller-steered outboard motor. Open top, no cabin space. Also commonly referred to as a ‘dingy’
Tug	TU	Work boat used to manoeuvre vessels by pushing or towing them. Medium to large, powerful inboard motors

Elizabeth Quay experienced dredging activities in January – May 2014. The theodolite team were able to observe the dredging platform from their hill station, and recorded when dredging occurred. Dredging was deemed to be occurring when the bucket was in motion and the pontoon being filled with sediment. In some instances, the dredger was present but not operational; in such cases, dredging was considered as being absent. Dredging works utilised a backhoe dredger, a common stationary type of dredger where the dredging operation is performed by a hydraulic excavator, mounted on a pontoon stabilised usually by means of spuds. All dredging works were enclosed by a silt-net to minimise environmental impact due to sediment plumes. Support vessels towed barges into position for collection and removal of dredged material.

3.2.3 Data Analysis

Use of these sites by dolphins was measured in three ways: 1) the occupancy of dolphins based on their presence/absence; 2) the relative abundance of dolphins; and 3) the duration of time dolphins spent in the study area. The assumption was made that all dolphin groups within the study area were available to be detected at some point during their occupation of the area. Mate *et al.* (1995) reported a tagged bottlenose dolphin (*T. truncatus*) to have an overall mean dive duration of 25.8 s and a highest mean travel speed of 4.9 km/h. Based on these values and considering that the Fremantle Inner Harbour study area has a length of approximately 1 km, a dolphin could be expected to take an average of 735 s (12 min) to transit this area and surface an average of 28 times in the process. This would provide multiple opportunities for observation by the survey team, particularly considering the good height and visibility provided by the observation platform and the fact that surveys were only conducted in excellent viewing conditions.

To investigate the relationship between site occupancy and vessel density, separate models with environmental covariates were fitted for each of these response variables. Due to the influence of tides, salinity and seasons described above, it was deemed prudent to include environmental variables in addition to anthropogenic variables. Responses were investigated at a daily scale, i.e., the presence/absence, relative abundance and total duration of time dolphins spent in an area in a day were considered as a single observation. The two sites themselves were not directly compared due to the daily timing of field work surveys (mornings in Fremantle Inner Harbour versus afternoons in Perth Waters), the seasonality of observations (not concurrently monitored in year two), and the different station heights at the two sites potentially resulting in dissimilar detection probabilities.

The explanatory variables initially considered for inclusion in each model were: vessel density, dredging presence/absence (for Perth Waters), year, tidal state, tidal height, water salinity, water temperature and maximum air temperature. Vessel density was calculated as the average number of vessels per hour effort for each survey (with a single survey undertaken per day), whilst the occurrence of dredging was recorded as a binary factor over the entire survey. Although year can be classed as a continuous variable, in this instance it was included as a factor to reflect that only two levels existed. Tidal state and height data were inferred from tidal charts available on the Department of Transport website (http://www.transport.wa.gov.au).

Tidal state was defined as a categorical variable with four levels (low, rising, high, and falling tide). The 'high slack' was defined as a period +/- 1.5hrs centred on the time of high water; 'low slack' was similarly defined for the time of low water. Consequently, a tidal state was defined as *high* if at least 50% of the survey overlapped with the 'high slack' period. Similarly, the tidal state was deemed *low* if at least 50% of the survey overlapped with the 'low slack' period. If a survey did not sufficiently overlap with either of these periods, it was categorised as either *falling* or *rising*, which respectively indicated if the tidal state was moving towards or away from the 'low slack' period. Tidal height varies according to the 'Rule of Twelfths'; a rule of thumb for estimating the height of the tide at any time given the time of day and height of high/low water (Pearson, 2007). Tidal height for each survey in this study was calculated for the median time of the survey. The Rule of Twelfths was used to calculate the start/end time of each tidal 'twelfth', as well as the start/end tidal height for each of these twelfths. The start/end time of each twelfth period was then matched with the corresponding median tidal height for that period. Finally, tidal height data were taken from the twelfth period which matched the median survey time, to give one tidal height value per survey.

While water-quality (salinity, water temperature, pH, dissolved oxygen) data are collected by the Department of Water (Western Australia), daily data were not available for these sites. Models were used to extend the weekly (Perth Waters) or fortnightly (Fremantle Inner Harbour) water-quality data available. Water salinity and temperature were selected as measures of interest. Due to the low resolution of water quality sampling, we investigated whether maximum daily air temperature could be used as a proxy for water temperature. This was justified by performing a Spearman's Rank correlation, using days on which water quality sampling was performed and investigating the relationship between recorded water temperature and the maximum air temperature recorded for that day. The correlation was applied to each study site independently.

Due to the low sample size, modelling was not appropriate for the Perth Waters dataset; instead, the number of dolphin sightings was visually represented in relation to each potential explanatory variable. However, in the Fremantle Inner Harbour dataset, Generalised Additive Models (GAMs) were used to model the presence/absence, abundance, and duration of dolphins in the study sites. A GAM is an extension of a Generalised Linear Model (GLM), which allows estimation of relationships between predictor and response variables using non-parametric functions, without making assumptions regarding the nature of such relationships (Waples *et al.*, 2013; Zuur *et al.*, 2009). GAM allows smoothing functions to be fitted to predictor variables, which generate curves that can flow more freely than a straight line for describing the data. For analyses using GAMs, explanatory variables were fitted in different combinations (i.e. including smoothers, linear terms, and factors) for each response variable. As not all surveys were equal in duration, the natural logarithm of survey effort was used as an offset variable in each model.

GAMs assume that model errors are independent. To verify their independence, model residuals were checked to ensure that there was no temporal autocorrelation using semi-variograms of the standardised residuals (Zuur *et al.*, 2009). Additionally, for each model, the absence of concurvity (i.e. the non-parametric analogue of multi-collinearity) between these explanatory variables was confirmed using variance inflation factors (VIFs; Zuur *et al.*, 2010). Overdispersion is commonly encountered in count data, meaning that data may vary more than expected compared to data following a Poisson distribution. Overdispersion was investigated using the sum of squared Pearson residuals divided by sample size, minus the number of parameters. QQ-Plots, histograms, residuals versus fitted values, fitted values versus observed values, and the percentage of deviance explained were used to quantify each model's goodness-of-fit (Zuur *et al.*, 2009; Zuur & Ieno, 2016).

To assess the occupancy of dolphins, firstly the presence/absence of dolphins during each survey was investigated using a binomial GAM with a logit-link function. Secondly, the abundance of dolphins was originally investigated using a GAM with a Poisson distribution and a log-link function to model the number of dolphins sighted in each survey at Perth Waters; however, overdispersion in the Inner Fremantle Harbour data resulted in this model being fitted with a negative binomial distribution. Finally, the duration of time dolphins spent in the study area was investigated at both sites using a negative-binomial GAM with a log-link function to model the number (counts) of minutes (rounded to the nearest minute) in each survey in which dolphins were present. A negative-binomial distribution was selected to account for overdispersion of the data (Linden & Mantyniemi, 2011; O'Hara & Kotze, 2010; Zuur *et al.*, 2009).

Model selection was conducted based on the maximum likelihood, considering the Akaike's Information Criterion corrected for small sample sizes (AICc; Burnham & Anderson, 2004). This approach stipulates that the lower the AICc the better the fit of the model, and is equally applicable to larger sample sizes as AICc converges with AIC in such cases. In addition, the difference between the AICc of each model and the lowest observed AICc of all models (i.e. ΔAICc) was calculated. Models with ΔAICc < 2 are equally plausible as the best model to explain the observed patterns in the data (Burnham & Anderson, 2004). To account for this, the Akaike's Information Criterion weight (wAICc) was calculated for models with similar plausibilities under the AICc. The wAICc expresses the relative contribution of the model to explain the observed patterns (Burnham & Anderson, 2004). In cases where the wAICc scores were identical for multiple models, the most parsimonious model was selected (Richards, 2008; Richards *et al.*, 2011).

All analysis was conducted in R (R Core Team, 2015), using the packages: *car* (Fox & Weisberg, 2011); *lattice* (Sarkar, 2008); *MASS* (Venables & Ripley, 2002); *mgcv* (Wood, 2006); *MuMIn* (Barton, 2016); and *stats* (R Core Team, 2015).

3.3 Results

Across the two-year study period, approximately 222 h and 168 h of observation effort were invested in the Perth Waters and Fremantle Inner Harbour study sites, respectively. The exact breakdown of these hours and the resulting dolphin sightings are summarised in Table 3.1.

An investigation of the relationship between water temperature and maximum air temperature returned a positive correlation for both study sites (Perth Waters: r_s = 0.72, p < 0.001; Fremantle Inner Harbour: r_s = 0.81, p < 0.01). Thus the decision to use maximum air temperature (hereafter 'temperature') as a proxy for water temperature was considered justified, given the high resolution of the former data compared to the latter.

Survey day was removed as a potential explanatory variable, due to concurvity issues with maximum air temperature and water salinity. Given the spread of surveys over several months and that an increase in survey day for each year corresponded with a decrease in temperature and an increase in water salinity, these variables were determined to show seasonal patterns. To avoid temporal confounding, survey day was thus removed from analysis.

3.3.1 Summary of Vessel Activity

At the Perth Waters site, a total of 2,656 vessels were sighted and tracked across the two-year study period, resulting in a vessel density of approximately 12 vessels per hour of effort. The maximum observed vessel density was 43 vessels per hour effort. The majority of these were small recreational vessels (44%), followed by ferries (15%) and tinnies (10%; Figure 3.2a). Approximately 72% of vessels spent 15 min or less in the study area (Figure 3.2b), illustrating its use as a transit area. However, this site is also used over longer periods (up to several hours) by recreational fishers, day-trippers utilising the public moorings, jetskis using the personal watercraft area, and transport ferries which cross the river at regular intervals. As a result of the wide range of activities available for boat users, there is no one vessel category which stands out as spending a long time in the area, on average; yet there are a few vessel categories which spend either little or no time in this area (Figure 3.2c).

Surveys generally occurred between 14:00 and 18:00 hrs at Perth Waters. The highest levels of vessel traffic occurred between 16:00 and 18:00 hrs, when approximately 60% of vessel activity occurred (Figure 3.2d). This is believed to reflect the evening 'rush hour' of recreational vessels heading home. However, as boat ramps and pens exist both up and down river of this site, there is no clear directional movement (Figure 3.2e). Additionally, two transport ferries operate during this time to meet the demands of city commuters crossing the river, as opposed to regular day-time service involving just one transport ferry. Approximately 76% of vessels were travelling at < 8 knots whilst using the Perth Waters area (Figure 3.2f). Jetskis and small recreational vessels had higher average speeds than other vessel types (Figure 3.2g).

At the Fremantle Inner Harbour site, a total of 2,601 vessels were tracked across the two-year study period – equivalent to a vessel density of approximately 16 vessels per hour effort. The maximum observed vessel density was 56 vessels per hour effort. The majority of these were small recreational vessels (46%), followed by large recreational vessels (18%; Figure 3.2a). Approximately 91% of vessels spent 15 min or less in the study site (Figure 3.2b), which also implies that the Inner Harbour is primarily a transit zone. Those vessels which had a longer duration were typically port work boats, such as barges, pilot vessels, or tugs (Figure 3.2c).

Surveys generally occurred between 07:00 and 10:00 hrs at Fremantle Inner Harbour, . During these hours, the Inner Harbour typically experienced the highest levels of vessel traffic between 08:00 and 10:00 hrs, when approximately 66% of vessel activity occurred (Figure 3.2d). This is believed to reflect the morning 'rush hour' of recreational vessel users heading out for the day, and is substantiated by the observation that the majority of vessels were travelling down-river (i.e. away from boat ramps/pens and out to sea) (Figure 3.2e). Approximately 69% of vessels had average speeds < 8 knots (14.8 km/h) within the Fremantle Inner Harbour; however, this varied with vessel type (Figure 3.2f and Figure 3.2g).

3.3.2 Dolphin Occupancy within Perth Waters

At the Perth Waters site, dolphins were present in 23% (18 of 78) of surveys conducted. This site had an average of 0.23 dolphin sightings per hour effort, with a maximum number of eight animals observed during a single survey. This maximum of eight dolphins in one survey is based on two groups and is a true sighting, not a re-sighting of the same animals: the first group comprised four adults and one calf, whilst the second was comprised of three juvenile dolphins. The comparison of group compositions between 'new' groups and groups previously sighted during that survey allowed counts of dolphin sightings to be made with relative confidence. Across 13,306 min of observational effort, dolphins were present for a total of 383 min (approximately 1.72 min per hour effort), with a maximum duration time of 93 mins in any one survey.

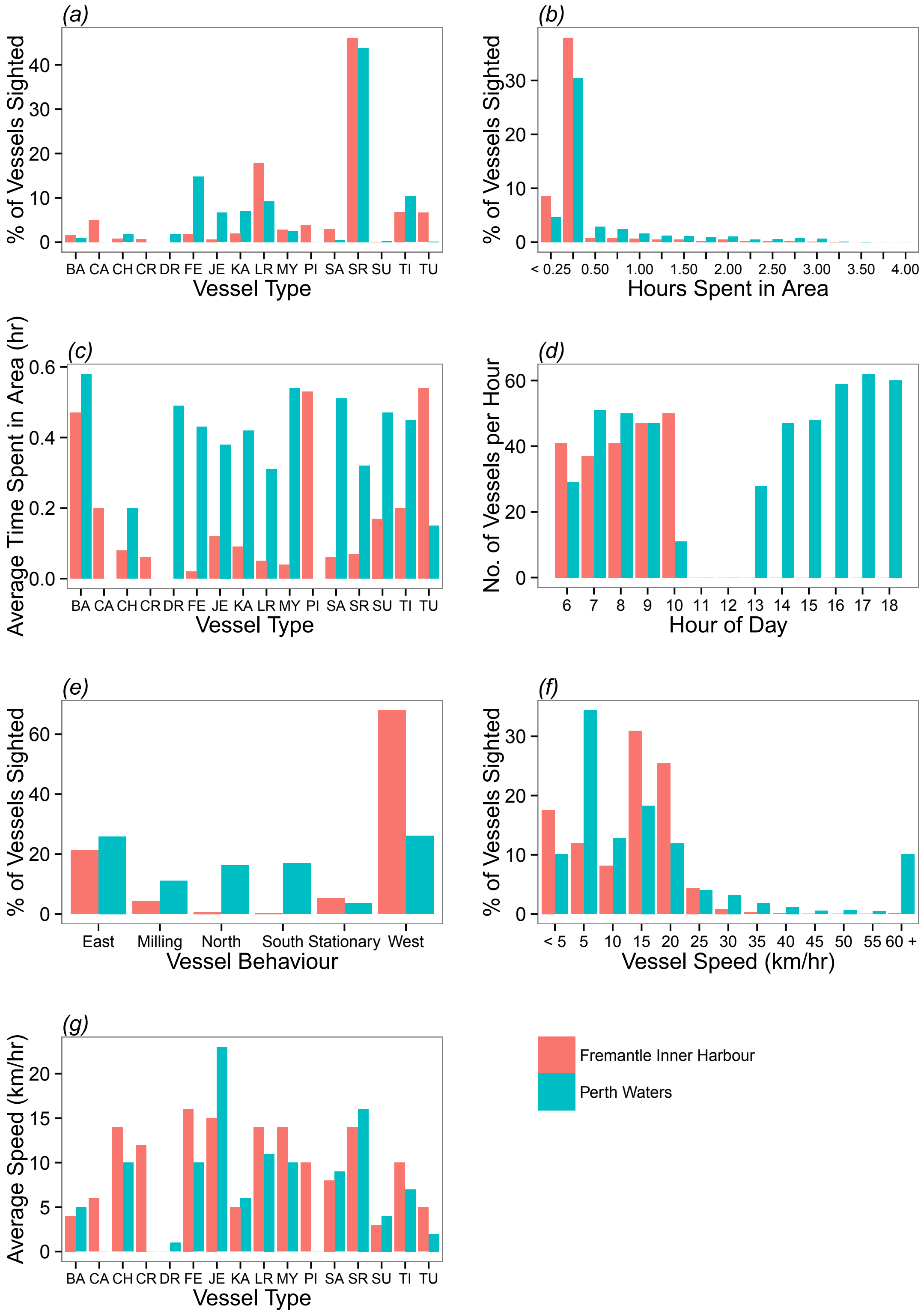

Figure 3.2: Summary of observed vessel traffic in Fremantle Inner Harbour (red) and Perth Waters (blue): (a) Percentage of vessel types sighted; (b) Duration of time vessels spent in the area; (c) Average duration of time spent in the area by different vessel types; (d) Number of vessels per hour effort present in the area by hour of day; (e) Frequency of vessel behaviours observed; (f) Frequency of vessel speeds recorded; and (g) Average speed recorded for each vessel type. See Table 2 for definition of vessel types. Note that the surveys generally occurred from 07:00 to 10:30 hrs (Fremantle Inner Harbour) and 14:00 pm to 18:00 hrs (Perth Waters), with some exceptions.

Due to the low sample size, modelling was not appropriate for this dataset; instead, the number of dolphin sightings was visually represented in relation to each potential explanatory variable (Figure 3.3). From these, overall dolphin sightings were more numerous when vessel density was low. No dolphins were sighted at vessel densities above 20 vessels per hour; however, there were few surveys conducted at these high densities. Dredging was directly observed on 12 days. No dolphins were sighted on days when the dredger was operating. A peak in dolphin sightings occurred in the middle temperature ranges. Relatively high numbers of dolphin sightings were made during low or falling tidal state in comparison to high or rising tidal states. Numbers of dolphin sightings were also greater with increased tidal height and water salinity. Additional, as yet unidentified, covariates could further explain the response data

To investigate the potential presence of any seasonal patterns, the number of dolphin sightings was also plotted by Julian Day in association with potential explanatory variables for each of the two study years (Figure 3.4). Both temperature and water salinity display seasonal patterns, reflecting the change from austral summer to winter during the study period. Low or falling tidal states were more commonly observed later in the study period. Dolphin sightings appear less abundant in the austral summer months at Perth Waters, suggesting a seasonal pattern to their occupancy at this site.

3.3.3 Dolphin Occupancy within the Fremantle Inner Harbour

Within the Fremantle Inner Harbour site, dolphins were present in 55 of the 58 surveys conducted (95%). Given the low number of absences, modelling of dolphin presence/absence was not attempted. Thus, it appears that dolphins are present in the Fremantle Harbour during the morning independent of vessel densities, temperature, tidal state, tidal height, or water salinity.

The maximum number of dolphins sighted within the Fremantle Inner Harbour across a single survey was 27 sightings; the average was 2.30 dolphin sightings per hour effort. Model selection retained temperature as being a significant predictor for the number of dolphins sightings in the study area (X^2 = 17.52, df = 2.605, p < 0.001; Table 3.3; Table 3.4; Figure 3.5a). The final model explained 27.2% of deviance.

Across 10,049 min of observational effort at the Fremantle Inner Harbour, dolphins were present for a total of 4,705 min (approximately 28.09 min per hour effort), with a maximum duration time of 181 min in any one survey. Model selection with AICc and wAICc identified multiple possible models (ΔAICc < 2); thus, the most parsimonious model was selected. This retained temperature as having a significant negative relationship with the amount of time dolphins spent in the study area (X^2 = 6.786, df = 0.893, p = 0.005; Table 3.3; Table 3.4; Figure 3.5b), but only explained 9.0% of deviance. This suggests that additional, as yet unidentified, covariates could further explain the response data.

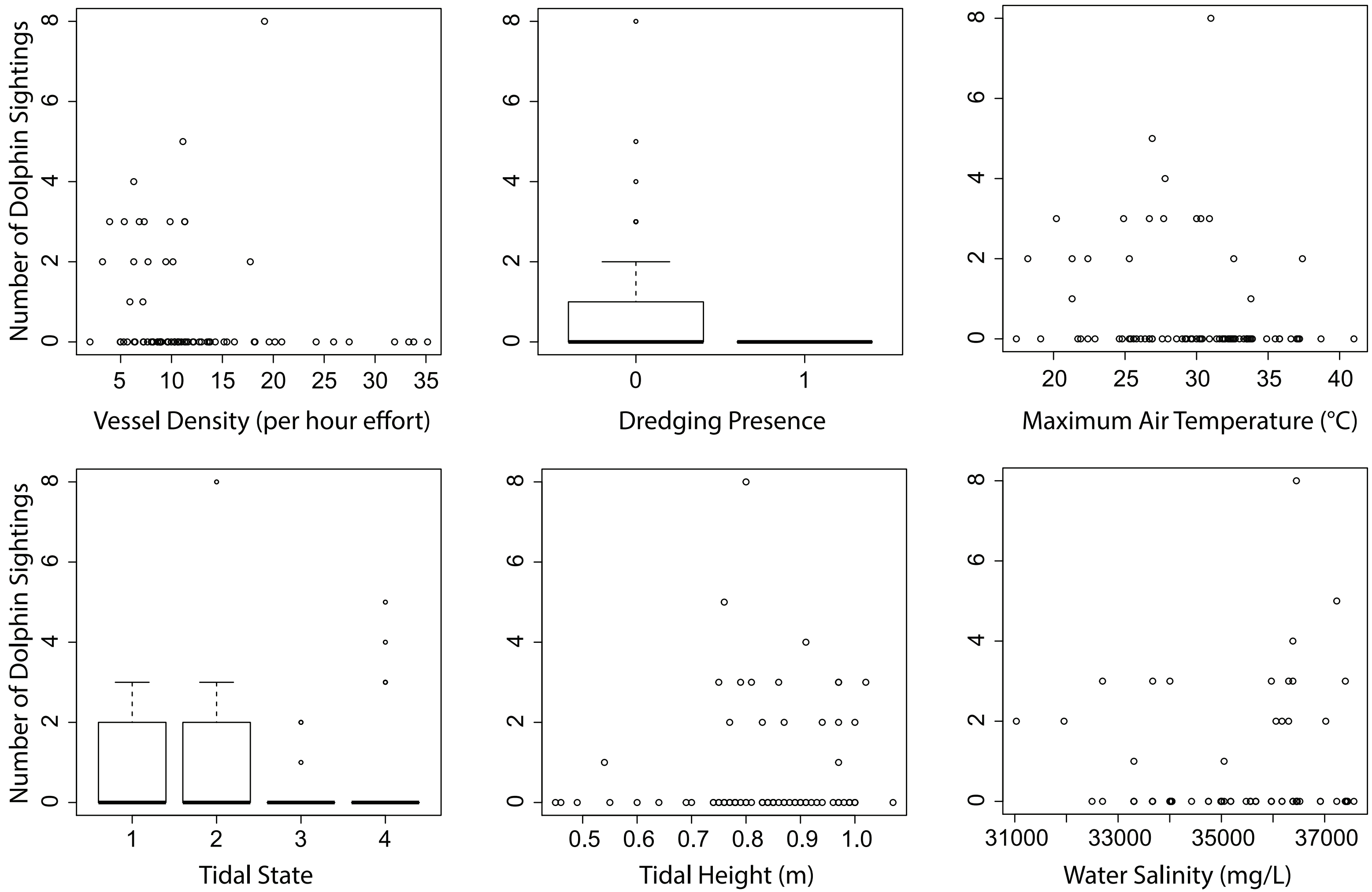

Figure 3.3: Number of dolphin sightings in Perth Waters in association with potential explanatory variables. It is worth noting that the maximum of eight dolphins sighted in one survey (which skews some perceived patterns, so may initially be thought an outlier) is a true sighting and not a re-sighting of the same animals. Two groups were sighted during this survey: the first comprised four adults and one calf, while the second comprised three juvenile dolphins.

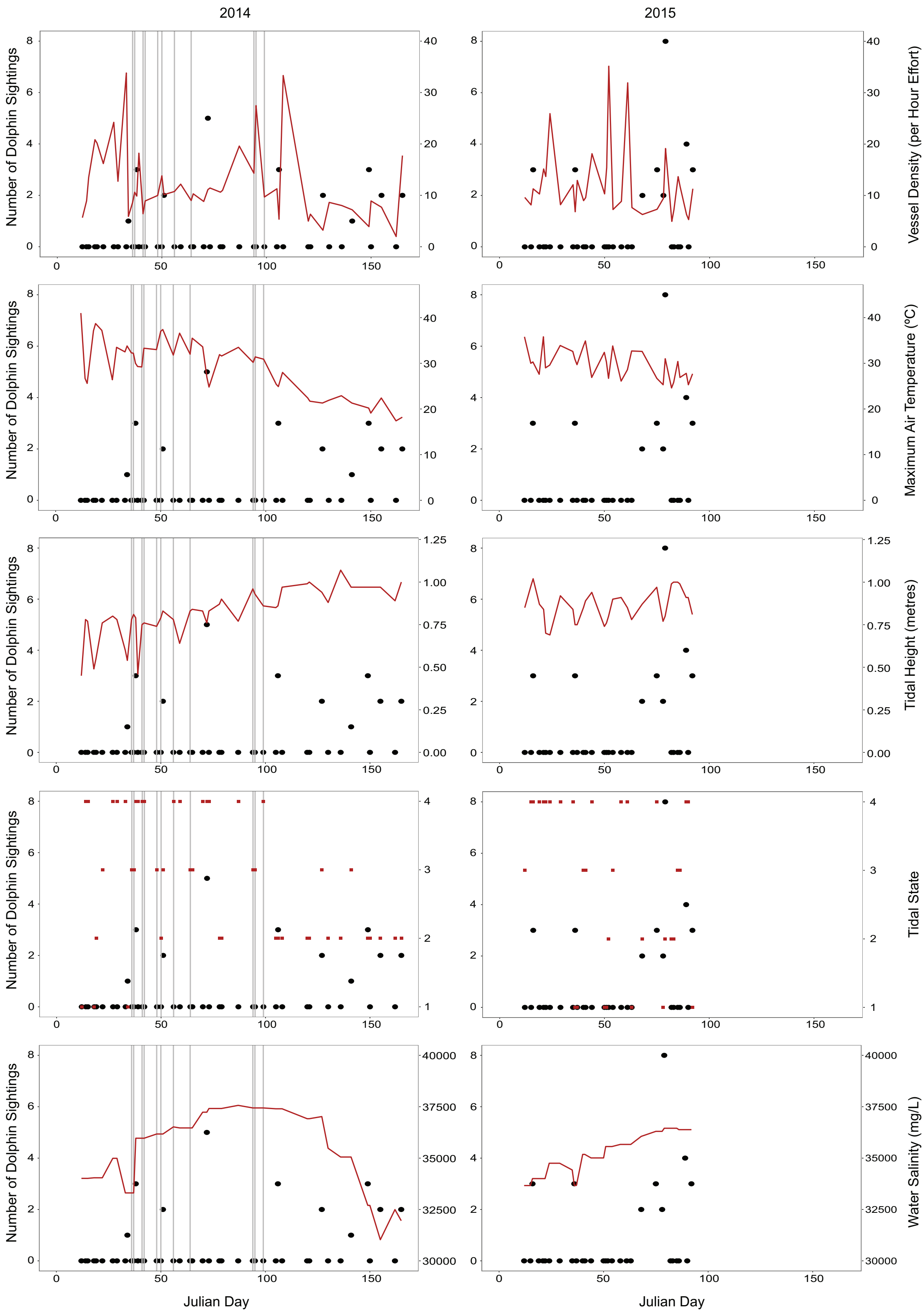

Figure 3.4: Number of dolphin sightings in Perth Waters in association with Julian Day and potential explanatory variables. Points represent number of dolphin sightings, red lines/points represent variation in explanatory variable, and grey vertical bars represent days when dredging was present.

Table 3.3: Model selection was conducted based on the Akaike's Information Criterion corrected for small sample sizes (AICc). Models with ΔAICc were compared using Akaike weights (wAICc). In cases where the wAICc scores were identical for multiple models, the most parsimonious model was selected. The final model selected for each dataset is indicated by *. Explanatory variables: Vessel Density (VD), Maximum Air Temperature (AT), Tidal State (TS), Tidal Height (TH), and Water Salinity (WS)

Model	Explanatory Variables Considered	AICc	R2	% Deviance Explained	wAICc
Number of dolphin sightings					
Mod 1	VD, AT, TS, TH	323.7	0.214	35.4	0.136
Mod 2	VD, AT, TS	323.7	0.214	35.4	0.136
Mod 3	AT, TS	323.0	0.201	34.1	0.190
Mod 4	AT	322.8	0.160	27.2	0.204*
Mod 5	VD, AT, TS, WS	323.7	0.214	35.4	0.136
Mod 6	AT, TH	322.9	0.188	29.0	0.199
Duration of time dolphins present					
Mod 1	VD, AT, TH, WS	622.7	0.162	8.98	0.125
Mod 2	AT, TH, WS	622.7	0.162	8.98	0.125
Mod 3	VD, AT, TH	622.7	0.162	8.98	0.125
Mod 4	VD, AT, WS	622.7	0.162	8.98	0.125
Mod 5	AT, WS	622.7	0.162	8.98	0.125
Mod 6	VD, AT	622.7	0.162	8.98	0.125
Mod 7	AT, TH	622.7	0.162	8.98	0.125
Mod 8	AT	622.7	0.162	8.98	0.125*

Table 3.4: Results from negative binomial GAMs with log-link functions investigating the number of dolphin sightings and duration of time spent by dolphins within Fremantle Inner Harbour. Significance level: ≤0.001 ***; ≤0.01 **; ≤0.05 *

Number of dolphin sightings					
	Estimate	**SE**	**z value**	**p value**	
Intercept	-3.32943	0.08779	-37.92	<2e-16	***
		χ^2	**df**	**p value**	
Temperature		17.52	2.61	0.000111	***
Duration of time dolphins present					
	Estimate	**SE**	**z value**	**p value**	
Intercept	-0.8199	0.1511	-5.427	<5.75e-08	***
		χ^2	**df**	**p value**	
Temperature		6.786	0.8926	0.00527	**

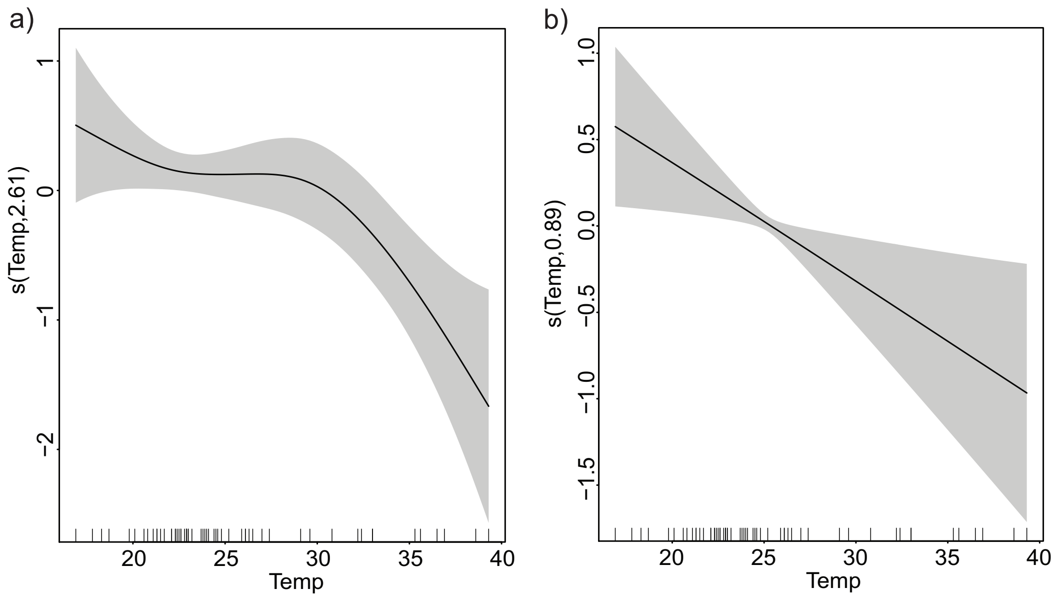

Figure 3.5: Results of the negative binomial GAMs for the Fremantle Inner Harbour dataset, showing (a) number of dolphin sightings in association with maximum air temperature, and (b) duration of time dolphins were present in association with maximum air temperature.

3.4 Discussion

In this study, dolphins were sighted much more often in the Fremantle Inner Harbour than at the Perth Waters site. At Perth Waters, there were fewer overall sightings of dolphins present when vessel densities were high. Additionally, of the relatively few sightings at Perth Waters, dolphins were never sighted on days when backhoe dredging was underway. However, within the Fremantle Inner Harbour, statistical analyses indicated that dolphins remained using the site despite high levels of vessel traffic. Instead, temperature showed a significant negative association with both the number of dolphin sightings and the duration of time dolphins spent in the study area. These results suggest that dolphins use sites differentially, and at the preferred site environmental factors influenced occupancy rather than vessel traffic. Although it should be noted that the surveys in each area were conducted at different times of day (Perth Waters in the afternoon, Fremantle Inner Harbour in the morning) due to glare.

3.4.1 Vessel Traffic

At Perth Waters, number of dolphin sightings in the afternoon appeared more frequent when vessel density was low. However, at the Fremantle Inner Harbour during the morning, dolphin occupancy displayed no observable change relative to vessel density. Despite reaching a maximum of 34 vessels per hour effort, dolphins continued to be present in almost all surveys and showed no response in either the number of dolphin sightings or the duration of time spent by dolphins in this area.

Both Perth Waters and Fremantle Inner Harbour experienced relatively high levels of vessel traffic throughout the study period. A variety of vessel types were observed within the Swan River; however, the majority of vessels at both sites were small recreational vessels, indicating high use of these areas by recreational boaters. Boats at both locations typically spent less than 15 min in the site, suggesting that the majority of vessel traffic is merely transiting through these areas. Peaks in vessel traffic were observed at both sites, occurring in the early morning and late evening. This corresponds with acoustic studies in parts of the Swan River, which have observed daily peaks in the presence of vessel noise hypothesised to represent “rush hour” as vessels head out shortly after sunrise and return home shortly before nightfall (Marley *et al.*, 2016a). Visual observations from the present study detailing both the time, duration and direction of vessel movements confirm this theory.

However, despite the low temporal presence of the majority of individual vessels, many vessels were recording travelling at high speeds. Two speed zones exist within Perth Waters. A large shallow area constitutes the majority of this site and is restricted to 8 knots (14.8 km/hr), whilst the remaining area is “non-speed restricted”. Similarly, a legal speed limit of 8 knots also applies within the Fremantle Inner Harbour. Ferries, small recreational vessels and jetskis typically had an average speed above this limit, although it appears that all vessel categories bar kayaks and SUPs had instances where the 8 knot level was broached. Additionally, despite a prohibition of fishing within the Fremantle Inner Harbour (for safety reasons), there were two days when dozens of recreational vessels were observed to stop and commence this activity within the site. This was due to the presence of large bait balls moving into the Inner Harbour from the ocean. Furthermore, throughout the study period a number of vessels were also observed to trail fishing lines behind them whilst transiting the Inner Harbour, although this was not quantified due to the difficulty of consistently observing fishing line from the hilltop station.

Despite these similarities in vessel activity, Perth Waters and the Fremantle Inner Harbour were used differentially by dolphins. The Fremantle Inner Harbour is known to be a foraging site for this dolphin community (Moiler, 2008), whereas Perth Waters appears to be primarily used as a transit area to reach different parts of the river system. It may be that the value of the Inner Harbour as a foraging site outweighs its cost as an area of high vessel traffic. In comparison, as a transit area, the presence of dolphins in Perth Waters would depend on the value of the habitat they are attempting to reach balanced with the cost of high vessel densities.

Sensitivity to vessel density may also reflect physical environmental features. Perth Waters is a large, shallow bay with an average depth of 1 m; in comparison, the Fremantle Inner Harbour is 13 m depth. Dolphins have been shown to avoid shallow areas as a predator avoidance response (Heithaus & Dill, 2002). This is hypothesised to reflect the riskiness of shallow habitats, due to the reduced efficiency of echolocation in shallow waters (a result of clicks scattering off the surface and bottom) and existence of fewer potential escape routes in shallow water compared to deeper habitats (Heithaus & Dill, 2002). Although no predation of dolphins by sharks has been observed within the Swan-Canning Rivers, high vessel traffic has been seen to invoke predator-avoidance responses in bottlenose dolphins from other populations (Frid & Dill, 2002; Lusseau, 2003b, 2006; Lusseau & Higham, 2004). If this occurs in the Swan-Canning dolphin community, then the Fremantle Inner Harbour would offer superior detectability and avoidance strategies compared to Perth Waters, facilitating use of the former despite high vessel densities.

Furthermore, the majority of vessel traffic in the Fremantle Inner Harbour typically transits through the centre channel. If dolphins forage primarily outside of this channel, they may avoid the more detrimental aspects of vessel traffic (e.g. risk of collision, intense underwater noise, disturbance of prey species). Consistent levels of vessel traffic may even alter the distribution of prey species within the Inner Harbour, forcing them to utilise refuges around the harbour periphery. If this is the case, there may be relatively little overlap in fine-scale spatial use of the Inner Harbour between dolphins and the majority of vessel traffic. However, as this site is also occasionally used by dolphins from other communities occuring in Perth coastal waters, a higher level of dolphin presence at this site may reflect its use by animals from multiple communities.

3.4.2 Temperature and Seasonality

Previous studies have found possible seasonality in the use of the Fremantle Inner Harbour, in that dolphins may occupy this area more often or for longer periods than other sites within the river system (Moiler, 2008). A study investigating spatial and temporal patterns of dolphin habitat-use in the Swan River found the highest abundance of dolphins occurred in the Fremantle Port, with greater numbers of dolphins observed in the austral autumn (Moiler, 2008). A similar pattern was indicated in a later study, but was confounded by the presence of pile-driving (Paiva *et al.*, 2015). It was suggested that this pattern was influenced by seasonal variation and abundance/migration of prey species, induced by seasonal water temperature changes (Moiler, 2008). The present study also found temperature to be a significant explanatory variable, negatively affecting both the number of dolphin sightings and the duration of time dolphins spent within the Fremantle Inner Harbour.

If the Fremantle Inner Harbour is subject to seasonal use by dolphins in response to seasonal availability of prey species (potentially driven by seasonal water temperature changes), the limited temporal availability of food in this area could increase the importance of this location as a foraging site. Bait balls were observed during this study, lending some additional support to theories relating to prey availability within the Inner Harbour. This may also contribute to explaining why dolphin occupancy does not appear to change in response to vessel density at this site. Dolphins may tolerate high levels of vessel traffic in order to maximise intake of seasonal prey present within the Fremantle Inner Harbour. Although no prey data were available for this study, previous research elsewhere has shown dolphin hotspots to be linked to foraging (Hastie *et al.*, 2004), and detailed foraging-related studies could be worthwhile at this site in the future. However, given the relatively low deviance explained by the models, there may be additional, as yet unconsidered covariates which could further explain dolphin occupancy within the Fremantle Inner Harbour.

There could have been patterns in dolphin occupancy associated with temperature and water salinity at the Perth Waters site. However, it was not possible to fully interpret any relationships due to limited sample size. Dolphin groups were generally seen travelling through this area, with foraging presumably occurring elsewhere; no bait balls or indicators of prey availability were observed. If Perth Waters has low significance as a foraging site, this may concur with the above theory that it is worth staying in busy areas if prey availability is high, explaining why dolphin sightings here were clustered around surveys of low vessel density.

3.4.3 Dredging

No dolphins were ever sighted during a survey in which dredging was also present. However, confident interpretation of the potential effects of dredging cannot be made as there was a relatively small number of days of observed dredging (15% of all Perth Waters surveys) compared with days with no dredging. Additionally, there was a relatively low overall sighting rate of dolphins at this site regardless of whether dredging was occurring or not. It was not possible to extend monitoring sufficiently after cessation of dredging activities, due to logistical constraints.

The most likely impact on cetaceans elicited by dredging is linked to underwater noise. Dredging generally produces continuous, broadband sound with main energy below 1 kHz. However, noise levels can vary according to dredger type, operational stage, or environmental conditions. Backhoe dredging (as used here) is one of the quietest forms of marine dredging compared to cutter-suction dredgers or trailing suction hopper dredgers (Todd *et al.*, 2015). The available literature has few studies on the effects of dredging activities on cetacean species (see Todd *et al.*, 2015, for review). Only one other study has investigated the influence of dredging on bottlenose dolphin occupancy. Dolphins were displaced by dredging works in Aberdeen Harbour, an important foraging site (Pirotta *et al.*, 2013). Unfortunately, the authors did not indicate what type of dredging was used during their study, limiting the potential for comparisons. A study on the effects of a trailing suction hopper dredger found harbour porpoises (*Phocoena phocoena*) to exhibit short-term avoidance at ranges of 600 m (Diederichs *et al.*, 2010). However, the majority of other dredging studies appear to be inconclusive, with many observing the study species both in proximity to operating dredgers whilst also showing an overall decline in numbers and possible avoidance (e.g. bowhead whales, *Balaena mysticetus*; Richardson *et al.*, 1987, 1985, 1990). In many reports, it is also difficult to separate the effects of dredging and of vessel traffic, as these activities often occur concurrently (Anderwald *et al.*, 2013). In the present study, the need to quantify vessel traffic was imperative, as vessels were present in all surveys; however, this also provided the opportunity to separate the potential effects of this activity from those of dredging.

3.4.4 Conclusion

It appears that although the Swan-Canning dolphin community is frequently exposed to vessel traffic, the dolphins may not have become fully habituated to this activity. Dolphins may tolerate relatively high levels of vessel traffic in some areas, but not in others. Reasons for this most likely reflect differences in the quality of those areas and their importance as sites for vital life processes. Seasonal presence of prey species at specific sites may account for tolerance of anthropogenic activities in order to maximise limited prey availability.

Therefore, beyond considering the occupancy of dolphins with regard to vessel traffic, future studies could consider the effect of this anthropogenic activity at a finer resolution by examining what spatial overlaps exist; the role that vessel type, speed and behaviour may play in dolphin behavioural responses; and how dolphin behavioural budgets may be affected by changes in vessel density. It may be that dolphins have specific strategies for coping with such busy environments. Studies investigating the availability of dolphin prey species within areas of the Swan-Canning Rivers would also contribute to our understanding of dolphin spatial use within this system. It would also be beneficial to consider surveying these areas across full days (morning and afternoon) to address data gaps in the present study.

In conclusion, to determine whether vessel traffic invokes a more subtle behavioural response, it is recommended that future work focusses on fine-scale changes to dolphin movement patterns, activity states, individual behaviours, and vocalisation patterns. These results provide managers and stakeholders with information on dolphin occupancy and vessel traffic, and also highlight the importance of considering multiple response variables and habitat characteristics.

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Chapter 4

Spatial and temporal variation in the acoustic habitat of bottlenose dolphins (*Tursiops aduncus*) within a highly urbanised estuary

There is growing awareness of underwater noise in a variety of marine habitats, and how such noise may adversely affect marine species. This is of particular concern for acoustically-specialised species, such as dolphins. In order to ascertain the potential impacts of anthropogenic noise on these animals, baseline information is required for defining the soundscape of dolphin habitats. The Swan-Canning River system in Western Australia flows through the city of Perth, and experiences numerous anthropogenic activities. Despite this, the river system is home to a community of Indo-Pacific bottlenose dolphins (*Tursiops aduncus*). To provide a baseline soundscape description of dolphin habitat, over 11,600 h of acoustic data were analysed from five sites within the Swan River (from Fremantle Inner Harbour to 20 km upstream) across an eight-year period. Multiple sound sources were recorded at these sites, including: snapping shrimp; fishes; dolphins; pile-driving; bridge and road traffic; and vessel traffic. The two most prevalent sound sources, vessel traffic and snapping shrimp, likely have very different effects on dolphin communication with the former expected to be more disruptive. Sites were characteristic in their prominent sound sources, showing clear among-site variations, with some sites being 'noisier' than others based on broadband noise levels, octave-band noise levels, and power spectrum density percentiles. Perth Waters had the highest broadband noise (10 Hz – 11 kHz; mean 113 dB re 1 µPa), whilst Heirisson Island was quietest (mean 105 dB re 1 µPa). Generalised estimating equations identified variation in broadband noise levels within sites at a fine temporal scale, although sites differed in the significance of temporal variables. At Mosman Bay, a long-term dataset spanning eight years highlighted inter-annual variation in broadband noise levels, but no overall upwards or downwards trend over time. Acoustic habitats of the Swan River displayed significant variations at a variety of temporal and spatial scales, throughout areas frequented by the local dolphin community. Such variations should be quantified when assessing dolphin acoustic habitat as they may provide significant clues to dolphin behaviour.

4.1 Introduction

Marine habitats are characterised by a unique combination of topographic structures, environmental conditions, and species compositions. These features contribute, either directly or indirectly, to the acoustic conditions of a particular environment as abiotic (e.g. wind, waves, precipitation, ice break-up, earthquakes) and biotic (e.g. crustaceans, fishes, marine mammals) sound sources. Habitats with human activities also have the added contribution of anthropogenic sound sources. As a result, the 'soundscape' of any particular habitat varies in space and time depending on the prevalence of the sound sources within it (Krause, 2008; Pijanowski *et al.*, 2011).

The distribution and occurrence of marine species is often related to physical features, such as depth, seafloor slope, or proximity to shore (Cañadas *et al.*, 2002; Elwen & Best, 2004; Elwen *et al.*, 2006; Forney, 2000). In other cases, species occurrence may be linked with more transient environmental variables, such as sea surface temperature, salinity, or primary productivity (Azzellino *et al.*, 2008; Forney, 2000; Mannocci *et al.*, 2014). Given the acute attenuation of light in water, many marine organisms rely on acoustics to investigate their environment (Nybakken & Bertness, 2005). As a result, introduced anthropogenic underwater noise has been increasingly recognised to act as a chronic, environmental stressor, which can affect both individual animals and ecosystem linkages (Boyd *et al.*, 2011; Erbe, 2010; Erbe *et al.*, 2014; Finneran, 2015; Hatch & Fristrup, 2009; Weilgart, 2007; Williams *et al.*, 2015a; Wright *et al.*, 2011). Thus, for acoustically-specialised fauna, species occurrence may also be influenced by the soundscape of a marine habitat.

Of the acoustically-specialised marine fauna, cetaceans show some of the most elaborate and extreme adaptations for auditory perception and sound production underwater (Tyack & Miller, 2002). Using sound allows these animals to overcome the challenges of limited vision to fulfill a series of vital processes, such as orientation, communication, and foraging. However, these auditory adaptations also make cetaceans especially susceptible to the impacts of anthropogenic noise. The potential effects of underwater noise on cetaceans are widely recognised, ranging from minimal short-term effects to severe long-term effects (Nowacek *et al.*, 2007; Richardson *et al.*, 1995; Southall *et al.*, 2007; Tyack, 2008). At low levels often corresponding with long ranges from the source, anthropogenic noise may be merely detectable by marine mammals. At higher levels, noise may interfere with animal communication and acoustic signal detection, or cause displacement, behavioural disturbance or induce stress. In extreme cases, acoustic exposure might even lead to hearing loss or physical injury (Erbe, 2012).

Coastal areas are among those marine habitats most at risk from human activities (McIntyre, 1999; Moore, 1999). As a result, coastal species – such as bottlenose dolphins (*Tursiops* sp.) – are among those marine fauna most vulnerable to anthropogenic threats (DeMaster *et al.*, 2001; Thompson *et al.*, 2000). In coastal habitats, the most ubiquitous source of anthropogenic underwater noise is vessel traffic, which has resulted in numerous dolphin behavioural response studies. Results have found evidence of physical and acoustical changes to dolphin behaviour, such as alterations to inter-breath intervals, inter-animal distances, movement patterns, activity states, whistle duration or rates, and frequency shifts in whistle characteristics, among others (Bejder *et al.*, 2006; Buckstaff, 2004; Weilgart, 2007; Ellison *et al.*, 2012; Hastie *et al.*, 2003; Heiler *et al.*, 2016; Lusseau, 2006; New *et al.*, 2013; Nowacek *et al.*, 2007; Pirotta *et al.*, 2015; Steckenreuter *et al.*, 2012). Significant changes to foraging success or energy demands (from altered movement, behaviour or vocal production patterns) could also affect individual health, reproductive rates, or even long-term population survival. This is of particular concern for small dolphin communities, which tend to exhibit naturally low reproductive rates (Ross, 2006; Wilson *et al.*, 1999). Therefore, knowledge regarding the response of dolphins to vessel traffic is of relevance to managers regulating activities in coastal areas.

However, in order to ascertain the potential impacts of anthropogenic noise on cetacean distribution, population dynamics, and behaviour, there is first a requirement for baseline information defining the soundscape of cetacean habitats. Such baseline studies involve describing the habitat in terms of prominent sound sources, levels of acoustic energy in particular frequency bands, and patterns of ambient and anthropogenic noise (e.g. Erbe *et al.*, 2014; Guan *et al.*, 2015; Parks *et al.*, 2009; Rice *et al.*, 2014). Once identified, the acoustic characteristics of critical cetacean habitats can be further examined to determine the potential impact of man-made noise. Such studies can go on to inform management decisions regarding human-use of these areas, and determine whether conservation efforts are best directed towards “fixing” noisy habitats or preserving the remaining quiet areas (Erbe *et al.*, 2014; Williams *et al.*, 2014b, 2015a). Given that the underwater soundscape contains sounds driven by weather conditions, environmental variables, and the presence of both marine fauna and human activities, it follows that an acoustic habitat will not be static in its composition. Consequently, whilst generalisations may be made about the acoustic characteristics of some underwater environments, many marine habitats will also display spatial and temporal variability in their acoustic components (Erbe *et al.*, 2015b; Guan *et al.*, 2015; Marley *et al.*, 2016a; McWilliam & Hawkins, 2013; Parks *et al.*, 2009; Radford *et al.*, 2010; Rice *et al.*, 2014). Thus, to understand the role acoustic characteristics may play in driving the habitat use of cetaceans, there is a need to quantify the marine soundscape over large areas and across long periods of time.

The Swan River is an estuarine river system flowing through the Western Australian state capital of Perth. It is joined in its middle reaches by the Canning River, and together these rivers form an extensive system with a combined shoreline of approximately 300 km length. The Swan River estuary has a mean depth of 6 m and covers a surface area of approximately 31 km^2 (Robson *et al.*, 2008). The system is composed of three distinct regions: an entrance channel at the river mouth; several shallow basins in the middle reaches of the river; and the riverine upper reaches. Despite transiting through a major metropolitan area (> 1.4 million people), the Swan-Canning River is home to a small resident community of approximately 18 adult bottlenose dolphins (*T. aduncus*), plus juveniles and calves (Chabanne *et al.*, 2012; Swan River Trust, 2015). The dolphins show daily use of this river system and high site fidelity (Chabanne *et al.*, 2012). Research investigating the spatial and temporal patterns of dolphin occurrence within the rivers has shown that animals are distributed heterogeneously, with certain areas experiencing higher numbers of dolphin sightings than others (Beidatsch, 2012; Marley *et al.*, 2016b; Moiler, 2008). In particular, the Fremantle Inner Harbour has been identified as a seasonal 'hotspot' strongly linked with dolphin foraging behaviour (Moiler, 2008). Other hotspots of dolphin sightings include Freshwater Bay, Melville Waters, Matilda Bay and Canning Bridge, located within the shallow basins region (Beidatsch, 2012; Moiler, 2008). Yet the dolphins are also sighted throughout the rest of the river system, with their range extending to the upper reaches of both the Swan and Canning Rivers (Beidatsch, 2012; Swan River Trust, 2015).

Like many urban estuaries, this river system experiences a range of environmental stressors. For example, in the past the Swan River has suffered from toxic algal blooms, nutrient enrichment, anoxia, pollution, introduced and invasive species, coastal flooding, and habitat modification (Adolf *et al.*, 2015; Eliot, 2012; Gosbell & Clemens, 2006; Hourston *et al.*, 2015; Morgan *et al.*, 2004; Rate *et al.*, 2000; Robson & Hamilton, 2003; Smale & Childs, 2012). These stressors were highlighted by the deaths of six dolphins within the river in 2009, which was hypothesised to be the result of a lowered immune system from multiple pressures, such as contaminant exposure and human activities (Holyoake *et al.*, 2010). Parts of the Swan River have been shown to receive high levels of human activities. Visual monitoring at Perth Waters and the Fremantle Inner Harbour has revealed high levels of vessel traffic engaged in a range of activities (Marley *et al.*, 2016b). Acoustic monitoring at The Narrows – a site mid-way along the Swan River in the Perth Waters area – revealed that vessel noise was present in approximately 52% of hourly underwater recordings across a six-week period (Marley *et al.*, 2016a). Similarly, the Fremantle Inner Harbour has been found to contain various sources of anthropogenic noise, including: vessel traffic, train and vehicle traffic passing over a nearby bridge; machinery noise; and wharf construction (Salgado Kent *et al.*, 2012). As underwater noise levels and characteristics increasingly become considered as an indicator of habitat quality, there is a need to characterise the soundscape of the Swan-Canning river system with regard to its bottlenose dolphin population and anthropogenic activities. While past studies have highlighted the variation in soundscape at specific locations (Marley *et al.*, 2016a; Salgado Kent *et al.*, 2012), they have not described how these change in time and over a broader spatial range.

This study aims to examine spatial and temporal variability in the soundscape of the Swan River. Acoustic data collected from five locations along the river across eight years were used to: (1) identify and compare prominent sound sources defining each site, (2) compare the spatial variability in soundscapes at four locations in the Swan River, (3) identify significant temporal scales (hourly, daily, monthly) of variability within the four sites, (4) describe long-term variability in the soundscape at peak vessel traffic periods (using one exemplary site), and (5) relate prominent sound sources and their spatio-temporal variability to dolphin communication. In particular, the prevalence of vessel noise within the river system was used to determine whether some sites are 'noisier' than others and thus have a potential to affect how dolphins use these habitats.

4.2 Methods

The Swan-Canning estuary is located along the Western Australian coast. Five locations within the estuary over a distance of 20 km were selected for collecting acoustic data (Figure 4.1). From west to east, these locations were: Fremantle Inner Harbour (in the lower reaches of the river); Mosman Bay (middle reaches); Matilda Bay (middle reaches); Perth Waters (middle reaches); and Heirisson Island (upper reaches). These five study sites comprise a mixture of dolphin sighting hotspots and areas of human activity along the lower, middle, and upper reaches of the Swan River.

The Fremantle Inner Harbour is part of the state's biggest general cargo port and Australia's fourth largest container port (http://www.fremantleport.com.au), experiencing high levels of vessel traffic from commercial and recreational sources (Marley *et al.*, 2016b). However, it has also been identified as a dolphin sighting hotspot, with animals reportedly spending several hours foraging within the Inner Harbour, regardless of vessel densities (Marley *et al.*, 2016b; Moiler, 2008).

Mosman Bay is up-river of the narrow entrance channel at the river mouth. A long tidal sandbar stretches across from the opposite bank, funnelling water flow, vessel traffic, and animals as they move down from the wide, shallow basins of the middle river reaches into the narrow, cliff-lined lower reaches. Three water ski areas line the periphery of this area with several boat pens located at the northern side, and the main Swan River ferry route passing through the middle of the bay. Dolphins transit through this site, with opportunistic foraging occurring around the boat pens. Mosman Bay has been identified as a spawning site for mulloway (*Argyrosomus japonicus;* Farmer *et al.*, 2005). Consequently, this is the site of a long-term fish acoustic monitoring study for the species, which exhibits characteristic spawning-related vocalisations of high source level (Parsons *et al.*, 2013b).

Matilda Bay is a dolphin sighting hotspot, which is primarily used for foraging (Moiler, 2008). This small bay has a boat ramp and series of boat pens located on the north-eastern shore, and is adjacent to the main ferry route utilising the Swan River. The southern river shore opposite Matilda Bay is used as a personal watercraft freestyle area.

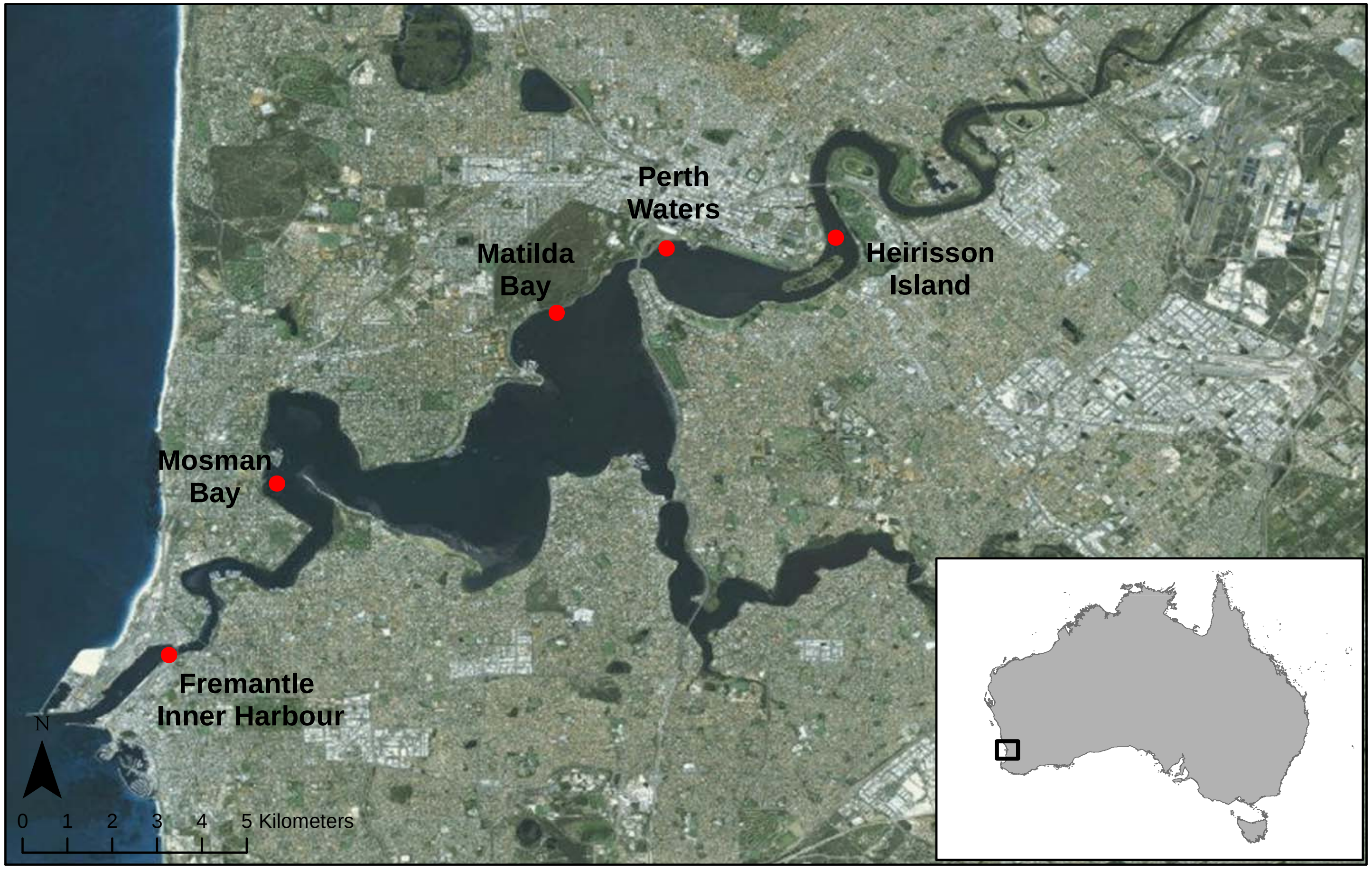


Figure 4.1: Map of the Swan River with the five acoustic monitoring sites indicated.

Perth Waters comprises a wide (ca. 1.5 km), shallow basin within the middle reaches of the Swan River. It has not been identified as a dolphin hotspot; however, animals travelling between the middle and upper reaches of the Swan River must transit through this area (Marley *et al.*, 2016b). This site contains the Barrack Street ferry terminal, and is also used by recreational boaters and crab fishermen. Additionally, at the time of this study, Elizabeth Quay (http://www.mra.wa.gov.au/projects-and-places/elizabeth-quay) was under development, involving construction and dredging activities.

Finally, Heirisson Island marks the beginning of the riverine upper reaches of the Swan River, characterised by a narrowing of the river as it winds through the Perth Hills. Although not a dolphin hotspot, animals are regularly sighted in the upper reaches of the Swan River. Heirisson Island experiences vessel traffic from both recreational boats and tourism ferries, and is also adjacent to a seasonally-used powerboat racecourse.

4.2.1 Data Collection

A total of 13 underwater acoustic recorders were used to collect soundscape data. Underwater acoustic recorders were one of two types. Low-frequency underwater sound recorders (McCauley *et al.*, 2017) were custom-built by Curtin University's Centre for Marine Science and Technology (CMST) and equipped with external hydrophones, entering the housing via a bulkhead connector to an impedance matching pre-amplifier with 20 dB gain. Digitised recordings (16 bit) were written on a flash card and, when full, to a hard disk in the logger. High-frequency recorders were assembled at CMST, using the same pre-amplifier as in the low-frequency recorders, and a programmable 16-bit data acquisition board made by Wildlife Acoustics Inc. Digitised recordings were written to four 128 GB SD cards. Both recorder types were calibrated by applying white noise of known power spectral density. High-pass filters (8 Hz cut-off) were employed to filter out high levels of low-frequency noise, enhancing the dynamic range of the recorder at the frequencies of interest.

Recorders were deployed on the riverbed for several weeks (Table 4.1). This allowed for temporal variations in the acoustic environment to be documented over hours, days and weeks, thus giving a representative insight into the acoustic conditions of each deployment over the temporal scales at which soundscape variations are likely to occur (Parsons *et al.*, 2016a). In some cases, multiple deployments within the same site were achievable, allowing longer-term measurements of underwater noise (Figure 4.1; Table 4.1). The specific recording dates, locations, settings and duty cycles used for each deployment are summarised in Table 4.1, along with hydrophone sensitivities.

Table 4.1: Summary of acoustic data collection within the Swan River

ID	Location	Start Date	End Date	Days Total	Sampling Frequency (kHz)	Total Gain (dB)	Duty Cycle	Hydrophone Sensitivity (dB)
MB	Matilda Bay	27/11/2013	19/01/2014	53	22	40	10 of 15 min	-194.0
PW1	Perth Waters	11/01/2014	05/03/2014	53	22	40	10 of 15 min	-197.7
PW2	Perth Waters	05/06/2014	28/07/2014	53	22	40	10 of 15 min	-197.7
HI	Heirisson Island	13/10/2014	27/10/2014	14	96	44	40 of 43 min	-202.8
PW3	Perth Waters	17/02/2015	09/04/2015	51	96	44	10 of 15 min	-202.8
FIH	Fremantle Inner Harbour	30/04/2015	14/06/2015	45	96	44	10 of 15 min	-202.8
Mos07	Mosman Bay	01/01/2007	01/02/2007	31	4	40	5 of 15 min	-197.7
Mos09	Mosman Bay	01/01/2009	01/02/2009	31	6	40	5 of 15 min	-196.8
Mos10	Mosman Bay	01/01/2010	01/02/2010	31	6	40	5 of 15 min	-196.8
Mos11	Mosman Bay	01/01/2011	01/02/2011	31	5	40	5 of 15 min	-196.0
Mos12	Mosman Bay	01/01/2012	01/02/2012	31	6	40	5 of 15 min	-197.0
Mos13	Mosman Bay	01/01/2013	01/02/2013	31	6	40	5 of 15 min	-197.5
Mos15	Mosman Bay	01/01/2015	01/02/2015	31	6	40	5 of 15 min	-197.7

4.2.2 Acoustic Analyses

Data were first reviewed in Matlab (Version R2013a, The MathWorks Inc.) using the toolbox CHORUS (Gavrilov & Parsons, 2014). This allowed prominent sound sources for each deployment to be identified. Protocols for further processing of acoustic data broadly followed the methodology of Marley *et al.* (2016a) and were applied to data collected from each deployment. Recordings were analysed in Matlab, and were first Fourier transformed in 1 s windows, producing a time series of power spectral density (PSD). Cable noise, where it existed, was identified as brief broadband spikes and the corresponding 1 s windows were discarded from further analysis. Due to the range of sampling frequencies employed, data were down-sampled to correspond with the lowest sampling frequency of 22 kHz. The exception to this were recorders used in Mosman Bay, which had an original sampling frequency of 4 – 6 kHz (here, down-sampled to 4 kHz), as these were part of a separate study targeting fish calls. Hence, these data were not used in the spatial comparison, and instead were utilised for a long-term temporal overview of soundscape changes in the Swan River.

For all datasets, the PSD was averaged into 10 s windows and the first 10 s PSD average of each minute was plotted in a weekly spectrogram (Mon – Sun). These spectrograms allowed initial visual inspection and comparison of the data. The first 10 s PSD average of each minute was used to compute PSD percentile plots. To reduce computational effort, the PSD was further averaged into a series of adjacent frequency bands, each 10 Hz wide. The n^{th} percentile of each plot gives the level that was exceeded n% of the time, with the 50^{th} percentile representing the median. Thus, these plots illustrate the statistical variability of underwater sound for each deployment across the study period, allowing visual comparison of acoustic power versus frequency, both within and between sites.

The 1 Hz PSDs of underwater sound were converted to linear units, averaged over 10 min of every acoustic recording and integrated into adjacent octave band levels (OBLs). This resulted in time series of noise levels in each octave band, with one sample corresponding with each acoustic recording, allowing comparison of the noise levels in each OBL across both sites and years. Dolphin whistles in the Fremantle Inner Harbour have been reported to range between 1.1 and 18.4 kHz, with a minimum frequency of 1.1 to 9.0 kHz (Ward *et al.*, 2016). Given this frequency range, it is possible to consider which sound sources may overlap with dolphin communication frequencies and identify which river sites may pose concern given noise levels in their upper OBLs.

4.2.3 Spatial and Temporal Variation

For each recording, broadband noise levels (NL_BB) were calculated as the root-mean-square sound pressure level over the duration of each file. These data were used to compare spatial and temporal variations in NL_BB, both between and within sites. Spatial comparisons were made across all sites except for Mosman Bay, as this dataset was down-sampled at a lower frequency that the other sites. Spatial variation was examined by conducting a Kruskal-Wallis test on the Fremantle, Matilda Bay, Perth Waters, and Heirisson Island datasets. Wilcoxon-Mann-Whitney Tests identified the source of any differences, and the power of these tests was assessed through post-hoc tests in G*Power (Vr 3.1.9.2).

To examine short-term temporal variation within sites, Generalised Estimating Equations (GEEs) were applied to the Fremantle, Matilda Bay, Perth Waters, and Heirisson Island datasets. For the purposes of these analyses, data were down-sampled to select only one recording per hour. Temporal variation in NL_BB was examined for hour of day ("Hour"), day type (weekday or weekend; "DayType"), and month of the year ("Month"). GEEs were deemed suitable for these analyses as they account for temporal autocorrelation whilst identifying temporal variation, thus allowing the use of repeated measures data (Bailey *et al.*, 2013; Photopoulou *et al.*, 2011; Zuur *et al.*, 2009). Modelling followed the methods of Marley *et al.* (2016a), with DayType and Month included as factors. However, as time of day forms part of a cycle, the variable Hour (h) was converted to a cyclical covariate using sine and cosine vectors, termed H_s and H_c respectively (Bailey *et al.*, 2013; Zuur *et al.*, 2009):

$$H_s = \sin(\frac{2\pi \times h}{24})$$

$$H_c = \cos(\frac{2\pi \times h}{24})$$

This allowed hours at the start and end of the day to be considered close to each other (e.g. 23:00 hrs and 01:00 hrs). A similar approach has been undertaken by other studies to include circular variables as model terms (Bailey *et al.*, 2013, 2009, 2010; De Boer *et al.*, 2014; Griffin & Griffin, 2003; Marley *et al.*, 2016a; Pirotta *et al.*, 2013). This approach was not applied to Month due to datasets generally being limited to only a few months.

The GEE model used a gamma error distribution with a log-link function. Gamma distributions are appropriate for continuous response variables which have positive values (Zuur *et al.*, 2009). Variance Inflation Factors (VIFs; Zuur *et al.*, 2010) were calculated, but revealed no collinear variables in the model. However, a Runs Test indicated that there was an issue with correlation in the model residuals ($p < 0.001$); therefore, a blocking structure was selected to model this correlation.

GEEs account for temporal autocorrelation via within-cluster correlations to increase the estimation efficiency, thus allowing maximum use of sequential or repeated measures data (Bailey *et al.*, 2013; Zuur *et al.*, 2009). To select clusters for the model blocks (ID), the autocorrelation of the model residuals by ID was plotted to check for a decline in correlation over time. During each separate “Date” (a sequential value beginning on Day 1 of sampling and ending on the final day of sampling), the correlation of observations made hourly declined to approximately zero within a 24-h period. Thus, separate days were treated as independent, and so “Date” was selected to define clusters of data points within which residuals were allowed to be autocorrelated. Given that the data were serially correlated and that GEEs are robust in providing consistent estimates of mean parameters even when the correlation structure is mis-specified, an AR-1 correlation structure was selected as the most logical option for the model.

Selection of the best model was assessed via a quasi-likelihood criterion (QIC; Pan, 2001) and model fit was assessed by plotting observed versus fitted values and fitted values versus scaled Pearson’s residuals. Once the final model was selected, repeated Wald’s tests were used to assess the significance of each temporal variable, and partial residual plots of significant terms were created.

Long-term temporal variation of high vessel traffic periods was assessed for Mosman Bay. This site included seven years of data collected between 2006 and 2015. Although several months of data were recorded each year, only January was retained because it was consistently captured each year and also represents the austral summer, when high levels of anthropogenic activities were expected to occur. In January, daily mulloway choruses were recorded in the late evening. To explore sources associated with “rush hour” as opposed to peak mulloway chorusing, only acoustic data from the morning (06:00 – 12:00 hrs) were used (Marley *et al.*, 2016a,b). A Kruskal-Wallis test was applied to this multi-year dataset to identify variations between years; the source of differences were then identified by Wilcoxon-Mann-Whitney Tests. Statistical power was again assessed using G*Power (Vr 3.1.9.2).

All statistical analyses were conducted in R (R Core Team, 2015) with the aid of the *geepack* (Højsgaard *et al.*, 2006; Yan, 2002; Yan & Fine, 2004), *MESS* (Ekstrom, 2014), *MRSea* (Scott-Hayward *et al.*, 2014) and *stats* (R Core Team, 2015) packages.

4.3 Results

A total of over 11,600 h of acoustic data were collected during 14 deployments at five sites within the Swan River. Of these, approximately 6,450 h from seven deployments at four sites were analysed for spatial and short-term temporal comparisons, whilst 5,200 h from seven annual deployments at Mosman Bay were analysed to assess long-term temporal variation.

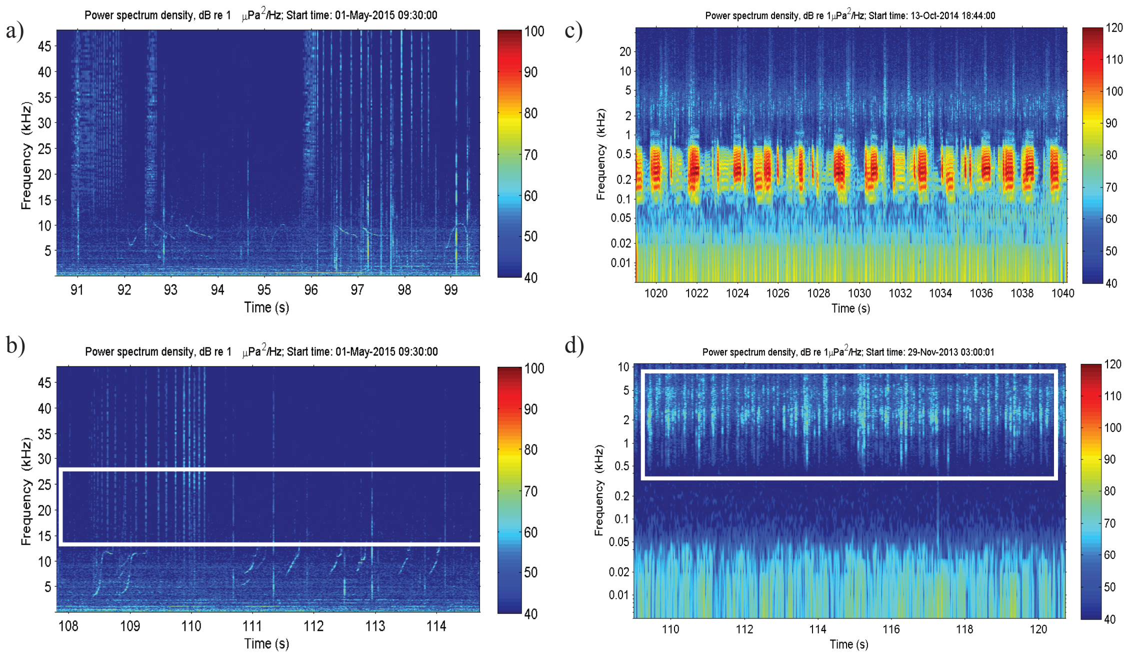


Figure 4.2: Biotic sound sources recorded within the Swan River included: (a and b) the clicks and whistles of Indo-Pacific bottlenose dolphins; (c) mulloway fish choruses; and (d) snapping shrimp.

4.3.1 Prominent Sound Sources

Prominent sounds recorded in this study came from biotic and anthropogenic sources. These included: snapping shrimp; fish choruses; dolphin clicks and whistles; impulse pile-driving; trains and/or vehicles passing over nearby bridges; and vessel traffic.

Dolphin sounds were most abundant in the Fremantle Inner Harbour, where both whistles and echolocation clicks were frequently recorded (Figure 4.2a and b). While sounds likely produced by fish occurred at all locations, fish choruses were only observed at the Heirisson Island site (Figure 4.2c), although they are known to occur in other areas of the river such as Blackwall Reach and Mosman Bay (Parsons *et al.*, 2013b). Snapping shrimp were observed in all locations to varying degrees (e.g. Figure 4.2d).

There were also a number of additional anthropogenic sounds. Pile-driving was heard at Heirisson Island, due to adjacent shore-based construction works (Figure 4.3a). The sound of pile-driving recorded in water consists of series of sharp pulses every few seconds (see Erbe, 2009, for pile driving recorded in equally shallow water). High-frequency 'blips' thought to originate from vessel echo-sounders were observed in Fremantle Inner Harbour (Figure 4.3b). In Matilda Bay, series of very low-frequency pulses were observed (Figure 4.3c). Similar pulses have been previously reported at the neighbouring Narrows Bridge site (Marley *et al.*, 2016a), where they were

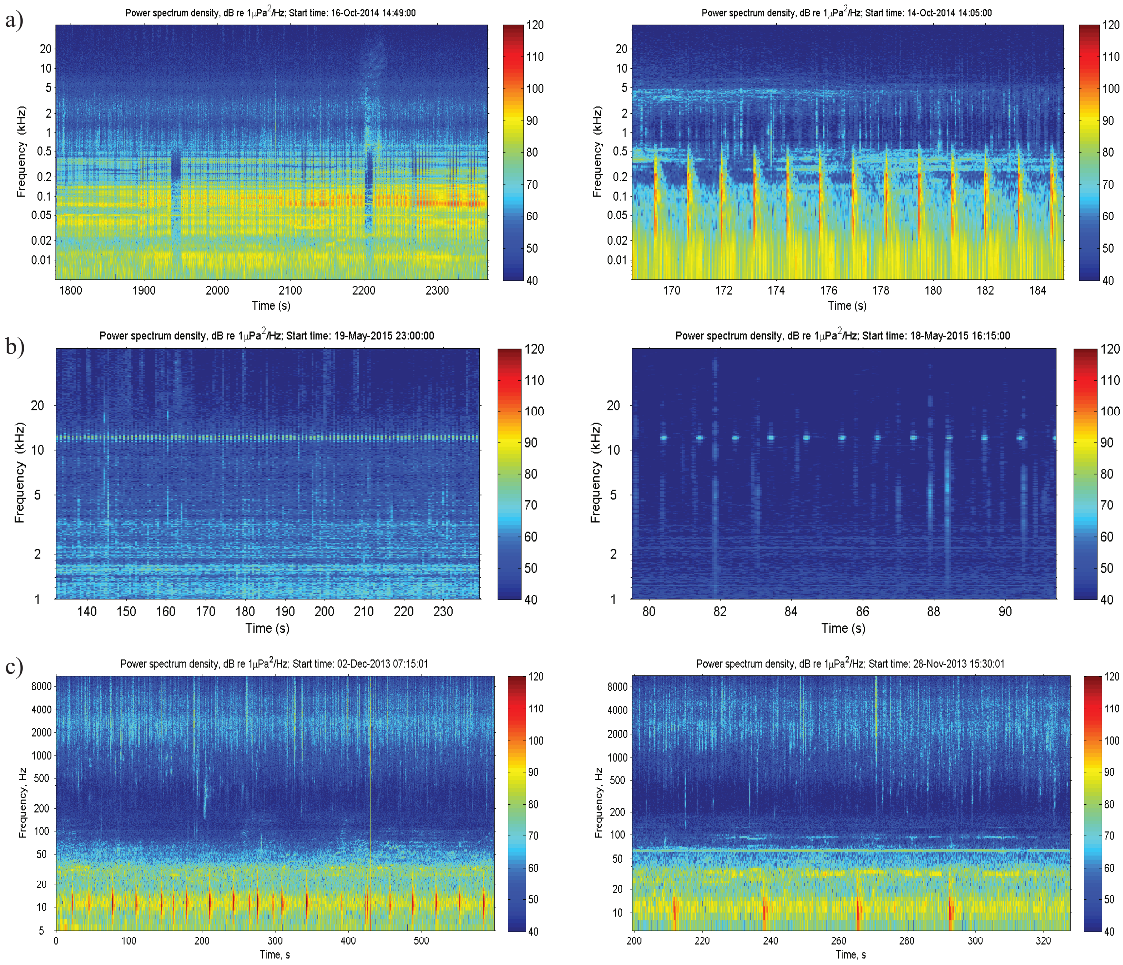


Figure 4.3: Anthropogenic sound sources within the Swan River included: (a) pile-driving; (b) vessel echosounders; and (c) and unknown series of low-frequency impulses thought to originate from vehicle traffic.

hypothesised to be the result of train or vehicle traffic crossing the bridge. The Matilda Bay deployment site was adjacent to a busy main road, which may be the source of this sound.

One of the most striking features was the variability in sounds produced by vessel traffic (Figure 4.4). In the Fremantle Inner Harbour, there was near-continuous background noise from transiting vessels and idling engines, in addition to sounds from near-passing vessels (Figure 4.4a). In other areas, vessel sounds included steady tones (Figure 4.4b and c), series of engine revs increasing with engine rotations per minute (Figure 4.4d; Erbe *et al.*, 2016), undulating tones with many harmonics from jet skis (Figure 4.4e; Erbe, 2013), and bands across the low and high frequencies (Figure 4.4b and f, respectively). Considering all the variations observed, vessel noise has the potential to range from 5 Hz to over 20 kHz. The highest frequency sounds were observed in the presence of small powerboats engaged in high-speed races near Heirisson Island (Figure 4.4f).

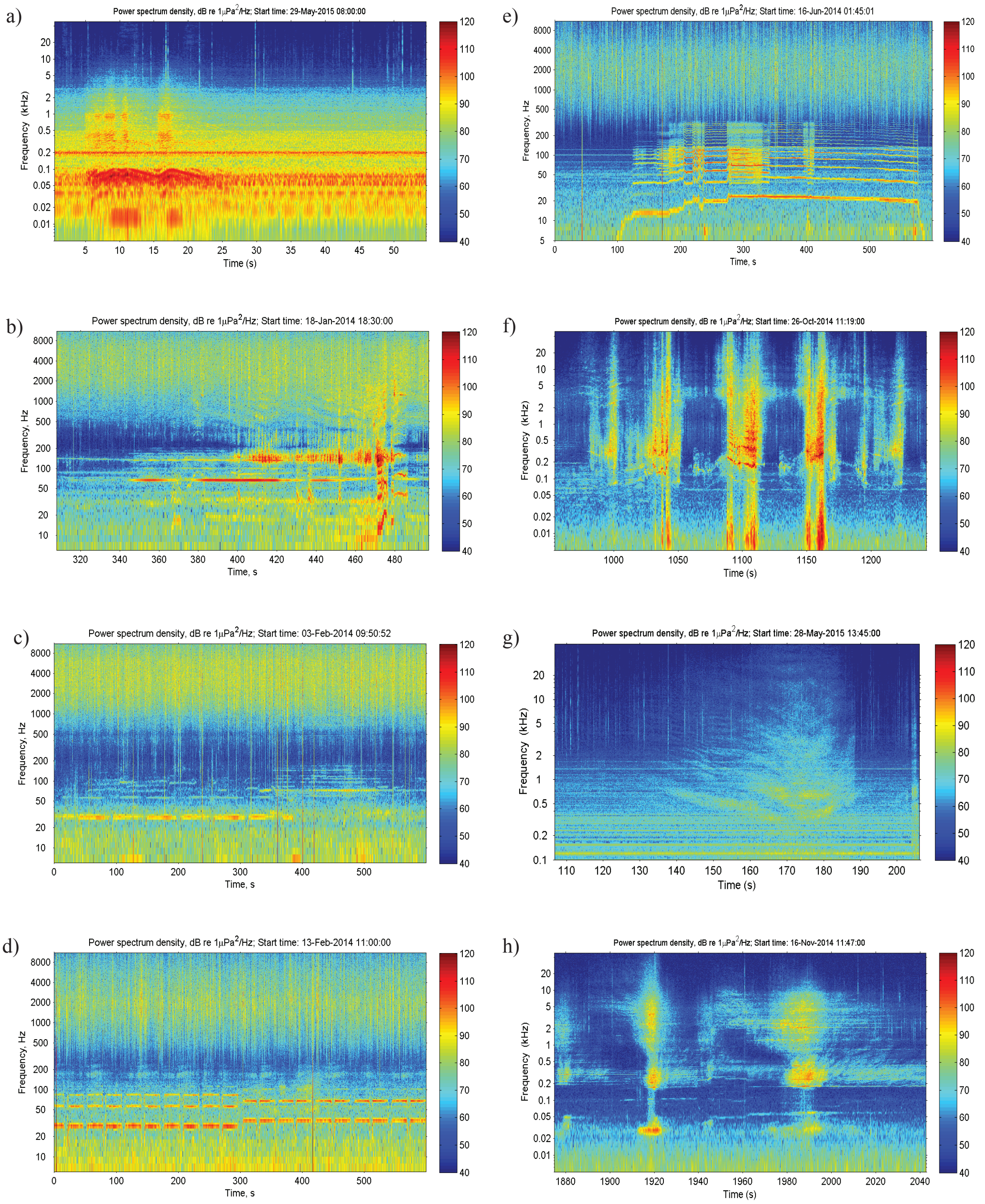


Figure 4.4: A sample of the various types of sounds produced by vessel traffic in the Swan River.

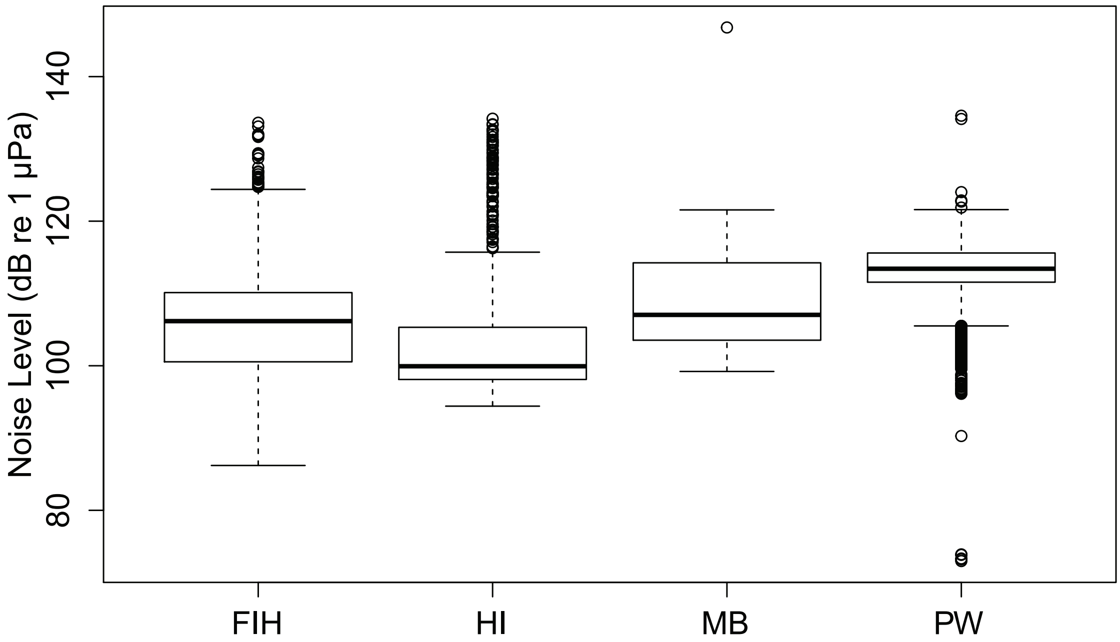


Figure 4.5: Overall broadband noise levels (NL_BB) of four Swan River sites.

4.3.2 Spatial Variation

Significant variation in NL_BB occurred among the four Swan River sites (Fremantle Inner Harbour, Matilda Bay, Perth Waters, and Heirisson Island; Kruskal-Wallis test X^2 = 4252.6, df = 3, p < 0.001; Figure 4.5). All sites were significantly different from each other (Wilcoxon-Mann-Whitney Tests all had p < 0.001). The effect size of site ranged from 0.12 – 1.15, achieving a power of 0.77 – 1.00.

The soundscapes of the four Swan River sites were further compared by investigating PSD percentile plots (Figure 4.6). The most obvious feature of the Fremantle Inner Harbour dataset was the presence of vessel traffic at 0.05 – 1 kHz. As a result of this sound source, the Fremantle site was only as quiet as other Swan River sites < 5% of the time. In addition to noise from vessel traffic, there was near-continuous background anthropogenic noise from Port operations, such as machinery and engine noise. Despite this site being located closest to the ocean and containing numerous structures for settlement, noise from snapping shrimp was not often detected. Shrimp clicks were detected sporadically, and did not dominate the weekly spectrograms or PSD percentile plots (unlike at other sites, such as Matilda Bay or Perth Waters).

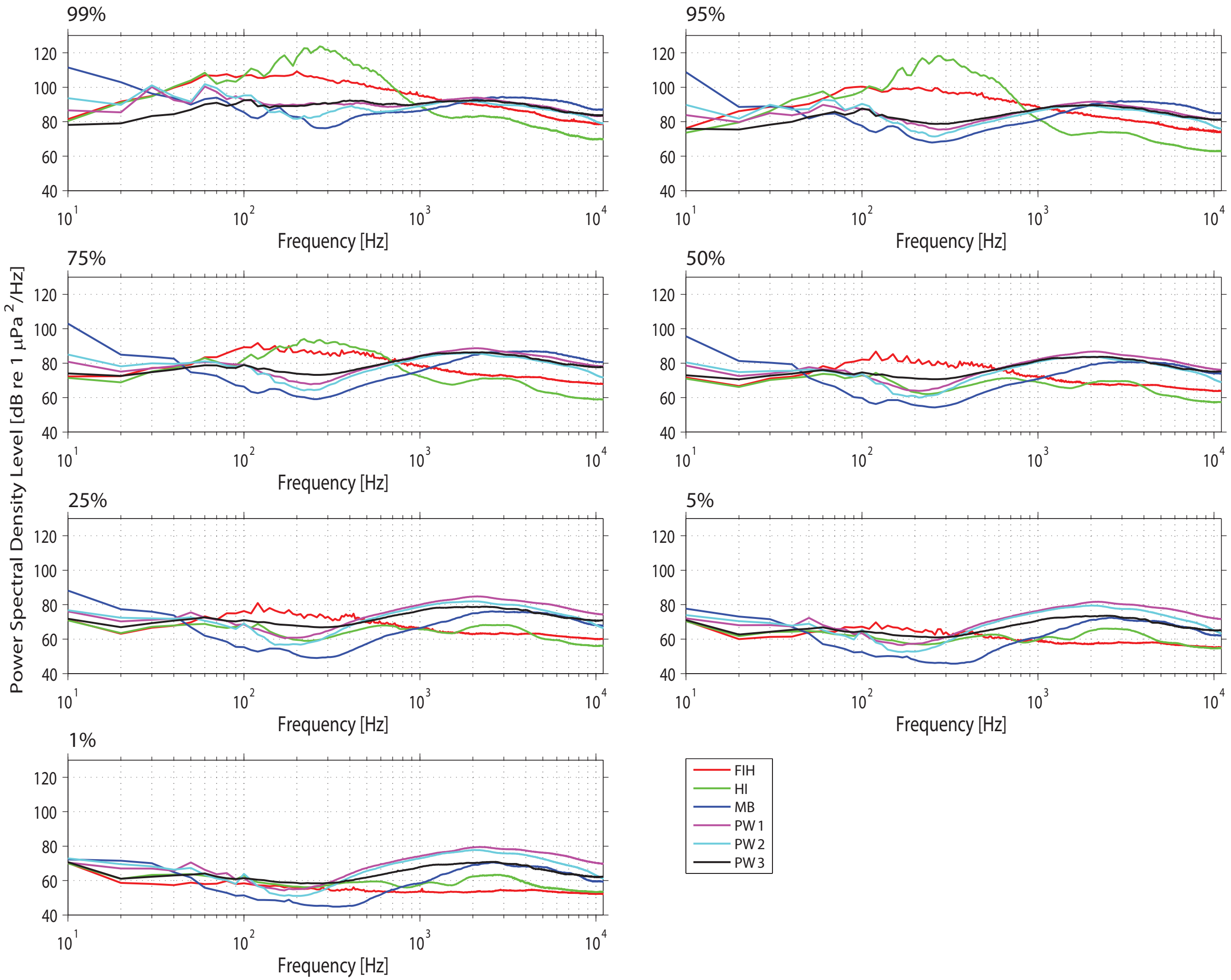


Figure 4.6: Power spectrum density (PSD) percentiles (averaged into 10 Hz bands) from the four sites considered in the spatial analysis. The nth percentile gives the level that was exceeded n% of the time.

Dolphin clicks and whistles were frequently present in manually reviewed acoustic files; however, these transient events did not cause any obvious spikes in PSD percentile plots.

The Matilda Bay acoustic measurements resulted in higher PSD levels in the lower frequencies (Figure 4.6), which corresponded with observed trends in the weekly spectrograms. Matilda Bay had the strongest prevalence of snapping shrimp of all sites. Numerous vessel transits were visible in the weekly spectrograms, particularly during the daytime; yet these did not form the same strong bands of vessel noise observed in the Fremantle Inner Harbour. Matilda Bay exhibited some of the quietest recorded ambient noise levels in the 100 – 1000 Hz band.

Three deployments occurred at Perth Waters. The first and second deployments were similar in terms of overall noise levels in the lower frequencies, whilst in the higher frequencies the second and third deployments showed greater similarity (Figure 4.6). Spectrograms from this site also showed daily patterns of low-frequency noise bands were present, which were particularly prominent in the second deployment. Snapping shrimp noise was a strong feature at this site and was slightly louder than in Matilda Bay (Figure 4.6).

One deployment occurred at Heirisson Island, the most prominent feature of which was the presence of a fish chorus from 50 to 500 Hz (Figure 4.6). Snapping shrimp were minimally observed at this site, which is located in the upper, riverine reaches of the Swan River. At the higher frequencies (> 1 kHz), there is evidence of high-frequency vessel traffic approximately 1% of the time. This corresponds to high-speed powerboats, which occasionally race in this area during the austral summer months (Figure 4.4f). Powerboats also contributed to the frequency band of fish chorusing (Figure 4.4f and Figure 4.2c) but occurred temporally out of sync, with boats recorded during the day and fish at night.

When individual OBLs are considered, it is evident that some levels vary between sites more substantially than others (Figure 4.7). Levels at Matilda Bay and Perth Waters were higher than other sites in the OBL centred at 20 Hz, reflecting the presence of unidentified low-frequency anthropogenic sounds (Figure 4.3c). All sites were similar at the 40 Hz OBL. Fremantle Inner Harbour was highest at mid-range OBLs centred at 80 Hz, 160 Hz, 320 Hz and 640 Hz, reflecting the high level of vessel traffic at this site. Levels at Heirisson Island also had a wide range across these OBLs, due to the presence of a fish chorus. Levels at Matilda Bay were highest in the OBLs centred at 1280 Hz, 2560 Hz and 5120 Hz, followed by the Perth Waters deployments. This energy reflected the prevalence of snapping shrimp at these sites.

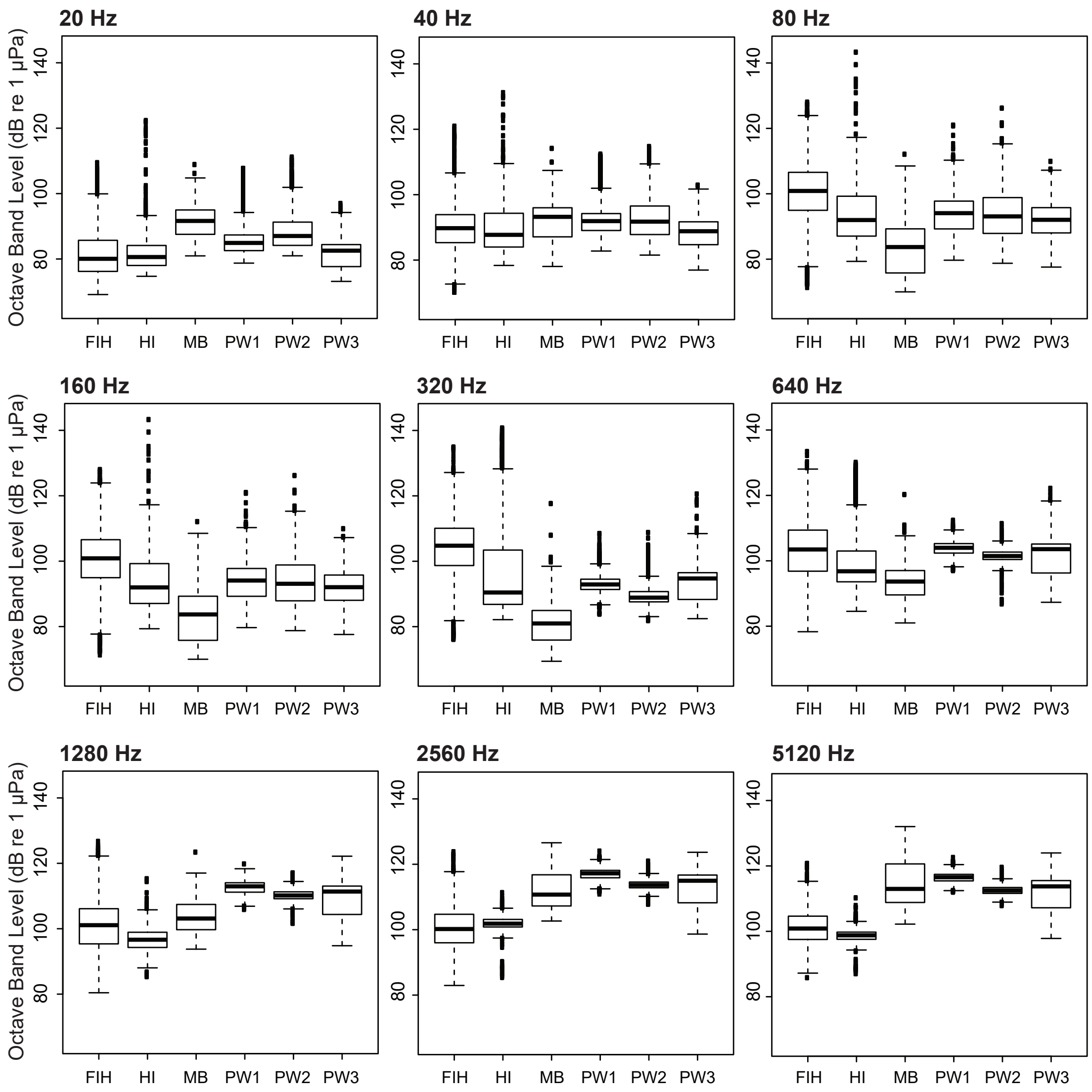


Figure 4.7: Variation in selected octave-band levels between the four sites considered in the spatial analysis: Fremantle Inner Harbour (FIH); Heirisson Island (HI); Matilda Bay (MB1); and Perth Waters (PW1-3).

4.3.3 Short-Term Temporal Variation

There were significant temporal variations within each site based on GEE results (Table 4.2; Figure 4.8). NL_BB at Fremantle Inner Harbour varied by Hour (X^2 = 55.848, p < 0.001), DayType (X^2 = 5.212, p = 0.022), and Month (X^2 = 8.301, p < 0.001). Noise levels were typically higher during the day at this site, peaking at approximately 09:00 hrs. Weekday noise levels were higher than those of the weekend, and May was noisier than June.

Table 4.2: Summary of generalised estimating equation (GEE) models investigating temporal patterns within Swan River sites at the scale of Month, DayType (Weekday or Weekend), and Hour (a cyclical variable represented by H_s and H_c). Significance level: ≤0.001 ***; ≤0.01 **; ≤0.05 *

Parameter	Coefficient Estimate	Standard Error	Wald	p value	
Fremantle Inner Harbour (FIH)					
Intercept	4.68328	0.00797	3.46e+05	< 2e-16	***
Month 6	-0.03107	0.01013	9.40e+00	0.022	**
Weekend	-0.03078	0.01350	5.20e+00	0.0226	*
H_s	-0.00659	0.00366	3.24e+00	0.0718	
H_c	-0.02787	0.00373	5.59e+01	7.8e-14	***
Matilda Bay (MB)					
Intercept	4.753883	0.005365	7.85e+05	< 2e-16	***
Month 11	-0.135897	0.005881	5.34e+02	< 2e-16	***
Month 12	-0.100433	0.006875	2.13e+02	< 2e-16	***
H_s	-0.005619	0.000736	5.83e+01	2.3e-14	***
H_c	0.000249	0.000732	1.20e-01	0.73	
Perth Waters (PW)					
Intercept	4.748788	0.002937	2.61e+06	< 2e-16	***
Month 2	0.007966	0.003615	4.85e+00	0.02758	*
Month 3	-0.044825	0.007522	3.55e+01	2.5e-09	***
Month 4	-0.109140	0.005000	4.76e+02	< 2e-16	***
Month 6	-0.028517	0.003224	7.83e+01	< 2e-16	***
Month 7	-0.028411	0.003263	7.58e+01	< 2e-16	***
H_s	-0.006599	0.000464	2.02e+02	< 2e-16	***
H_c	-0.002113	0.000619	1.16e+01	0.00065	***
Heirisson Island (HI)					
Intercept	4.64622	0.00506	8.42e+05	< 2e-16	***
H_s	-0.08831	0.00590	2.24e+02	< 2e-16	***
H_c	-0.00496	0.00628	6.30e-01	0.43	

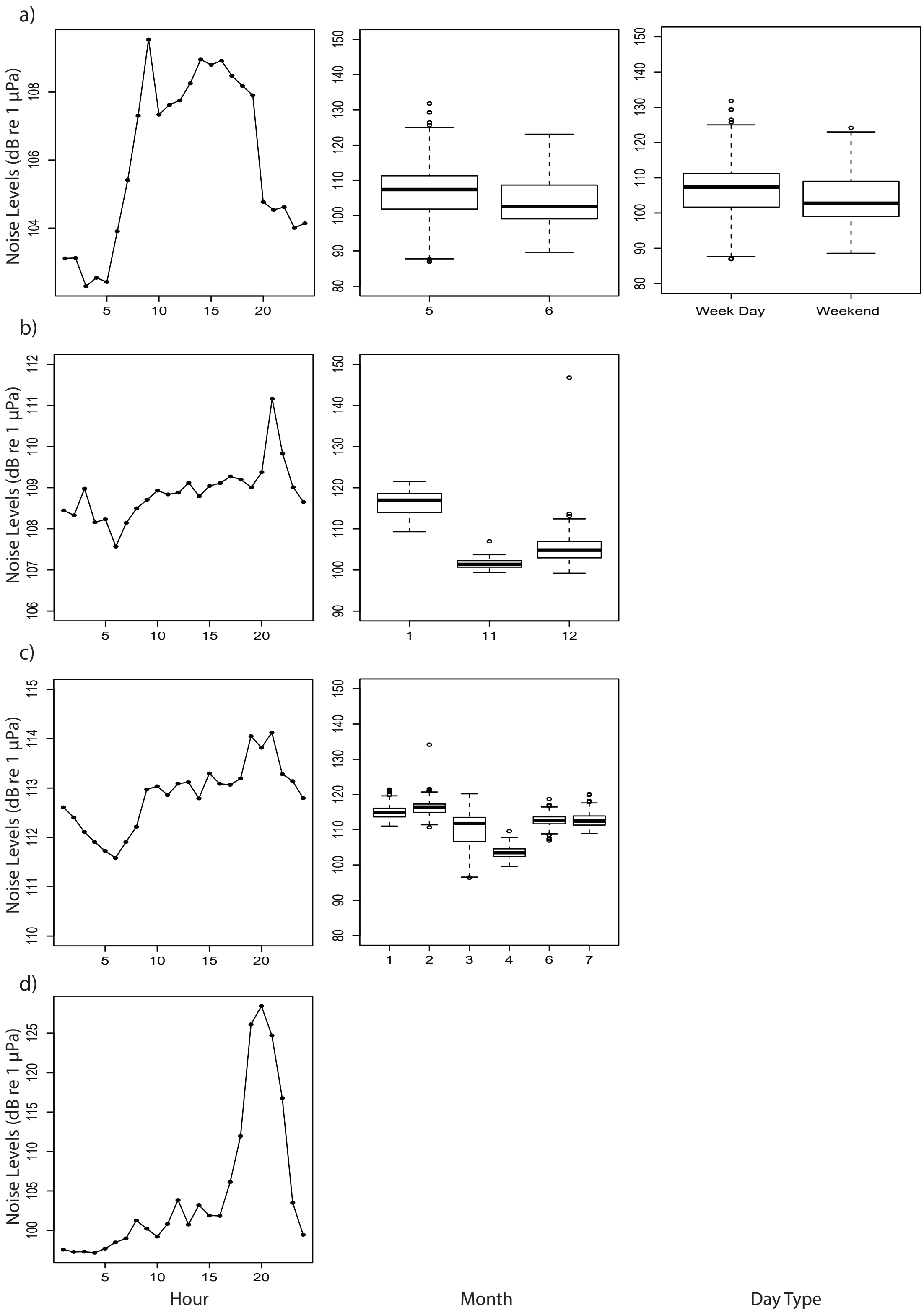


Figure 4.8: Results from generalised estimating equations (GEEs) based on hourly broadband noise levels from a) Fremantle Inner Harbour, b) Matilda Bay, c) Perth Waters, and d) Heirisson Island. Only significant explanatory variables are shown.

The Matilda Bay GEE retained Hour (X^2 = 59.07, p < 0.001) and Month (X^2 = 515.05, p < 0.001) as significant variables. At this site, noise levels gradually increased throughout the day before peaking at 20:00 hrs. Noise levels increased over the austral summer months (November to January).

Perth Waters retained Hour (X^2 = 11.64, p < 0.001) and Month (X^2 = 780.37, p < 0.001) as significant variables. Noise levels sharply increased between 08:00 – 10:00 hrs then peaked between 19:00 – 21:00 hrs before decreasing overnight. April was the quietest month.

Heirisson Island only retained Hour (X^2 = 223.739, p < 0.001) as a significant variable. It showed a gradual increase in noise levels throughout the day, then a sharp peak between 18:00 – 22:00 hrs; this period coincided with the evening fish chorus identified in the weekly spectrograms.

4.3.4 Long-Term Temporal Variation

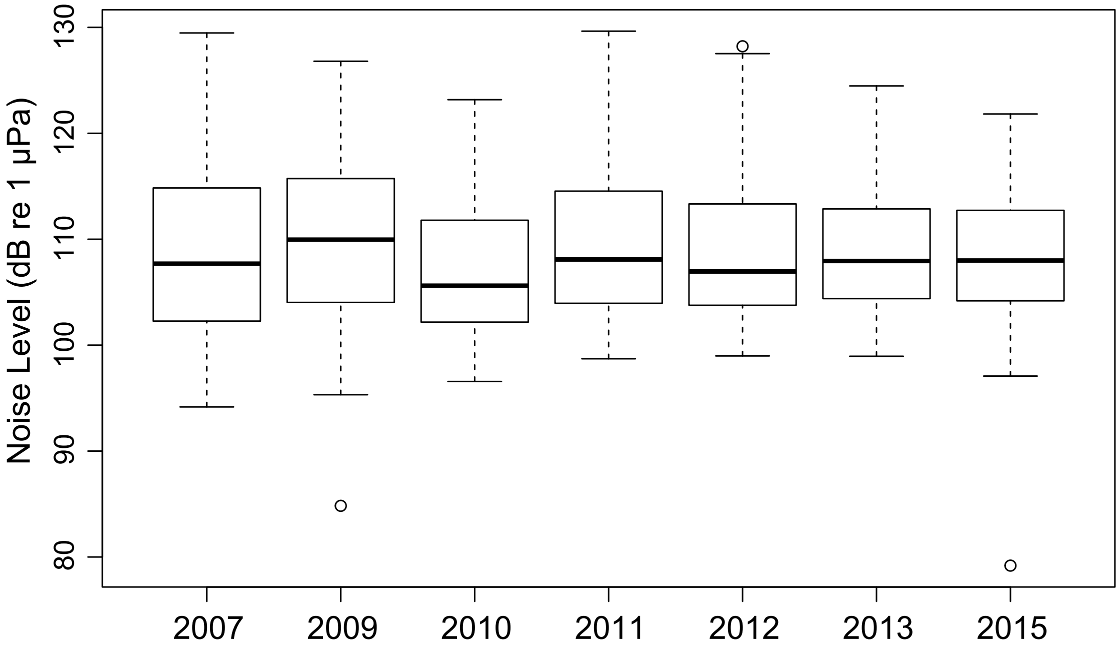
In Mosman Bay, NL_BB measured in January differed among the seven years of measurement (Kruskal-Wallis X^2 = 102.75, df = 6, p < 0.001; Figure 4.9). NL_BB in 2010 was greatest, whilst NL_BB in 2013 and 2015 were most similar. The effect size of year ranged from 0.01 – 0.49, achieving a power of 0.06 – 1.00.

The Mosman Bay PSD percentile plots and OBLs show that the soundscape at this site was very similar over the years (Figure 4.10 and Figure 4.11). Most noise occurred in the 70 – 300 Hz frequency band. Closer examination in the weekly spectrograms suggested the noise was produced by vessel traffic. About 5% of the time, noise in this band was above 100 dB re 1 μPa^2/Hz for all years considered. This noise only dropped to below 70 dB re 1 μPa^2/Hz less than 5% of the time. There was no trend of decreasing or increasing noise levels at any frequency over the seven-year period of acoustic monitoring in Mosman Bay.

4.3.5 Relevance to Dolphin Communication

Dolphin whistles could be expected to overlap with OBLs centred at 1280 Hz, 2560 Hz and 5120 Hz (Figure 4.7). High mean noise levels at these OBLs were present at Matilda Bay and Perth Waters due to the presence of snapping shrimp. In comparison, Heirisson Island and the Fremantle Inner Harbour had lower mean values. However, the high variability of levels at the Fremantle Inner Harbour resulted in levels occasionally surpassing those of Matilda Bay and Perth Waters. Due to the relatively low levels of snapping shrimp noise in Fremantle Inner Harbour when compared to other study sites, these 'noisiest' periods are likely attributable to high vessel traffic.

When considered as individual sound sources, snapping shrimp and vessel traffic produce noise across a wide frequency band that can overlap with dolphin whistles (Figure 4.2d and



	2007	2009	2010	2011	2012	2013	2015
2007		***	***	***	ns	ns	ns
2009	***		***	ns	***	**	***
2010	***	***		***	***	***	***
2011	***	ns	***		*	ns	ns
2012	ns	***	***	*		ns	ns
2013	ns	**	***	ns	ns		ns
2015	ns	***	***	ns	ns	ns	

Figure 4.9: Overall broadband noise levels (NL_BB) at Mosman Bay over the month of January across a nine-year period, including a table of significant differences as determined by Wilcoxon-Mann-Whitney Tests: ≤0.001 ***; ≤0.01 **; ≤0.05 *

Figure 4.4, respectively). However, the spectro-temporal structures of these sounds differ considerably. Whilst colonies of snapping shrimp produce frequent impulsive broadband clicks, each lasting a few milliseconds, vessels produce continuous broadband noise from propeller cavitation and long-lasting tonal sounds due to engine and propeller rotations (e.g. Erbe *et al.*, 2016). Propeller cavitation is a stochastic process, and the resulting power spectrum resembles that of Gaussian white noise. Shrimp snaps, on the other hand, show a higher degree of comodulation across frequency (Branstetter *et al.*, 2013). It is the different temporal structures and comodulation degrees that will likely reduce the risk of acoustic masking by snapping shrimp over that of vessels (Erbe *et al.*, 2015a). In other words, high levels of vessel traffic in Fremantle Inner Harbour are more likely to mask dolphin whistles than high levels of snapping shrimp in Matilda Bay.

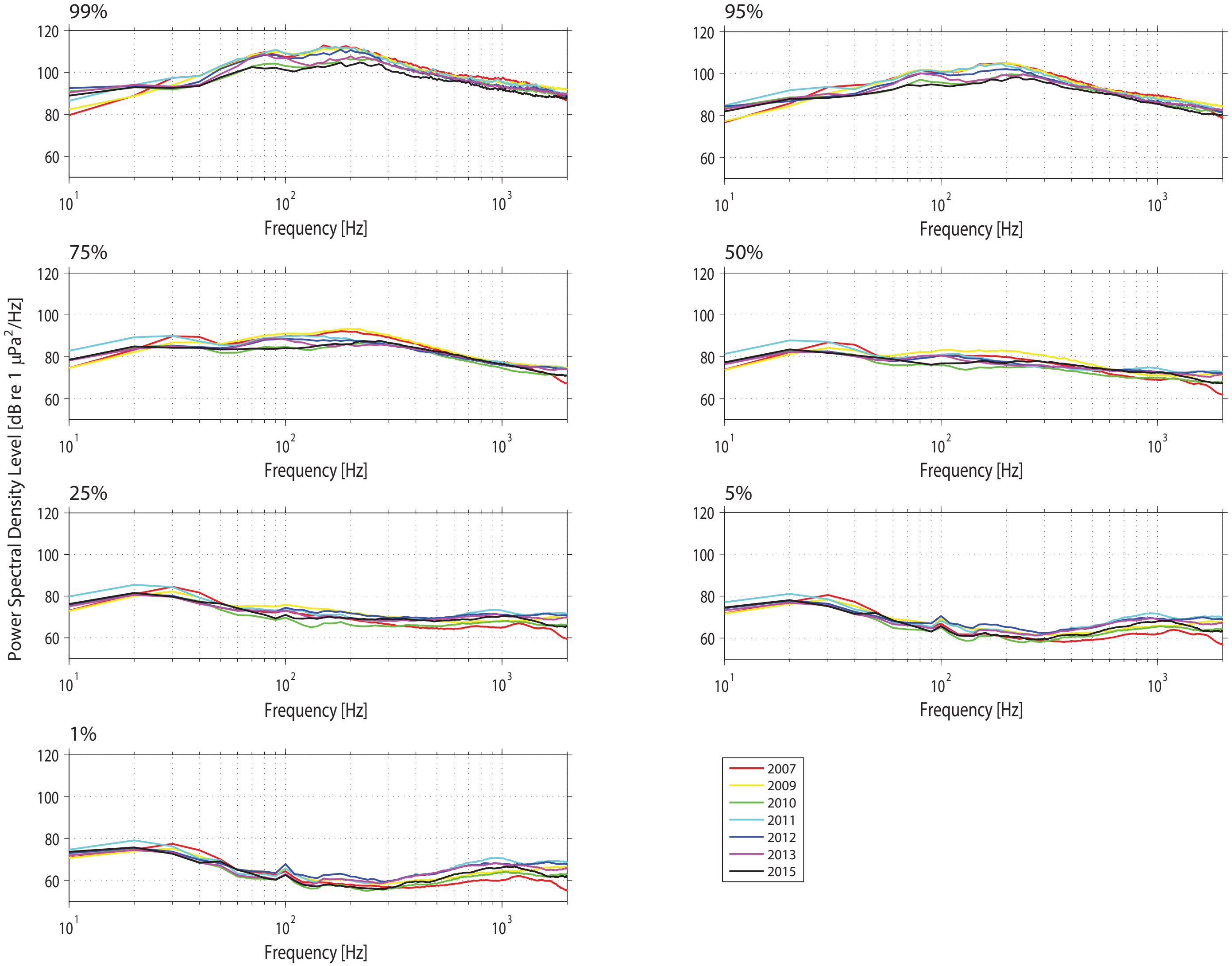


Figure 4.10: Power spectrum density (PSD) percentiles (averaged into 10 Hz bands) at Mosman Bay over the month of January across the nine-year period considered in the temporal analysis. The n^{th} percentile gives the level that was exceeded n% of the time.

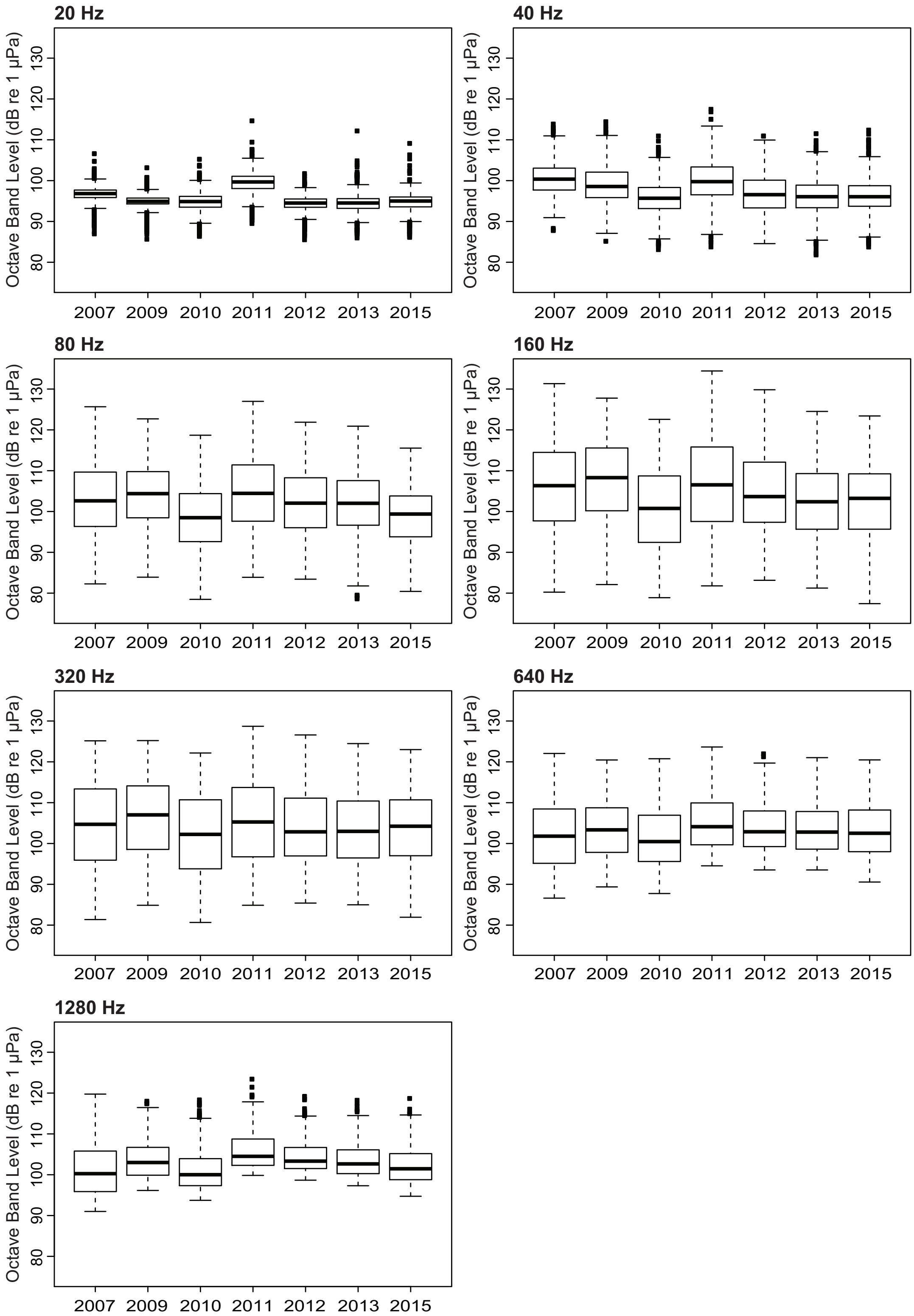


Figure 4.11: Variation in selected octave-band noise levels across the seven years considered in temporal analysis of Mosman Bay.

4.4 Discussion

This study describes the acoustic habitat in the core range of the Swan River dolphin community, at varying spatial and temporal scales. Overall, there were two predominant sound sources which occurred at multiple sites: snapping shrimp and vessel traffic. From the acoustic perspective of the resident dolphin community, both of these sound sources overlap with the frequency range of dolphin whistles used for communication. However, whilst snapping shrimp sounds are brief, impulsive, repetitive, and their spectrum comodulated across multiple frequencies, the propeller cavitation noise produced by vessel traffic is temporally continuous and spectrally not comodulated. Thus, the latter is more likely to interfere with dolphin whistles, particularly where multiple vessels are simultaneously contributing to the soundscape. Additionally, the number of sound sources identified and their changeability throughout the river system clearly illustrates the spatially variable acoustic environment experienced by this community of bottlenose dolphins. High within-site temporal variability observed over small and large temporal scales (hours to years) adds another layer of complexity to this acoustic environment.

In this study, the most ubiquitous sound source was vessel noise, which was present at all sites to some degree. The Swan River is known to be a site of high vessel traffic, used by vessels of numerous types engaged in a range of activities (Marley *et al.*, 2016b). However, despite their prevalence, vessel sounds were not consistent. In fact, the extreme variation in vessel sounds was in marked contrast to the much lower variability in characteristics of prominent biotic sounds, such as shrimp snaps and fish calls, which were of comparatively predictable duration and frequency. The high variability in vessel acoustic features is a result of differences in vessel type, speed and behaviour; the physical characteristics of the environment; and varying distances from the receiver (see Erbe, 2013; Erbe *et al.*, 2016) for variability of underwater noise from jetskis and small boats with outboard motors, which are the most common type of vessel in the Swan River). For example, some vessels produced bursts of low-frequency "revs" with relatively few harmonics, whilst others produced mid-frequency tonal sounds with several harmonics for a few minutes, and many dominated the entire frequency band for the whole recording period of 10 min. Low-frequency sounds (centred at 35 Hz) have previously been recorded from passenger ferries operating in Perth Waters (Marley *et al.*, 2016a). Some of these ferries also venture to other parts of the river, travelling past Heirisson Island, Perth Waters, Matilda Bay and the Fremantle Inner Harbour. Vessels are often observed milling in some parts of the river (e.g. Perth Waters), where they circle an area at low speeds for a prolonged period of time, and the engine may be stopped and started several times as the vessel moves between particular spots (Marley *et al.*, 2016b). Such vessel behaviour, which often coincides with fishing or crabbing activities, likely contributes to the low-frequency acoustic environment of the river system. The highest frequency vessel sounds were observed in the presence of small powerboats engaged in high-speed races near Heirisson Island. Such races can involve several competing powerboats at any one time, with the most powerful boats claimed to "regularly achieve over 170 kph" (http://www.wasbc.com.au). This race site is situated at the start of the upper riverine reaches of the Swan River system, where the river narrows to only 450 m wide. Given the high frequency noise produced by these vessels and the narrow nature of the river in this area, there could be potential for displacement of dolphins whose communication whistles could be masked.

The wide array of sound characteristics – even from the same source type – contributed to the spatial and temporal variability of the acoustic environment experienced by this dolphin community. Each of the sites considered had its own characteristic combination of contributing sound sources. The minimum distance between any two of these sites is approximately 2.5 km, highlighting the site-specific nature of acoustic habitats within the same system. This agrees with findings of previous studies. Soundscape studies in New Zealand (Radford *et al.*, 2010), Pacific Panama (Kennedy *et al.*, 2010), the U.S. east coast (Rice *et al.*, 2014) and Taiwan (Guan *et al.*, 2015) have also noted site-specific sound fields at locations several kilometres apart, generally as the result of biotic or anthropogenic activities. Additionally, there was considerable temporal variation within sites. The Fremantle Inner Harbour was noisiest between the hours of 08:00 – 20:00 hrs, particularly on weekdays. The presence of both recreational vessel traffic and port activities at these times combine to increase average noise levels. Matilda Bay and Perth waters also displayed increased noise levels during the day, likely from vessel traffic. Noise levels at Heirisson Island only slightly increased during the day; instead, the 'noisiest' period occurred between the hours of 18:00 – 22:00 hrs as a result of the evening fish chorus. In the Swan River, the 'noisiness' of each site also varied according to the frequency band considered; all sites were uniformly quieter in the lowest frequency OBLs, but at the mid- and upper-frequency OBLs there were considerable differences between sites. Overall, snapping shrimp sounds were prevalent at Matilda Bay and Perth Waters, whilst Heirisson Island displayed a strong fish chorus, and the Fremantle Inner Harbour was dominated by sounds from vessel traffic and port activities. In the OBLs centred on frequencies also utilised by dolphins, noise from vessel traffic and snapping shrimp caused the greatest variation.

How dolphins may respond to vessel traffic in the Swan River is still under investigation. A previous study on dolphin occupancy in response to vessel traffic found that despite similarities in vessel densities, dolphins showed differential use of two monitored sites within the river (Marley *et al.*, 2016b). Fewer dolphin sightings were recorded at Perth Waters when vessel densities were high, whereas vessel traffic appeared to have no relationship with dolphin occupancy in the Fremantle Inner Harbour (Marley *et al.*, 2016b). The acoustic data presented here from Perth Waters 1, Perth Waters 3 and the Fremantle Inner Harbour overlap temporally with the visual observations presented in Marley *et al.* (2016b). It can be clearly seen that dolphins are not experiencing the same acoustic environment at these two separate sites; yet dolphins remained present at the anthropogenically busiest, noisiest one. Future research investigating whether certain vessel characteristics (physical, behavioural or acoustical) elicit responses in Swan River dolphins beyond changes in animal occupancy would provide insight into finer scale responses. These responses could be physical behavioural changes such as alterations to swim speed, activity state, movement patterns, or acoustical behavioural changes such as variations in whistle frequency, repetition, or duration.

To determine the level at which dolphin communications are being masked at anthropogenically noisy sites (such as the Fremantle Inner Harbour), future work on source levels and transmission of whistles in the Swan River is required. In addition, data on how the structure of Swan River dolphin whistles may change in different contextual scenarios should be measured. The acoustic characteristics of whistles appear to vary between dolphin populations, in terms of frequency content, bandwidth, duration, extrema, steps and inflection points (Ding *et al.*, 1995; Hawkins, 2010; May-Collado & Wartzok, 2008; Ward *et al.*, 2016). These differences may be due to distance (e.g. separate vocal evolution, low exchange rates of individuals) or as a result of context (e.g. group composition, behaviour). Variations in whistle characteristics could also reflect different environments in terms of physical or environmental characteristics, such as water depth, sediment type, salinity and/or temperature. Ambient noise is increasingly becoming considered an indicator of environmental quality, which could also influence features and use of dolphin whistles (Buckstaff, 2004; Guerra *et al.*, 2014; Heiler *et al.*, 2016; May-Collado & Quiñones-Lebrón, 2014; Morisaka *et al.*, 2005). Furthermore, different dolphin populations also appear to vary in the source levels of the whistles they produce (Jensen *et al.*, 2012). To date, the only published analysis of the Swan River dolphins' repertoire describes the characteristics of whistles recorded in the Fremantle Inner Harbour and does not include source levels or contextual analysis (Ward *et al.*, 2016). Additionally, little is known about the source levels of different sound types in the Swan River, particularly from anthropogenic activities. Anthropogenic noise has the potential to degrade habitat through a loss of 'acoustic space'. In areas which experience high levels of anthropogenic noise, habitat fragmentation may even occur if animals are unable or unwilling to transit through noisy areas in order to reach necessary habitat (Rice *et al.*, 2014). Thus, it would be beneficial to document the structure and source levels of dolphin whistles and human activities at multiple sites throughout the Swan River to see if differences exist in 'noisy' versus 'quiet' habitats.

The lack of any long-term increase or decrease in noise levels at Mosman Bay suggests a degree of temporal stability within this site. There is growing concern regarding the increasing level of underwater noise in many coastal areas as a result of expanding anthropogenic activities. Mosman Bay is the site of a long-term acoustic monitoring study due to a prominent fish chorus associated with seasonally-breeding mulloway. To focus on potential increases in anthropogenic noise and avoid including the evening fish chorus in analyses, only data from 06:00 – 12:00 hrs were assessed. This period was expected to overlap with the morning vessel "rush hour" reported in other studies at different points in the river (Marley *et al.*, 2016a,b), during a month of increased recreational time due to the austral summer holidays. Although years were not all the same, their mean noise levels were all within 3 dB, displaying no overall upwards or downwards trend in yearly noise levels within Mosman Bay. The relatively low effect size associated with the majority of yearly comparisons suggests that, although significant, differences are not considerable. Thus, despite some inter-year variability, there appears to be a general long-term stability in the soundscape of this site.

Such acoustic stability in localised soundscapes could be beneficial for long-lived animals such as dolphins, as this may indicate the possibility of predictability in a variable environment. If dolphins are able to use acoustics to aid predictions of when and where different sound sources occur in the river system, this may influence their habitat use. For example, fish calls may indicate prey availability and signal an 'attractive' area, whereas vessel or pile-driving noise may signal an 'unattractive' area where animals are at risk of disturbance or harm. This information could be particularly important for the decision-making of mother-calf pairs, who may have a greater preference for quieter areas for vital nursing and resting activities. Previous studies within the Swan River have found differential site use by dolphins in response to site-specific environmental and anthropogenic variables (Beidatsch, 2012; Marley *et al.*, 2016b; Moiler, 2008). It could therefore be particularly beneficial to ascertain the relationship between the acoustic characteristics of the environment and dolphin occurrence or behaviour.

In conclusion, the Swan River is a highly variable acoustic environment, experiencing a large range of different sound sources. The most ubiquitous noise in the Swan River came from vessel traffic, which was persistent at all sites considered, followed by snapping shrimp which had site-specific prevalence. Although these two sound sources are both strong acoustic components of the Swan River soundscape over similar frequency ranges, their impact on dolphin communication is likely to contrast due to structural differences, with vessel noise suggested to be the more detrimental. The prominence of these sound sources varied spatially, resulting in characteristic soundscapes at different sites within the same river system. Some sites are therefore 'noisier' than others, with the Fremantle Inner Harbour the noisiest from an anthropogenic perspective. However, there was variation in 'noisiness' within sites, with different sites showing temporal variation in broadband noise levels at the scale of hours, days, months or even (to some degree) years. This spatial and temporal variation illustrates the acoustic complexity of the Swan River soundscape. How dolphins effectively navigate this spatially and temporally complex environment, and at what stage anthropogenic noise becomes too much to maintain a healthy dolphin community, has yet to be determined. Thus, when considering dolphin acoustic habitat, it is beneficial to consider the context of soundscape contributors – their frequency structure, duration, variability within source type, and spatio-temporal prevalence.

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Chapter 5

Effects of vessel traffic and underwater noise on the movement, behaviour and vocalisations of bottlenose dolphins (*Tursiops aduncus*) in a highly urbanised estuary

The potential disturbance of bottlenose dolphins (*Tursiops* sp.) from tourism boats has been widely discussed in the literature, in terms of both physical vessel presence and associated underwater noise. However, less attention has been paid to the potential impact of non-tourism vessels, despite these being much more widespread and occurring in greater numbers throughout coastal dolphin habitats. The Indo-Pacific bottlenose dolphin (*T. aduncus*) community inhabiting the Swan-Canning River system in Western Australia is exposed to high levels of vessel traffic. To investigate whether behavioural responses could be occurring at a fine scale, a non-invasive combination of visual and acoustic monitoring was conducted using a theodolite and an autonomous acoustic logger. Dolphins significantly increased their average movement speeds in high vessel densities, but only for some activity states. Markov chain models revealed that these behavioural budgets also changed in the presence of vessels, with animals spending greater time travelling and less time resting or socialising. Whilst foraging behaviour may correlate positively with vessel density, further work is needed to confirm this response. Finally, generalised additive models showed multiple whistle characteristics to vary with rising levels of broadband noise. During noisier periods, whistles typically became shorter, with a wider frequency range and multiple inflection points; however, whistles also varied naturally according to activity state, group size and calf presence. Despite being acoustically specialised for higher frequencies, dolphins showed the strongest acoustic response to low-frequency noise. Overall, vessel traffic and broadband noise levels appear to elicit both behavioural and acoustical responses in dolphins using the Fremantle Inner Harbour, which may have energetic implications. This study highlights the complexity of disturbance responses in this species, confirming the need for consideration of both surface and acoustic behaviour alongside appropriate contextual data.

5.1 Introduction

In coastal marine environments, vessel traffic is the most ubiquitous anthropogenic activity with the potential to disturb marine wildlife (Bittencourt *et al.*, 2014; Kelly *et al.*, 2004). With wildlife-watching tours becoming increasingly popular, tourism vessels have been the focus of concerns regarding animal disturbance. Whale and dolphin ecotourism is a multi-million dollar industry; in 2008 for instance, 13 million people participated in cetacean-watching trips in 119 countries and territories, generating approximately 2.1 billion US dollars (O'Connor *et al.*, 2009). As a result, many studies have investigated the impacts of tourism vessels on cetaceans, particularly coastal species such as bottlenose dolphins (*Tursiops* sp.) whose core habitats overlap with human activities and are relatively accessible for research programmes (Arcangeli & Crosti, 2009; Bejder *et al.*, 2006; May-Collado & Quiñones-Lebrón, 2014; Pérez-Jorge *et al.*, 2016; Scarpaci *et al.*, 2000; Steckenreuter *et al.*, 2012; Stensland & Berggren, 2007; Symons *et al.*, 2014; Christiansen *et al.*, 2010; Constantine *et al.*, 2004; Guerra *et al.*, 2014; Heiler *et al.*, 2016; Lusseau, 2003a,b, 2005, 2006). They report varying degrees of disturbance – from relatively subtle changes in vocal behaviour to broad-scale animal movements away from the affected area. Regardless of the response size, all behavioural changes come at an energetic cost which can negatively impact individual health, and even lead to population consequences if reproductive or survival rates are reduced (Frid & Dill, 2002). Furthermore, comparatively little attention has been paid to the potential impacts of recreational vessels, despite predictions of significant growth in vessel traffic over coming years (McCarthy, 2004). Recreational vessels already occur in high numbers in some areas (Buckstaff, 2004; Davenport & Davenport, 2006; Lloret *et al.*, 2008; Marley *et al.*, 2016b; Mattson *et al.*, 2005), and thus have the potential to elicit dolphin behavioural responses despite not being actively engaged in wildlife-watching activities. This is of concern with regard to coastal dolphin species whose use of inshore habitats exposes them to higher levels of human activities in general, and possibly cumulative impacts from repeated exposure to vessel traffic in particular (Nowacek *et al.*, 2001; Ross, 2006; Wilson *et al.*, 1999).

Investigating disturbance effects from tourism vessels often focuses on dolphin displacement or changes in occurrence/site occupancy (Bejder *et al.*, 2006; Lusseau, 2005; Pérez-Jorge *et al.*, 2016; Pirotta *et al.*, 2013; Rako *et al.*, 2013). However, such an approach ignores the complex array of factors determining animal habitat use in human-dominated seascapes (Llaneza *et al.*, 2012). For example, animals may remain in a specific area to forage, engage in conspecific interactions or avoid predators, in spite of of anthropogenic activities. Individuals may therefore choose to tolerate disturbance rather than leave the affected area, but still display a 'subtler' behavioural response (Ellison *et al.*, 2012). As a result, it is worth looking beyond patterns of presence/absence to consider fine-scale behavioural responses such as changes to movement patterns, behavioural budgets and acoustic behaviour, particularly in cases where no site displacement is observed.

Some studies have taken this next step, and yielded evidence that dolphins may alter their movement patterns, for example by changing travel direction to orient away from or move around approaching vessels, beginning to travel erratically, or significantly increasing their travelling speeds (Au & Perryman, 1982; Lemon *et al.*, 2006; Lusseau, 2006; Mattson *et al.*, 2005; Nowacek *et al.*, 2001; Stensland & Berggren, 2007). Changes to activity states or behavioural budgets have also been reported, with travelling behaviour generally increasing with vessel presence, whilst resting and socialising become more infrequent (Arcangeli & Crosti, 2009; Constantine *et al.*, 2004; Lusseau, 2003a; Steckenreuter *et al.*, 2012; Stensland & Berggren, 2007). Foraging is less predictable, with some studies reporting greater foraging activity in the vicinity of boats (Christiansen *et al.*, 2010), whilst others suggest the contrary (Arcangeli & Crosti, 2009; Pirotta *et al.*, 2015; Steckenreuter *et al.*, 2012). At an even finer scale, dolphins have also been documented to alter their dive and surfacing patterns, breathing synchrony, inter-animal distance, and use of individual behaviours (such as side-flops, tail-out dives, etc.) in relation to vessel traffic (Hastie *et al.*, 2003; Janik & Thompson, 1996; Lusseau, 2003b, 2006; Nowacek *et al.*, 2001; Stensland & Berggren, 2007). Furthermore, behavioural responses may be age- or sex-specific (Lusseau, 2003b; Stensland & Berggren, 2007; Symons *et al.*, 2014).

Dolphins may also change their acoustic behaviour in response to anthropogenic activities. Such is the case with vessel traffic, of which underwater noise is a by-product. The acoustic behaviour of animals is not static; there are multiple ways in which animals may alter their acoustic behaviour with increased noise levels (Radford *et al.*, 2014). Dolphins have been observed to adjust some characteristics of their whistles in elevated noise conditions or in the presence of tourism vessels, for instance by modifying their frequency range (Guerra *et al.*, 2014; Heiler *et al.*, 2016; May-Collado & Quiñones-Lebrón, 2014; May-Collado & Wartzok, 2008; Morisaka *et al.*, 2005; Rako Gospić & Picciulin, 2016), duration (Guerra *et al.*, 2014; May-Collado & Quiñones-Lebrón, 2014; May-Collado & Wartzok, 2008), or the number of frequency modulations (Morisaka *et al.*, 2005). Increases in whistle production rates have also been reported (Buckstaff, 2004; Guerra *et al.*, 2014; Scarpaci *et al.*, 2000). These changes presumably stem from impaired communication efficiency as a result of vessel noise (Jensen *et al.*, 2009). Therefore, increases in underwater noise levels appear to be related with changes in the type or timing of dolphin vocalisations (Nowacek *et al.*, 2001).

However, changes in acoustic behaviour can also occur in association with other factors, for example different surface behaviours, group sizes, or group compositions (Acevedo-Gutiérrez & Stienessen, 2004; Díaz López, 2011; Esch *et al.*, 2009; Guerra *et al.*, 2014; Hernandez *et al.*, 2010; Jones & Sayigh, 2002; May-Collado & Quiñones-Lebrón, 2014; Quick & Janik, 2008). Additionally, variations in whistle structure appear to naturally exist between dolphin populations (Hawkins, 2010; Jones & Sayigh, 2002). Therefore, in order to understand the effects of vessel or ambient noise on dolphin whistle characteristics, it is necessary to consider additional explanatory variables to provide suitable context. Yet few other studies control for these additional covariates, or recognise that behavioural and acoustical responses are not necessarily mutually exclusive. In practice, it can be difficult to disentangle the effects of physical boat presence and associated noise (Ellison *et al.*, 2012; Pirotta *et al.*, 2013). Responses can also be confounded by the fact that behavioural studies are frequently conducted from research vessels that could elicit responses (Constantine *et al.*, 2004; Guerra *et al.*, 2014; Heiler *et al.*, 2016). Moreover, the way in which one population responds to vessel traffic does not necessarily mean that all populations will respond in the same manner (Ellison *et al.*, 2012). Dolphin communities vary in their vessel exposure histories, environmental conditions in their home range, and survival pressures such as prey availability or predator densities. Thus, there is a need to work on a "case by case" basis, especially when considering the conservation of small communities or populations particularly susceptible to threats due to their small numbers and low reproductive rates (Ross, 2006; Wilson *et al.*, 1999). Investigation of dolphin behavioural and acoustical responses to vessels therefore necessitates consideration of multiple covariates. There is a need for studies investigating a range of dolphin-vessel contexts, from both behavioural and acoustical perspectives, preferably conducted from land-based research platforms.

Australia is experiencing rapidly growing recreational use of marine resources. Between 1999 and 2009, there was a 44% increase in the number of recreational vessels registered in Western Australia (Burgin & Hardiman, 2011). There are currently approximately 95,000 recreational vessels registered in the state, with over half of these within the Perth Metropolitan area (J. Nunn; personal communication, 21st January 2014). Consequently, the Swan-Canning River system, which flows through the centre of Perth, receives high levels of vessel traffic (Marley *et al.*, 2016b). The Fremantle Inner Harbour is part of an industrial port at the river mouth, and acts as a gateway between the Swan River and the Indian Ocean. It has been identified as the anthropogenically noisiest site in the river, with transits of up to 56 vessels per hour (Marley *et al.*, 2016b, Chapter 3).

Despite being a busy, noisy site, the Fremantle Inner Harbour is frequently used by the river's resident community of Indo-Pacific bottlenose dolphins (*T. aduncus*). This community consists of approximately 18 adults, plus several juveniles and calves, which use the harbour as one of several "hotspots" (Beidatsch, 2012; Chabanne *et al.*, 2012; Moiler, 2008; Swan River Trust, 2015). Dolphins have been shown to remain within the Fremantle Inner Harbour during periods of high vessel traffic, with no alterations to their presence/absence, number of sightings, or duration of time spent in this area in relation to vessel density (Marley *et al.*, 2016b). However, behavioural responses could be occurring at a finer scale despite the lack of site avoidance. Since the manner in which dolphins respond to vessel traffic could have implications to their health, the effects of vessel traffic and underwater noise must be quantified.

This study aims to investigate the behavioural and acoustical responses of bottlenose dolphins to vessel traffic and underwater noise in the Fremantle Inner Harbour. To achieve this, dolphin movement speeds, activity states and whistle characteristics in varying levels of vessel traffic and underwater noise were examined. Data were collected using autonomous acoustic recordings and land-based visual observations to minimise bias from the presence of a research vessel. Additionally, contextual covariates (such as behaviour, group size, and calf presence) were recorded for inclusion in analyses. The resulting knowledge on fine-scale behavioural response to vessels will improve management practices and conservation outcomes.

5.2 Methods

5.2.1 Visual Data Collection

Land-based visual surveys were conducted from Cantonment Hill (32.043634° S, 115.754284° E), a 32 m vantage point overlooking the Fremantle Inner Harbour (Figure 5.1). Surveys occurred in May – June 2012, January – June 2014 and April – June 2015, covering months which coincided with a period of peak dolphin sightings in this area (Swan River Trust, 2015). Surveys were timed to occur primarily in the morning (typically 07:00 – 10:00 hrs) as strong glare affected the observers' ability to sight dolphins in the afternoon. Additionally, surveys were only undertaken in good weather conditions (high visibility, Beaufort < 4, temperatures < 35°C) to ensure accurate data collection and to reduce observer fatigue.

A surveyor's theodolite (TopCon GTS-603 AF Electronic Total Station) was used to obtain positions of dolphin groups and vessels, with data recorded in real-time using the Vadar (vr 2.00.01b) software (E. Kniest, University of Newcastle). When dolphins were sighted, an initial position was taken with the theodolite, whilst group size, composition (calf presence/absence) and activity state were noted by observers using 7 x 50 mm Bushnell binoculars. For the purposes of this study, a "group" was defined as an association of dolphins in close proximity engaged in the same direction of travel and/or general activity. Five activity states were used: foraging, milling, resting, socialising, and travelling (Table 5.1). These activity states were mutually exclusive, and similar to those used in other studies (e.g. Lusseau, 2003a). The predominant activity state was considered as the activity based on the most frequently observed behaviours, rather than the proportion of individuals engaged in an activity, to account for the varying availabilities of different individuals for observation. A theodolite position was taken at every surfacing interval while within the study area, with the exception of times when the surfacing interval was too brief to obtain an accurate reading. Where possible, theodolite positions were taken on the leading animal. Dolphins were continuously tracked until the shift ended or the group was lost.

Vessels were tracked continuously during their time in the study area (irrespective of dolphin presence), using the same theodolite. Vessel identity was noted based on either the name or

Figure 5.1: Map of the Fremantle Inner Harbour study area, showing the location of the theodolite hill-top station (red star).

a relevant physical description (hull/canopy colour, crew, distinguishing features, etc.) to allow continual tracking, regardless of the number of vessels present.

5.2.2 Acoustic Data Collection

A high-frequency autonomous acoustic logger was deployed in the Fremantle Inner Harbour (-32.042033° S, 115.752810° E) from April to June 2015, overlapping with the third season of visual observations. The logger was assembled at the Centre for Marine Science and Technology (CMST); it was equipped with a programmable 16-bit digital sound recorder (made by Wildlife Acoustics Inc.) and an external hydrophone (Reson TC4033-1, sensitivity –202.8 dB re 1 µPa/V), which entered the housing via a bulkhead connector to an impedance matching pre-amplifier with 20 dB gain. Digitised recordings were written to four 128 GB SD cards. Before deployment, the

Table 5.1: Definition of dolphin activity states (adapted from Shane *et al.* (1986) and Lusseau (2003a))

Activity State	Definition
Foraging (FO)	Dolphins involved in any effort to capture and consume prey, often involving quick, steep dives of long duration. Diving birds or jumping fish may also be observed.
Milling (MI)	Dolphins show frequent changes in heading, but stay in same location with no net movement.
Resting (RE)	Dolphins engaged in slow movements or 'logging' at the surface.
Socialising (SO)	Dolphins engaged in a diverse number of interactive behavioural events, including body contact, chasing, leaping, or hitting the water surface with body parts. Groups may split or join.
Travelling (TR)	Dolphins engaged in persistent, directional movement with short, relatively constant dive intervals.

logger was calibrated by applying white noise of known power spectral density. A high-pass filter was employed to filter out high levels of low-frequency noise, thus enhancing the dynamic range of the recorder at the frequencies of interest. The logger recorded at a duty cycle of 10 min every 15 min at a sampling frequency of 96 kHz.

5.2.3 Data Analysis

Each survey was divided into 5-min samples, starting at integer multiples of 5 min. For example, if a shift commenced at 06:47 hrs then the first sample was 06:50 – 06:55 hrs, the second sample 6:55 – 07:00 hrs, and so on. For each 5-min behavioural sample, the dolphins' predominant activity state was determined based on the most frequently observed behaviour. Group size and composition for each sample were also noted. A 5-min period was selected as this best captured the occurrence of behavioural states that were exhibited often over a relatively short period, such as resting and socialising.

To determine the context of vessel traffic conditions, vessel densities were calculated based on the number of vessels present in the study area during any 5-min sample. This definition was based on previous research that found the majority of vessels to transit through this area in less than 15 min, with the exception of vessels associated with port or bridge works (Marley *et al.*, 2016b). Vessel densities were then categorised according to a cut-off value based on the median number of vessels observed in any 5-min sample across the whole study period (median = 3). This resulted in 'low' and 'high' vessel traffic respectively being 0 – 3 and 4 – 16 vessels per 5-min sample.

5.2.3.1 Changes to Movement Speeds

The Vadar program automatically calculates a target's speed of travel based on the time and location of the previous versus the current theodolite position. In this study, a 'target' was considered to be a dolphin group, and speed calculations were based on the group speed rather than that of individual animals. Only samples with a minimum of two theodolite measurements were used, to ensure sufficient observations for speed calculations. This also ensured reliable speed estimates for animals 'looping' around the area. The average speed across all theodolite positions was then calculated for each 5-min sample, and paired with the corresponding dolphin activity state and level of vessel traffic, as defined above.

Analyses were undertaken by first comparing all activity states using a Kruskal-Wallis Test to determine whether activity state was associated with average speed. Mann-Whitney U Tests were subsequently used to identify the source of differences. To investigate whether dolphin average speed varied according to vessel traffic, a series of Mann-Whitney U Tests were conducted comparing average speeds during low and high vessel traffic for each activity state. These non-parametric tests were applied because a Shapiro-Wilk Test showed that the data were not normally distributed. All tests were conducted in R using the *stats* package (R Core Team, 2015).

5.2.3.2 Changes in Activity State

Assessing variation in animal behaviour is difficult due to the inherent temporal dynamics of activity states and changing contextual conditions. To quantify this temporal dependence and how context may change behaviour, Markov chains were employed to model dolphin responses to vessel density based on surface behaviour. First-order Markov chains were chosen, as these describe events which depend on the immediately preceding event (Caswell, 2001); thus, each activity state was examined with regard to the immediately preceding behaviour. The following methodology is an adaptation of Lusseau (2003a), where the background statistics are extensively described.

Vessel traffic conditions were categorised as either: (1) Low, (2) High, (3) Increasing, or (4) Decreasing. These definitions considered the preceding and succeeding samples, and were based on the cut-off value of 3 vessels per 5-min sample as per Section 5.2.3. For example, if both the preceding and succeeding behaviours occurred in low vessel density, conditions were classed as 'Low' (low-low). Likewise, if both the preceding and succeeding behaviours occurred in high vessel density the conditions were 'High' (high-high). However, the preceding behaviour could occur at low vessel density and the succeeding behaviour at high vessel density, or vice versa, creating third and fourth category options – respectively 'Increasing' (low-high) or 'Decreasing' (high-low).

A "transition" occurred when a dolphin group changed from a preceding activity state i to a succeeding activity state j, under a given vessel context. These transitions were recorded in a three-way contingency table, considering preceding versus succeeding activity state for each vessel traffic condition. Transition between a preceding and succeeding activity state was thus tallied into the appropriate section of the table that matched the vessel traffic conditions at that time. Based on this table, transition probabilities were computed to detect the effect of changing vessel densities on dolphin activity states. The transition probability was calculated by dividing the number of transitions by the total number of times i was seen as the preceding behaviour:

$$p_{ij} = \frac{a_{ij}}{\sum_{j=1}^{5} a_{ij}}, \sum_{j=1}^{5} p_{ij} = 1,$$

where i is the preceding behaviour, j is the succeeding behaviour, a_{ij} is the number of transitions observed from behaviour i to j, and p_{ij} is the transition probability from i to j in the Markov chain. Both i and j range from 1 to 5 because there are five activity states in this study. So, for example, when considering a Low vessel context, if there were 44 occasions when travelling transitioned into milling and 230 total observations where travelling was the preceding behaviour, then the transition probability for this pairing would be (44 / 230) = 0.19.

The transition probabilities from the Low chain were then compared to those of the three other vessel traffic conditions. A Z-Test for proportions was used for those comparisons where cell sample size was greater than five. Although a Yates' continuity correction could have been applied to account for small sample sizes in some cells, recent literature suggests this correction may be too strict so was not applied here (see Collins & Morris, 2008 and Hitchcock, 2009, for a review and discussion). All Z-Tests were conducted using the online EpiTools calculator (http://epitools.ausvet.com.au).

The activity budgets of dolphins in each vessel traffic condition were computed based on the same transition probabilities. The transition probabilities were arranged in four matrices (one for each vessel context chain), which were used to calculate the left eigenvectors of the dominant eigenvalues of each matrix. The left eigenvectors were calculated in Matlab (Version 2014a, The Mathworks Inc.) based on code provided in Caswell (2001). This produced five left eigenvectors for each of the four vessel conditions, representing each of the five activity states. To translate these into behavioural budget percentages, the proportion that each left eigenvector contributed to the sum was calculated. For example, when considering the left eigenvectors obtained from the Low vessel context, the left eigenvectors were 1.0195 (travelling), 0.0792 (resting), 0.4264 (milling), 0.4115 (foraging) and 0.2995 (socialising). These summed to give 2.2361, resulting in behavioural budgets of 46%, 4%, 19%, 18% and 13% for each activity state respectively. These behavioural budgets were then assessed via a Z-test for proportions to compare the Low (control) vessel context with the other three (impact) contexts, using the sample sizes of each vessel context.

5.2.3.3 Changes to Whistle Characteristics

Acoustic data were first subsampled to select acoustic files which overlapped with periods of visual monitoring, when only one dolphin group was present. This was firstly to ensure that data on group composition and behaviour were available, and secondly to have certainty as to which group was producing sounds.

The acoustic data were manually reviewed in Adobe Audition (Vr 8.1.0.162) to identify the presence, number and location of whistles in each file. Whistles were visually graded based on their signal-to-noise (SNR) ratio (as per Heiler *et al.*, 2016). Whistles were Grade 1 if the signal was faint, but visible on the spectrogram; Grade 2 if the signal was clear and unambiguous; and Grade 3 if the signal was prominent and dominant. Grades 2 and 3 were considered high-quality whistles, and only these were selected for further analysis. This ensured that only whistles with the entire contour clearly visible were measured, thus avoiding erroneous measurements due to masking of whistle components by other sources of noise. The grading system resulted in the elimination of a considerable number of whistles; however, since the aim of this study was to measure whistle characteristics rather than the number or occurrence of whistles, this was not expected to significantly affect the results. No attempt was made to distinguish signature whistles, although it has been suggested that they exist for this population (Ward *et al.*, 2016).

For each of these high-quality whistles, 11 acoustic characteristics were measured (Figure 5.2): (1) Duration, (2) Minimum Frequency, (3) Maximum Frequency, (4) Delta Frequency, (5) Start Frequency, (6) End Frequency, (7) Number of Inflection Points (where the curvature changes sign, second derivative = 0), (8) Number of Extrema (where the slope changes sign, first derivative = 0), (9) Presence/Absence of Harmonics, (10) Number of Steps, and (11) Number of Saddles (multiple derivatives = 0). Characteristics 1-4 were automatically measured using the Raven Pro software, whilst characteristics 5-11 were manually measured from visual inspection.

To investigate the relationship between underwater noise and dolphin whistles, separate Generalised Additive Models (GAMs) with contextual covariates were fitted for each of the whistle characteristics in turn. The explanatory variables initially considered for inclusion in each model were: dolphin activity state, dolphin group size, dolphin calf presence, and broadband noise levels. To attribute these data, whistles were first paired with a visual observation record of the dolphins, based on the temporally closest theodolite data. These data points provided an instantaneous

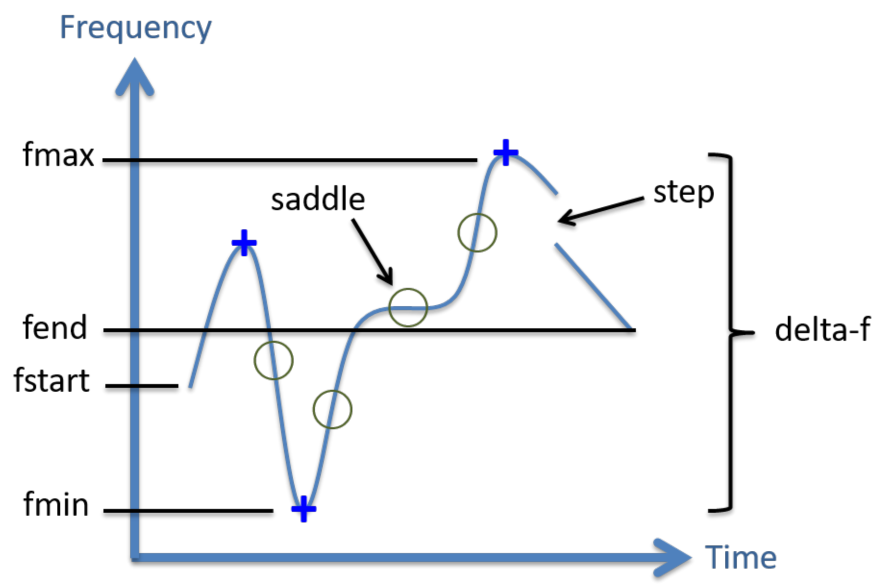

Figure 5.2: Example spectrogram showing several of the characteristics measured from each whistle. Inflection points are represented by '◯' and local extrema by '+'. Note that the saddle point is also an inflection point.

measure of activity state, group size and calf presence. If there was no theodolite observation within 10 min, the whistle was excluded from analysis. Secondly, the anthropogenic acoustic context in which whistles occurred was recorded as the broadband noise level (NL_BB) across the 2 s period immediately prior to each whistle. There is no literature regarding the time delay required before increased noise levels induce an acoustic change in dolphin whistles. However, studies of the Lombard effect in bats suggest that acoustic alteration to vocal emissions may occur at the neural level (< 200 ms; Gillam *et al.*, 2007; Hase *et al.*, 2016). With no other studies to refer to, a 200 ms (2 s) period was selected and the NL_BB calculated for this period immediately prior to each whistle. Although short, this period is longer than the average dolphin whistle recorded in the Fremantle Inner Harbour (Ward *et al.*, 2016).

GAMs were selected as they allow smoothing functions to be fitted to explanatory variables, generating curves which can flow more freely than a straight line for describing data. Although activity state and calf presence were included as factors and group size as a linear term, explanatory analyses indicated that NL_BB required fitting as a smoothed nonlinear term. A GAM with a logit-link binomial distribution was fitted for predicting the presence/absence of harmonics, whilst GAMs with a log-link Poisson distribution were fitted to predict counts of inflection points, extrema, steps and saddles. The remaining whistle characteristics represented continuous data, and so were fitted with a log-link gamma distribution.

The appropriateness and assumptions for each model were assessed in R (R Core Team, 2015). To verify independence of model errors, semi-variograms of standardised residuals were checked to ensure no temporal autocorrelation existed (Zuur *et al.*, 2009). Variance inflation factors (VIFs; Zuur *et al.*, 2010) were used to confirm the absence of concurvity (i.e. the non-parametric analogue of multi-collinearity) between explanatory variables. The absence of overdispersion was confirmed using the sum of squared Pearson residuals divided by sample size, minus the number of parameters.

Only the best fitting explanatory variables, chosen using the second-order Akaike information criterion corrected for small sample sizes (AICc; Burnham & Anderson, 2004), were included in the final model for each whistle characteristic. Models with a difference of < 2 AICc units are equally plausible as the best model to explain observed patterns in the data (Burnham & Anderson, 2004). In such situations, the Akaike's Information Criterion weight (wAICc) was calculated; the model with the greatest weight was then selected (Burnham & Anderson, 2004). The QQ-plots, histograms, and percentage of deviance explained were examined to quantify each model's goodness-of-fit (Zuur & Ieno, 2016). To further investigate where differences existed between activity states for each whistle characteristic, post-hoc tests with Tukey contrasts were calculated from the fitted model to conduct pairwise comparisons.

All analyses of whistle characteristics were conducted in R (R Core Team, 2015), using the packages: *car* (Fox & Weisberg, 2011); *MASS* (Venables & Ripley, 2002); *mgcv* (Wood, 2006); *multcomp* (Heiler *et al.*, 2016; Hothorn *et al.*, 2008); and *MuMIn* (Barton, 2016).

5.3 Results

A total of 217 h of visual observations were undertaken during 83 surveys over three years. Surveys ranged in duration from 0.5 to 4.1 h, and yielded a total of 185 dolphin group sightings in the study area. Of the cumulative 83 h of the 5-min samples collected, 28% of dolphin observations occurred in high vessel density conditions (i.e. a median of over three vessels per 5-min sample).

5.3.1 Dolphin Movement Speed

Average dolphin group speeds ranged from 0.03 to 2.67 m/s per 5-min sample (n = 782), and differed significantly among the five activity states (Kruskal-Wallis Test; X^2 = 77.381, df = 4, p < 0.001).

Average speeds for travelling (mean 0.81 ± standard deviation 0.02 m/s) were significantly higher than during all other activity states (Mann-Whitney U Tests; p < 0.01), whilst averaging speeds during resting (0.4 ± 0.05 m/s) were significantly lower than during all other activity states (p < 0.05; Figure 5.3a). There were no significant differences (p > 0.05) between average speed during foraging (0.61 ± 0.03 m/s), milling (0.59 ± 0.03 m/s) and socialising (0.69 ± 0.05 m/s).

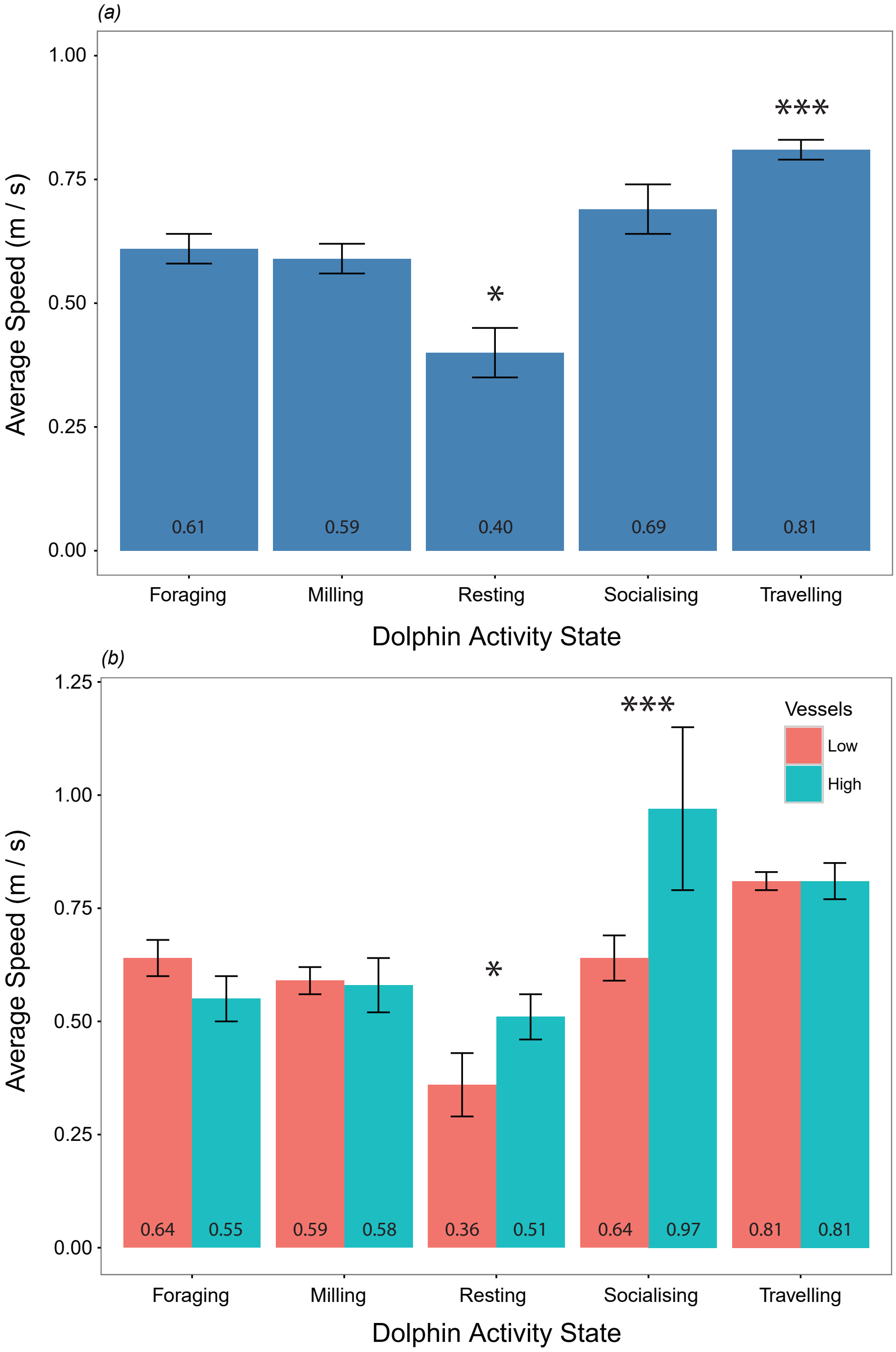

Figure 5.3: Average dolphin group movement speed according to (a) activity state and (b) high and low vessel densities for each activity state. Definitions for each activity state are provided in Figure 5.1. Numbers represent the average speed in m/s. Error bars represent the standard error.Significance level: ≤0.001 ***; ≤0.01 **; ≤0.05 *

Activity states were considered independently for different levels of vessel traffic (low or high). Mann-Whitney U Tests showed no significant differences ($p > 0.05$) in average speed between vessel contexts for travelling (low 0.81 ± 0.02 m/s; high 0.81 ± 0.04 m/s), foraging (low 0.64 ± 0.04 m/s; high 0.55 ± 0.05 m/s) or milling (low 0.59 ± 0.03 m/s; high 0.58 ± 0.06 m/s). Both resting (low 0.36 ± 0.07 m/s; high 0.51 ± 0.05 m/s) and socialising (low 0.64 ± 0.05 m/s; high 0.97 ± 0.18 m/s) average speeds significantly increased with increasing vessel densities (respectively, $U = 176.5$, $p = 0.01673$; $U = 503$, $p = 0.04216$; Figure 5.3b). However, these results should be interpreted with caution given the low sample sizes associated with high vessel densities (high $n = 10$ and 11, respectively).

5.3.2 Dolphin Activity State

A total of 714 activity state transitions were extracted from sequences of two adjacent 5-min samples. Transitions included 462 in Low vessel traffic, 139 in High vessel traffic, 56 in 'Increasing' vessel traffic, and 57 transitions in 'Decreasing' traffic conditions.

In any vessel traffic context, transition probabilities indicated that dolphins were most likely to continue travelling or foraging if that was the behaviour they were engaged in previously (with some exceptions, Figure 5.4). At High vessel densities, resting was most likely to transition to travelling, as was socialising. For Decreasing vessel densities, milling and resting animals were both most likely to begin travelling. By contrast, at Increasing vessel densities, resting and socialising were as likely to continue as they were to transition into travelling or milling activities.

Small sample sizes for some behaviours and vessel contexts prevented these from being statistically tested. Out of 75 possible activity state comparisons between the Low vessel density and the higher vessel impact conditions, 12 statistical comparisons were possible. For Low versus Increasing, activity state comparisons were made between travelling-to-travelling and milling-to-milling transition probabilities. For Low versus High, activity state comparisons were travelling-travelling, travelling-milling, travelling-foraging, milling-travelling, milling-milling, milling-foraging, and foraging-foraging. Finally, for Low versus Decreasing, activity state comparisons were travelling-travelling, travelling-milling and foraging-foraging. Of these 12 possible comparisons, only three were significantly different to the Low vessel context. When vessel density was Increasing, the probability of travelling-to-travelling (i.e. no transition in travelling behaviour) increased ($z = 2.1$, $p = 0.038$). When vessel density was High, the probability of milling transitioning to travelling decreased ($z = 2.1$, $p = 0.036$) and the probability of foraging to continue (foraging-to-foraging transition) increased ($z = 2.2$, $p = 0.028$).

Behavioural budget comparisons indicated that dolphins spent a greater proportion of time travelling ($z = 2$, $p = 0.0476$) and less time socialising ($z = 2.2$, $p = 0.0292$) when exposed to Increasing vessel densities than in Low conditions (Figure 5.5). When vessel density was

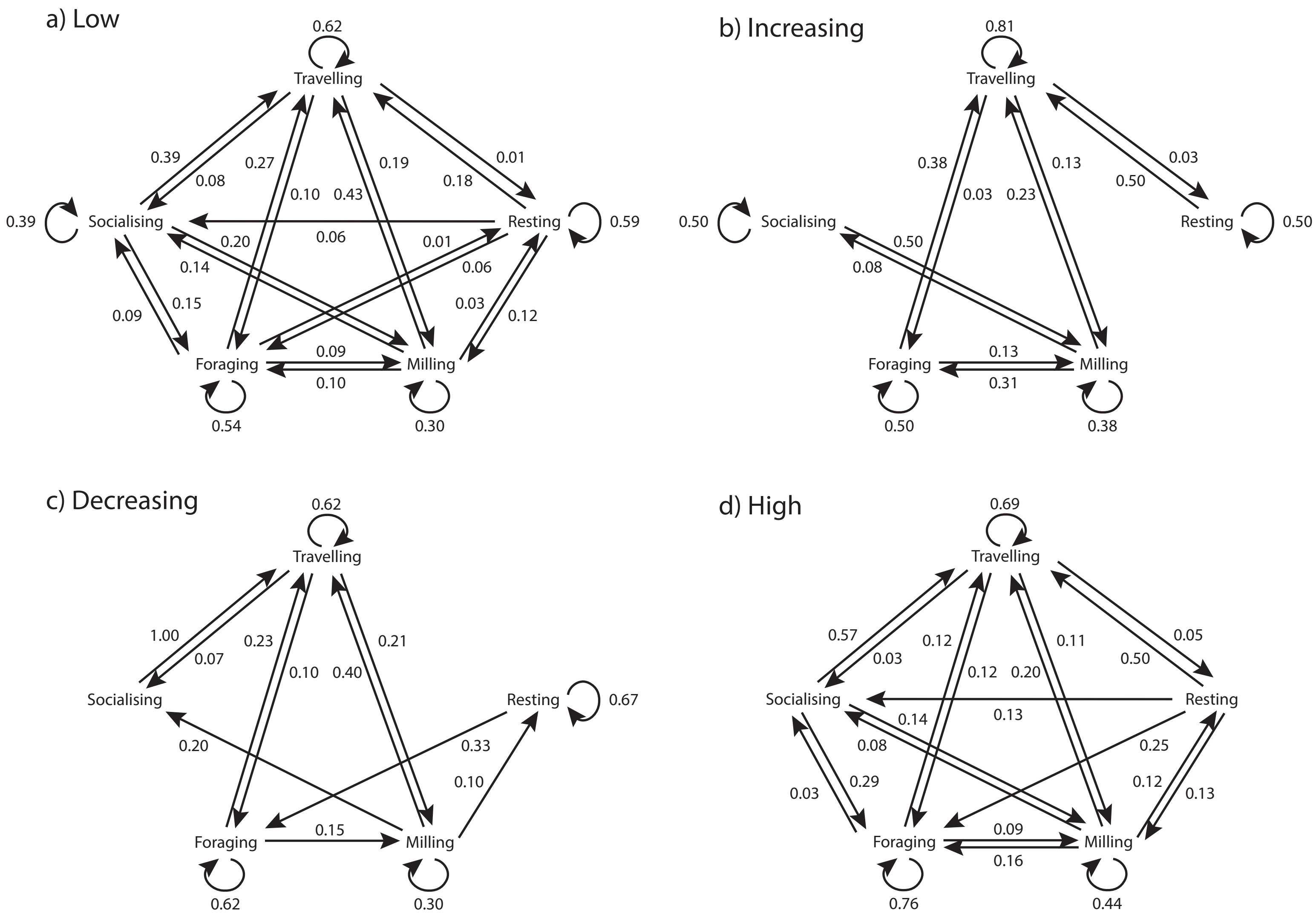

Figure 5.4: Markov chains representing transition probabilities between preceding and succeeding activity states in four different vessel contexts: (a) Low; (b) Increasing; (c) Decreasing; and (d) High vessel traffic. Definitions for each activity state are provided in Table 5.1.

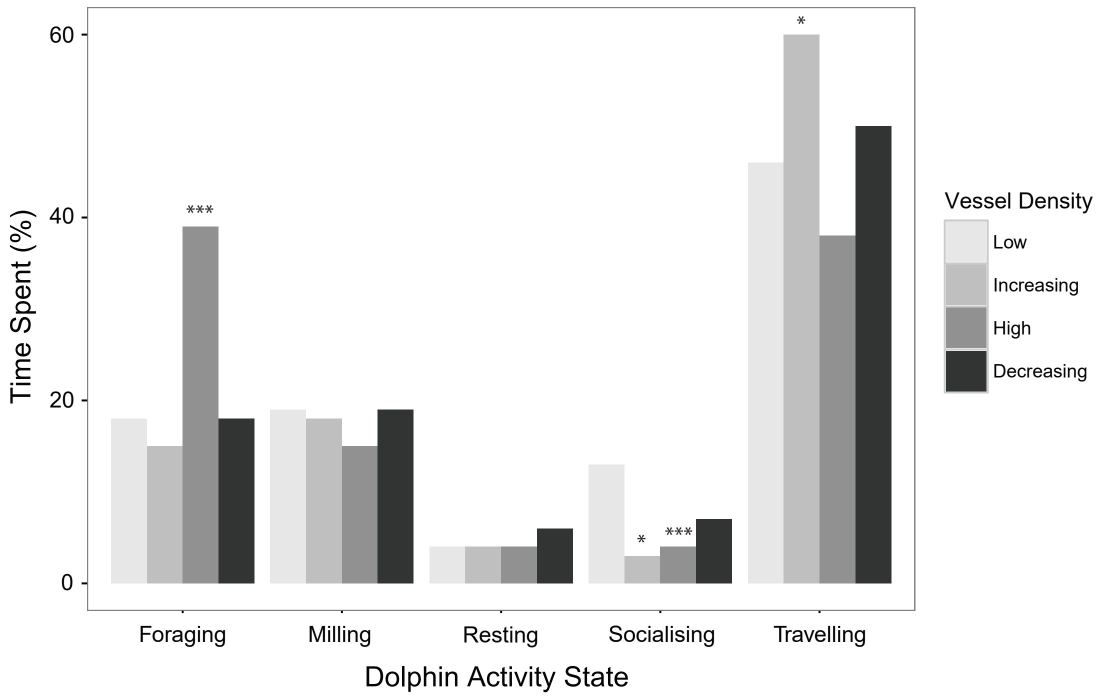

Figure 5.5: Behavioural budgets of dolphins in four different vessel contexts (Low, Decreasing, Increasing, and High). Results of Z-Test comparisons between Low and other vessel contexts are indicated: ≤0.001 ***; ≤0.01 **; ≤0.05 *

High, the proportion of time spent socialising was also significantly reduced ($z = 3$, $p = 0.0029$), whereas foraging significantly increased relative to Low vessel densities ($z = 5.2$, $p < 0.001$). The proportion of time spent in different activity states was not significantly different between Low and Decreasing vessel densities (all $p > 0.05$).

5.3.3 Whistle Characteristics

A total of 1,080 h of acoustic recordings were collected from 30th April to 14th June 2015. Mean broadband noise levels (NL_BB) over the whole recording period were approximately 110 dB re 1 µPa rms (10 Hz – 48 kHz; Figure 5.6). Approximately 35 h of these acoustic recordings overlapped with periods of visual monitoring; this low overlap was due to restricted visual survey opportunities during the single acoustic monitoring season. The recordings contained a total of 336 whistles when only one dolphin group was present in the study area. After visual assessment, 164 of these (captured during 2.7 h over nine days from 11 dolphin groups) were considered sufficiently high in quality to be measured and analysed.

The 164 whistles were produced in the presence of groups composed of 1 to 5 dolphins (mean = 2.4), 41% of which comprised calves. The majority of the 164 whistles were produced when the predominant activity state of the group was travelling (51%), followed by foraging (25%

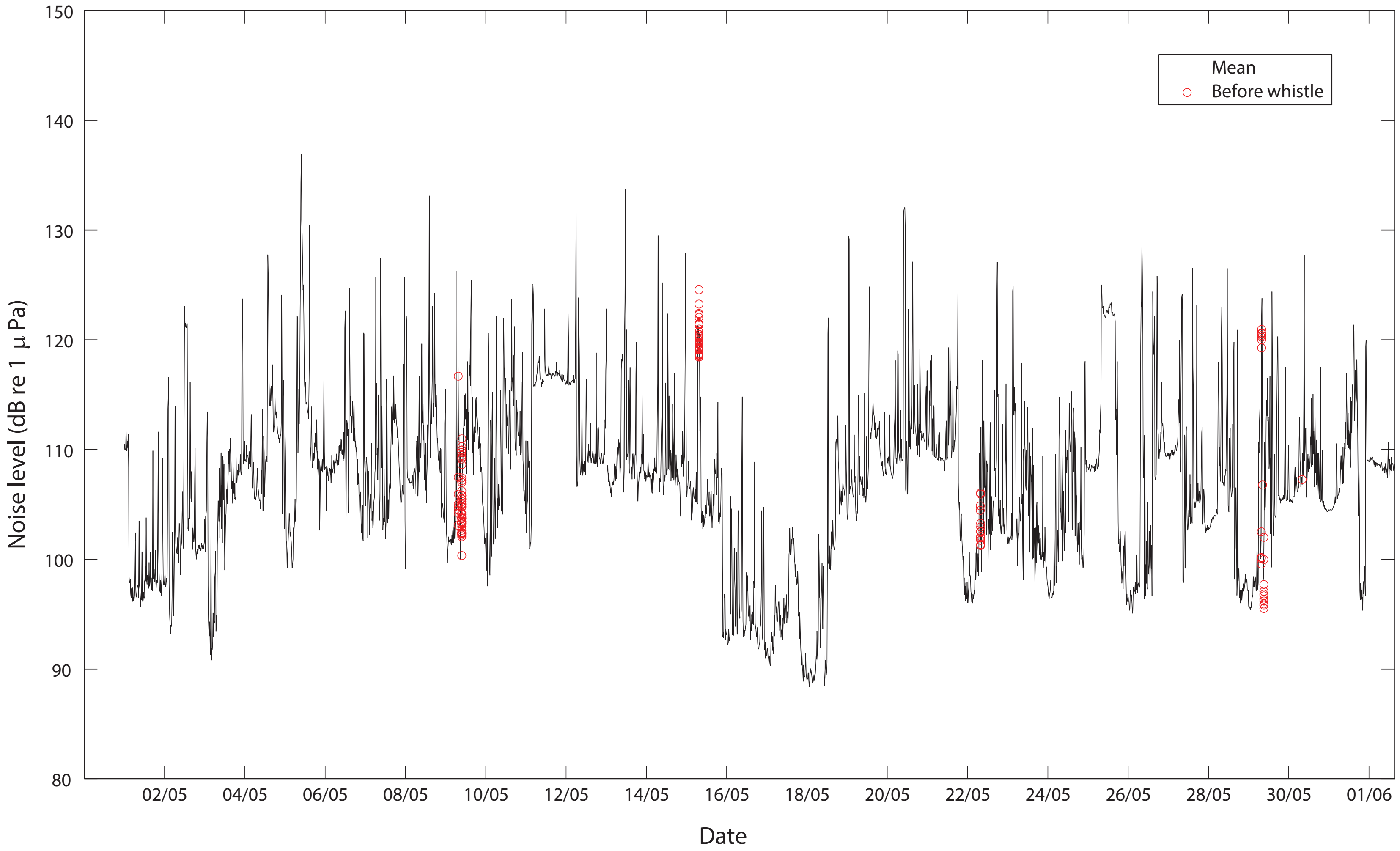

Figure 5.6: Mean broadband noise levels over the entire recording period in Fremantle Inner Harbour (-), including indications of the time and noise levels two seconds prior to analysed dolphin whistles (red circles).

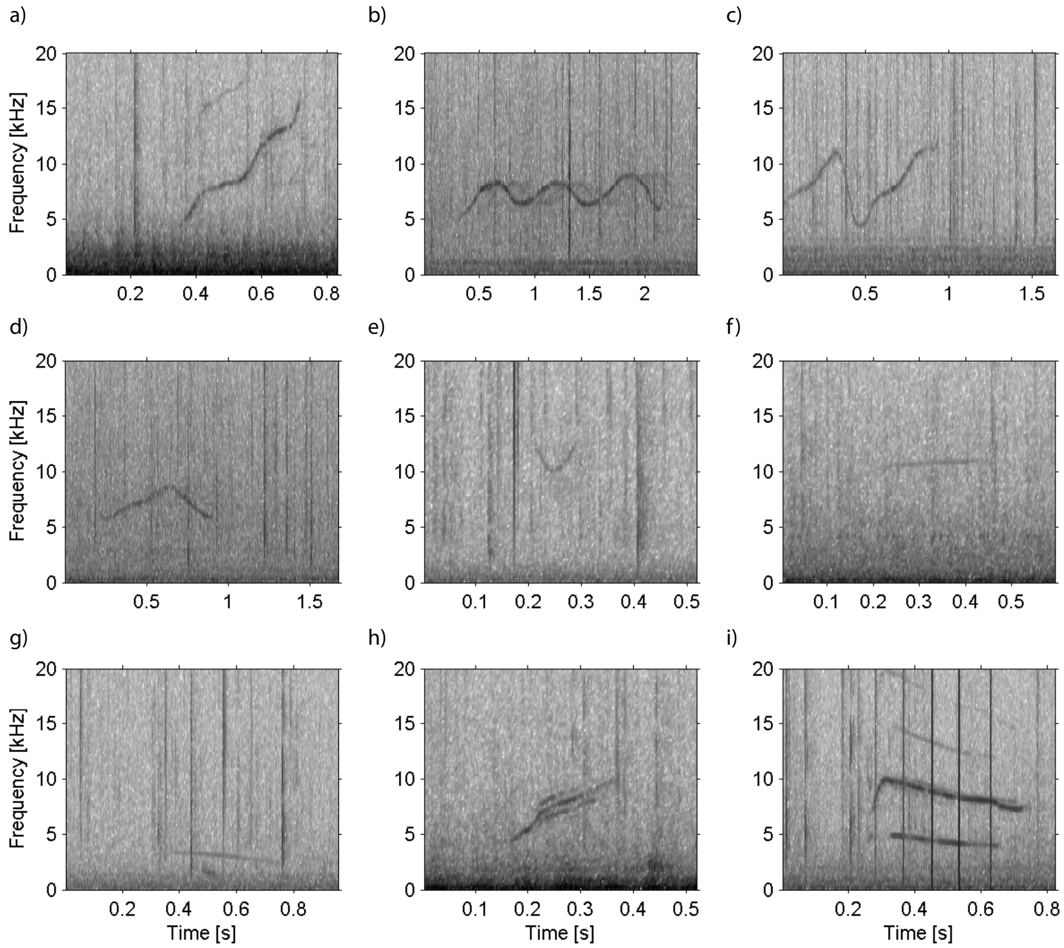

Figure 5.7: Examples of the seven whistle types recorded in association with dolphins within the Fremantle Inner Harbour: a) upsweep, b) sine (with reflection in the background), c) complex, d) convex, e) concave, f) constant, and g) downsweep. Also presented are some 'unusual' whistles, unlike others previously observed at this site: h) upsweep with sidebands, and i) biphonation.

association), milling (13%) and socialising (10%). No high-quality whistles were obtained whilst animals were resting. Seven whistle types were recorded (Figure 5.7): upsweep (51% of high-quality whistles), sine (24%), complex (15%), convex (7%), concave (≤ 1%), constant (≤ 1%), and downsweep (≤ 1%). These included some unusual whistles with sidebands (Figure 5.7h) and a potential biphonation (Figure 5.7i). Also apparent was an effect from the sound propagation environment, where whistles were recorded reflecting off either the harbour walls or vessel hulls near the receiver (Figure 5.7b). The 164 whistles had a mean duration of 0.59 s (± 0.48 standard deviation; Table 5.2), mean minimum frequency of 4.5 kHz (± 1.5), mean maximum frequency of 11.8 kHz (± 2.5), mean delta frequency of 7.4 kHz (± 3.4), mean start frequency of 4.7 kHz (± 1.7), mean end frequency of 11.1 kHz (± 3.3), mean number of inflection points of 2.7 (± 2.4), mean number of extrema of 1.4 (± 2.3), mean number of steps of 0.1 (± 0.7), and mean number of saddles of 0.1 (± 0.4). Harmonics were present in 35% of the whistles.

Table 5.2: Summary statistics for all whistle characteristics, excluding Harmonics as this was a binary response variable. Note that 'count' refers to the number of whistles in which a characteristic was observed (e.g. only six whistles contained the 'step' characteristic).

	Duration (s)	Min Freq (Hz)	Max Freq (Hz)	Delta Freq (Hz)	Start Freq (Hz)	End Freq (Hz)	Inflections	Extrema	Steps	Saddles
Count	164	164	164	164	164	164	144	81	6	19
Minimum	0.0700	1152	3658	1055	1152	2054	0	0	0	0
Mean	0.5893	4480	11833	7352	4710	11070	3	1	0	0
Maximum	4.8630	9821	17498	14230	12626	17497	20	21	5	2

All of the whistle characteristics measured were associated with NL_BB and dolphin activity state (Table 5.3), and to a lesser extent with group size and the presence of calves. GAMs were fit to 161 of the 164 whistles, as three were removed as outliers. GAMs included all whistle characteristic measures as response variables, except for the number of steps or saddles due to small sample sizes (< 20 whistles). Whistle duration, minimum frequency, start frequency, number of extrema and presence of harmonics decreased with increasing NL_BB (Figure 5.8). In comparison, maximum frequency, end frequency, and change in frequency (delta frequency) typically increased with increasing noise. Therefore, when noise levels were high, recorded whistles were typically of shorter duration but increased frequency range, starting lower and ending higher, with more inflection points but fewer extrema and harmonics. These changes typically occurred around NL_BB ≥ 110 dB re 1 μPa rms (10 Hz – 48 kHz).

Differences in all whistle characteristics occurred between travelling and foraging dolphins (Table 5.3; Tukey post-hoc tests, Figure 5.9). All frequency measurements and harmonics were significantly different between milling and foraging dolphins, representing two-thirds of all whistle characteristics. Similarly, two-thirds of whistle characteristics significantly differed between travelling and socialising dolphins, namely: duration, minimum frequency, delta frequency, start frequency, inflection points, and extrema. Fewer differences existed between the remaining activity state pairs. Differences included those in duration, inflection points, and extrema between travelling and milling; minimum and delta frequencies between socialising and milling; and the presence of harmonics between socialising and foraging. The whistles of foraging and socialising dolphins were typically short but covered a wide frequency range, generally starting low and ending high, with few inflections, extrema or (in the case of foraging dolphins) harmonics. Whistles recorded in the presence of milling dolphins were also relatively short but had a smaller frequency range, with low numbers of inflection points and extrema, though they generally included harmonics. Finally, whistles recorded in the presence of travelling dolphins were usually of longer duration and a lower frequency range, but contained the highest numbers of inflections and extrema.

Group size and the presence of calves had a mixed association with whistle characteristics. Group size was only significantly related to whistle duration, maximum frequency, delta frequency, inflection points and extrema (Table 5.3; Figure 5.10). Values for these characteristics were typically highest for group sizes of two or three animals. Therefore, whistles recorded when dolphin duos or trios were present were typically of longer duration, with higher maximum and delta frequency values (but unchanged minimum frequency) and contained a greater number of inflections and extrema compared to singletons and group of four and five animals.

The presence of a calf significantly affected all frequency characteristics and inflection points (Table 5.3; Figure 5.11), with all mean values increasing, except for the minimum and start frequencies. Consequently, whistles recorded when calves were present typically started at a lower frequency and ended at a higher frequency (giving a correspondingly high delta frequency), plus had lower minimum and higher maximum frequency values and a greater number of inflection points.

Table 5.3: Summary of the best fitting model for each whistle characteristic considering broadband noise levels, dolphin activity state, group size and calf presence. Explanatory variables with 'NA' were not included in the final model. Significance level: ≤0.001 ***; ≤0.01 **; ≤0.05 *

Duration					
Smooth Term	**EDF**	**F**	**p value**		
NL_BB	3.814	4.45	0.00107		**
Parametric Terms	**Parameter Estimate**	**Std. Error**	**t value**	**p value**	
Intercept	-1.27040	0.13895	-9.143	3.66e-16	***
Activity State					
Milling	-0.12007	0.11740	-1.023	0.3080	
Socialising	-0.74158	0.15895	-4.666	6.69e-06	***
Travelling	0.20874	0.08920	2.340	0.0206	*
Group Size	0.25221	0.05753	4.384	2.16e-05	***
Calf Presence	NA	NA	NA	NA	
Min Frequency					
Smooth Term	**EDF**	**F**	**p value**		
NL_BB	3.26	6.187	0.000102		***
Parametric Terms	**Parameter Estimate**	**Std. Error**	**t value**	**p value**	
Intercept	8.30880	0.04726	175.793	< 2e-16	***
Activity State					
Milling	0.17376	0.07937	2.189	0.03010	*
Socialising	0.07199	0.09986	0.721	0.47205	
Travelling	0.17464	0.06088	2.869	0.00471	**
Group Size	NA	NA	NA	NA	
Calf Presence	-0.09619	0.05534	-1.738	0.08149	

Max Frequency					
Smooth Term	**EDF**	**F**	**p value**		
NL_BB	3.14	21.46	1.08e-14		***
Parametric Terms	**Parameter Estimate**	**Std. Error**	**t value**	**p value**	
Intercept	9.37662	0.02303	407.127	< 2e-16	***
Activity State					
Milling	-0.14304	0.03867	-3.699	0.000302	***
Socialising	-0.13646	0.04846	-2.816	0.005506	**
Travelling	-0.11681	0.02961	-3.944	0.000122	***
Group Size	NA	NA	NA	NA	
Calf Presence	0.20377	0.02692	7.570	3.28e-12	***
Delta Frequency					
Smooth Term	**EDF**	**F**	**p value**		
NL_BB	3.839	20.83	3.51e-16		***
Parametric Terms	**Parameter Estimate**	**Std. Error**	**t value**	**p value**	
Intercept	8.88953	0.05168	172.010	< 2e-16	***
Activity State					
Milling	-0.35244	0.08673	-4.064	7.72e-05	***
Socialising	-0.29466	0.11114	-2.651	0.00887	**
Travelling	-0.35491	0.06701	-5.297	4.06e-07	***
Group Size	NA	NA	NA	NA	
Calf Presence	0.45766	0.06094	7.510	4.7e-12	***
Start Frequency					
Smooth Term	**EDF**	**F**	**p value**		
NL_BB	4.474	6.929	3.94e-06		***
Parametric Terms	**Parameter Estimate**	**Std. Error**	**t value**	**p value**	
Intercept	8.35023	0.04850	172.158	< 2e-16	***
Activity State					
Milling	0.15909	0.08120	1.959	0.05194	

Socialising	0.09588	0.10589	0.905	0.36667	
Travelling	0.18008	0.06320	2.849	0.00499	**
Group Size	NA	NA	NA	NA	
Calf Presence	-0.10563	0.05756	-1.835	0.06843	
End Frequency					
Smooth Term	**EDF**	**F**	**p value**		
NL_BB	3.243	17.68	1.71e-12		***
Parametric Terms	**Parameter Estimate**	**Std. Error**	**t value**	**p value**	
Intercept	9.35074	0.03489	267.968	< 2e-16	***
Activity State					
Milling	-0.15346	0.05860	-2.619	0.00971	**
Socialising	-0.21389	0.07368	-2.903	0.00425	**
Travelling	-0.21882	0.04494	-4.869	2.77e-06	***
Group Size	NA	NA	NA	NA	
Calf Presence	0.23310	0.04084	5.707	5.80e-08	***
Inflections					
Smooth Term	**EDF**	**Chi-square**	**p value**		
NL_BB	4.108	14.58	0.0139		*
Parametric Terms	**Parameter Estimate**	**Std. Error**	**t value**	**p value**	
Intercept	-0.29536	0.29108	-1.015	0.310256	
Activity State					
Milling	-0.76595	0.24421	-3.136	0.001710	**
Socialising	-1.23611	0.36062	-3.428	0.000609	***
Travelling	0.04023	0.15075	0.267	0.789573	
Group Size	0.45154	0.11981	3.769	0.000164	***
Calf Presence	0.61350	0.13797	4.446	8.73e-06	***
Extrema					
Smooth Term	**EDF**	**Chi-square**	**p value**		
NL_BB	3.353	26.12	3.84e-05		***

Parametric Terms	Parameter Estimate	Std. Error	t value	p value	
Intercept	-2.6727	0.4758	-5.618	1.94e-08	***
Activity State					
Milling	0.8539	0.613	1.851	0.064129	
Socialising	-1.3227	0.7810	-1.694	0.090323	
Travelling	1.6834	0.3735	4.508	6.56e-06	***
Group Size	0.5887	0.1655	3.558	0.000374	***
Calf Presence	NA	NA	NA	NA	
Harmonics					
Smooth Term	**EDF**	**Chi-square**	**p value**		
NL_BB	7.306	16.04	0.0455		*
Parametric Terms	**Parameter Estimate**	**Std. Error**	**t value**	**p value**	
Intercept	-2.7016	0.6562	-4.117	3.83e-05	***
Activity State					
Milling	3.0940	0.8174	3.785	0.000154	***
Socialising	0.8052	1.0343	0.778	0.436307	
Travelling	2.5907	0.7374	3.513	0.000442	***
Group Size	NA	NA	NA	NA	
Calf Presence	NA	NA	NA	NA	

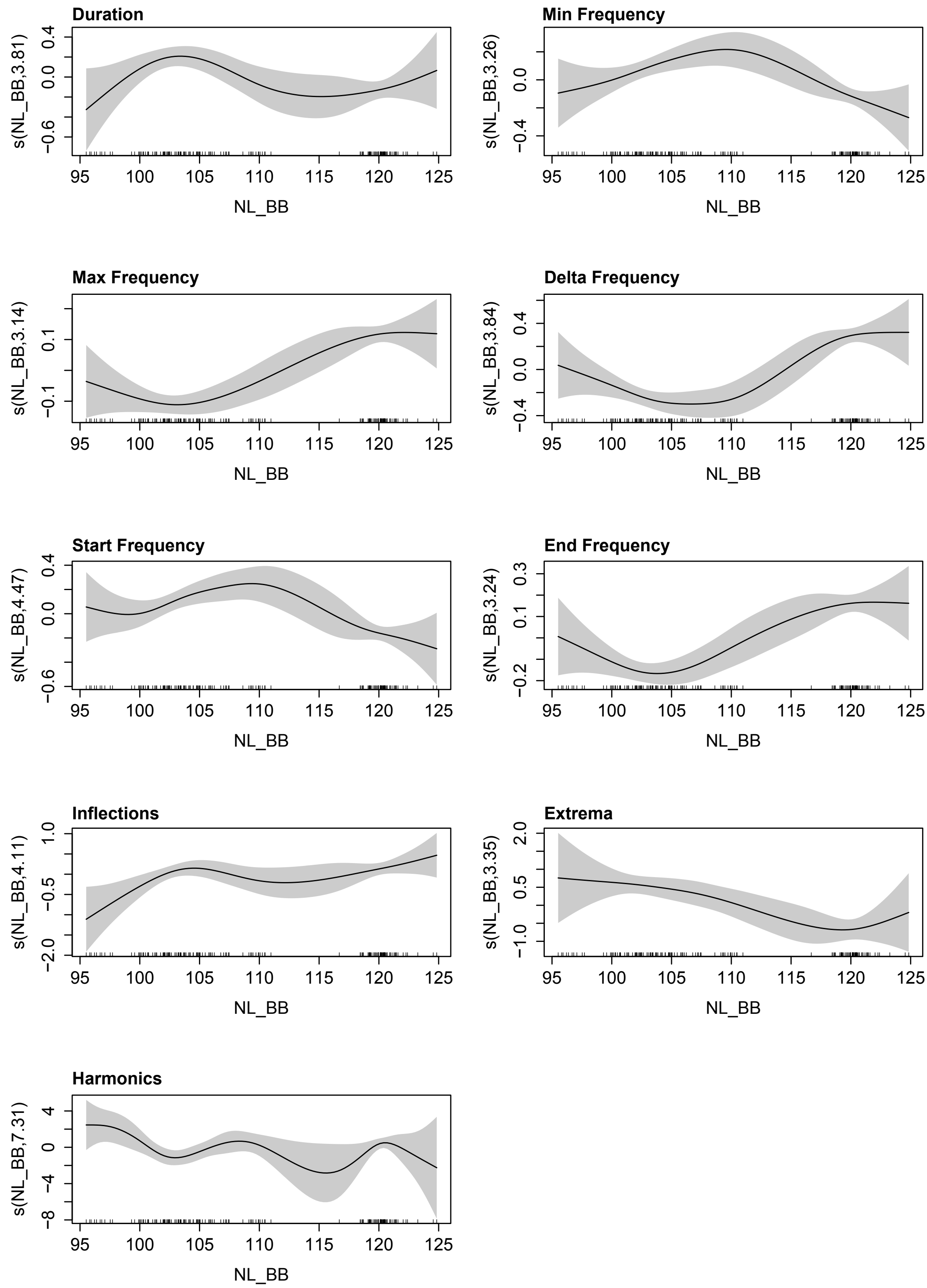

Figure 5.8: Results of the nine whistle characteristic GAMs which selected broadband noise level (NL_BB) as a significant explanatory variable.

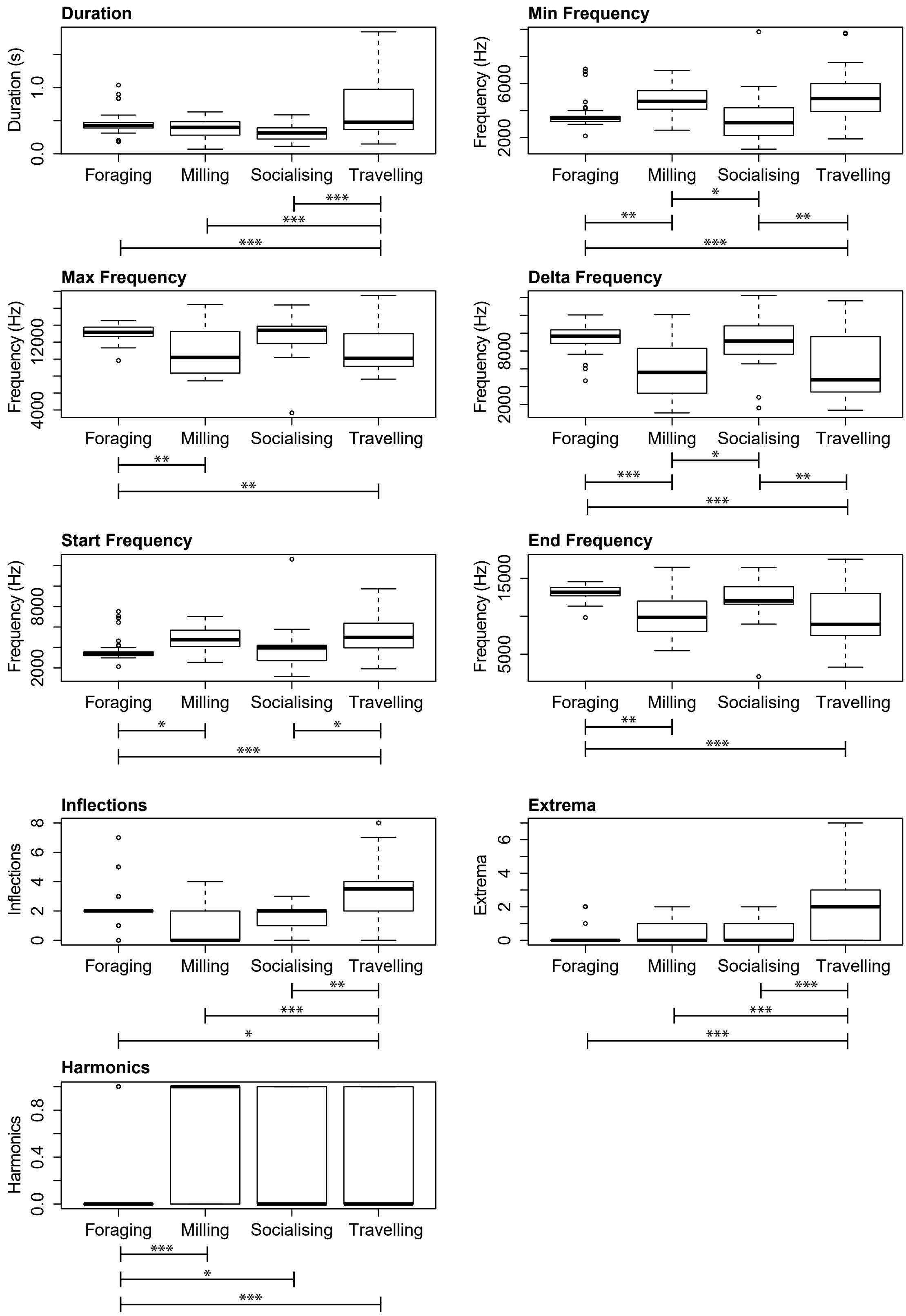

Figure 5.9: Results of the nine whistle characteristic GAMs which selected dolphin activity state as a significant explanatory variable. Post-hoc tests were used to test for differences between behavioural states. Significance level: ≤0.001 ***; ≤0.01 **; ≤0.05 *

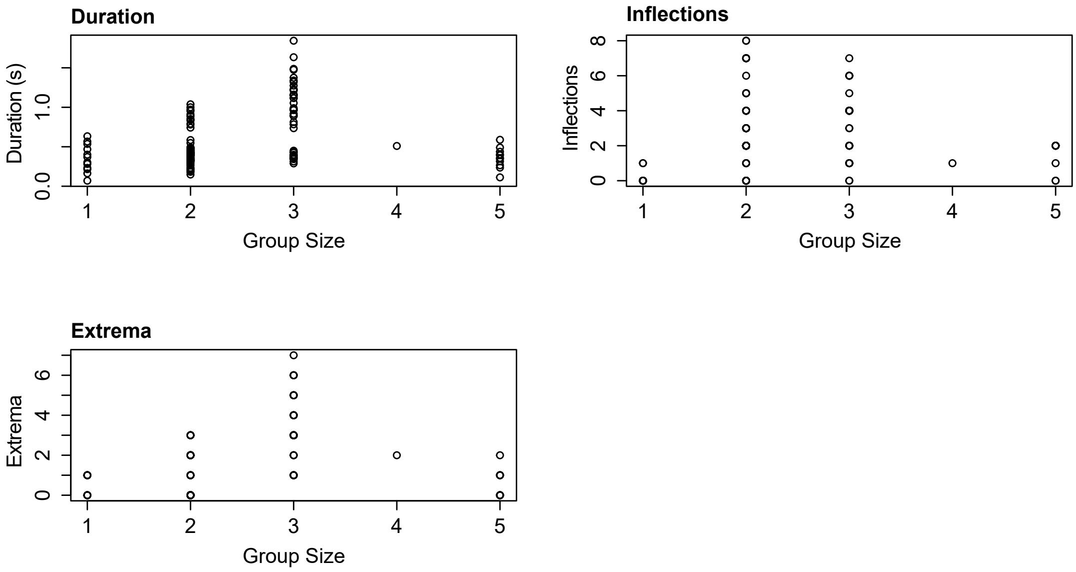

Figure 5.10: Results of the three whistle characteristic GAMs which selected dolphin group size as a significant explanatory variable.

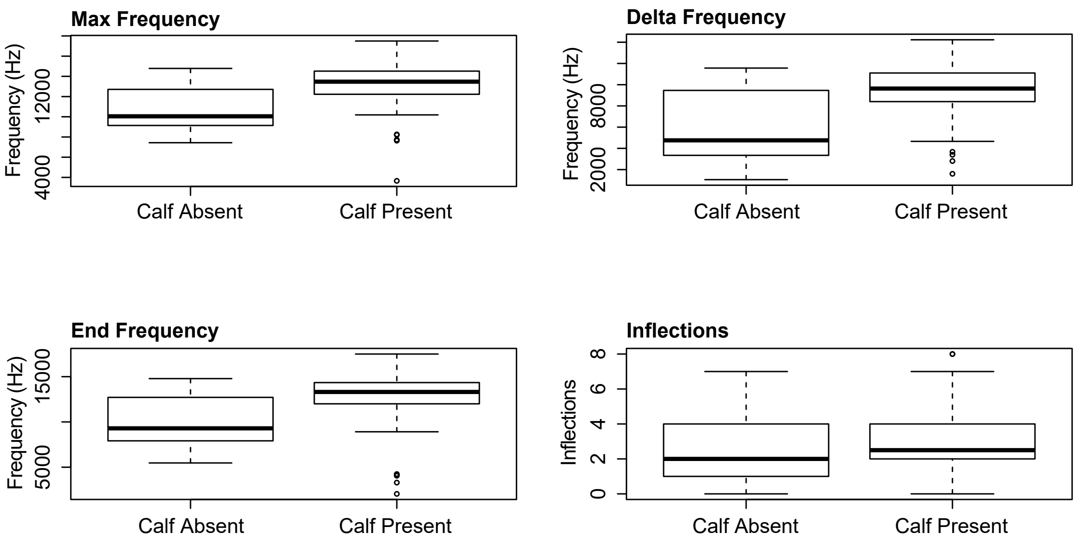

Figure 5.11: Results of the four whistle characteristic GAMs which selected the presence of dolphin calves as a significant explanatory variable.

Investigation into noise levels at specific frequency levels revealed associations between whistle characteristics and twelve octave-band levels (OBLs). However, the bands showed high collinearity, and only three (with VIFs < 5) were accordingly included in GAMs: 1 kHz, 16 kHz and 32 kHz. While dolphins have been reported to show sensitivity to noise at 100 Hz (Johnson, 1967; Turl, 1993) and even to produce sounds with fundamental frequencies as low as 260 Hz (Schultz *et al.*, 1995), only the three OBLs listed above were included as they are within the frequency range of most dolphin whistles recorded.

The 1 kHz OBL (NL_1000) was associated with all whistle characteristics in the best fitting models (Table 5.4; Figure 5.12). Whistle duration, minimum frequency, start frequency, extrema and harmonics generally declined when NL_1000 was high, whereas the remaining frequency characteristics typically increased. Inflections showed variable results. The 16 kHz OBL (NL_16000) was associated with maximum frequency, inflections and harmonics, which all decreased as NL_16000 increased (Figure 5.13). Finally, the 32 kHz OBL (NL_32000) was associated with six whistle characteristics; typically with increasing duration, extrema and harmonics, decreasing delta frequency and end frequency, and displaying mixed results for inflections (Figure 5.14). Based on the number of characteristics affected, lower-frequency noise generally was overall more strongly associated with dolphin whistle characteristics than higher-frequency noise.

Table 5.4: Summary of the best fitting model for each whistle characteristic, considering octave-band levels (OBLs) centred around 1 kHz (NL_1000), 16 kHz (NL_16000), and 32 kHz (NL_32000). Explanatory variables with 'NA' were not included in the final model. Significance level: ≤0.001 ***; ≤0.01 **; ≤0.05 *

Duration					
Parametric Terms	**Parameter Estimate**	**Std. Error**	**t value**	**p value**	
Intercept	-0.65978	0.03453	-19.11	< 2e-16	***
Smooth Term	**EDF**	**F**	**p value**		
NL_1000	8.423	7.810	9.84e-10		***
NL_16000	1.000	3.820	0.052602		
NL_32000	8.000	3.532	0.000665		***
Min Frequency					
Parametric Terms	**Parameter Estimate**	**Std. Error**	**t value**	**p value**	

Intercept	8.3862	0.0213	393.8	< 2e-16	***
Smooth Term	**EDF**	**F**	**p value**		
NL_1000	8.103	10.024	5.02e-12		***
NL_16000	4.765	1.675	0.114		
NL_32000	NA	NA	NA		
Max Frequency					
Parametric Terms	**Parameter Estimate**	**Std. Error**	**t value**	**p value**	
Intercept	9.37007	0.01236	758.0	< 2e-16	***
Smooth Term	**EDF**	**F**	**p value**		
NL_1000	3.808	25.40	< 2e-16		***
NL_16000	1.000	20.17	1.34e-05		***
NL_32000	NA	NA	NA		
Delta Frequency					
Parametric Terms	**Parameter Estimate**	**Std. Error**	**t value**	**p value**	
Intercept	8.84362	0.02947	300.1	< 2e-16	***
Smooth Term	**EDF**	**F**	**p value**		
NL_1000	3.868	19.24	5.20e-05		***
NL_16000	NA	NA	NA		
NL_32000	1.000	17.28	5.23e-05		***
Start Frequency					
Parametric Terms	**Parameter Estimate**	**Std. Error**	**t value**	**p value**	
Intercept	8.4294	0.0228	369.7	< 2e-16	***
Smooth Term	**EDF**	**F**	**p value**		
NL_1000	8.092	10.11	3.62e-12		***
NL_16000	3.528	1.58	0.188		
NL_32000	NA	NA	NA		
End Frequency					
Parametric Terms	**Parameter Estimate**	**Std. Error**	**t value**	**p value**	

Intercept	9.29580	0.01806	514.6	< 2e-16	***
Smooth Term	**EDF**	**F**	**p value**		
NL_1000	5.045	14.148	1.29e-13		***
NL_16000	NA	NA	NA		
NL_32000	1.428	9.049	0.000271		***
Inflections					
Parametric Terms	**Parameter Estimate**	**Std. Error**	**t value**	**p value**	
Intercept	0.89326	0.05163	17.3	< 2e-16	***
Smooth Term	**EDF**	**Chi-square**	**p value**		
NL_1000	7.902	19.253	0.0169		*
NL_16000	2.824	9.063	0.0599		
NL_32000	8.483	18.271	0.0267		*
Extrema					
Parametric Terms	**Parameter Estimate**	**Std. Error**	**t value**	**p value**	
Intercept	-0.3372	0.1702	-1.981	0.0476	*
Smooth Term	**EDF**	**Chi-square**	**p value**		
NL_1000	6.753	49.354	2.49e-08		***
NL_16000	2.108	3.846	0.19614		
NL_32000	1.000	10.734	0.00105		**
Harmonics					
Parametric Terms	**Parameter Estimate**	**Std. Error**	**t value**	**p value**	
Intercept	-1.5032	0.7219	-2.082	0.0373	*
Smooth Term	**EDF**	**Chi-square**	**p value**		
NL_1000	6.847	21.969	0.01558		*
NL_16000	1.000	5.974	0.01452		*
NL_32000	4.089	16.820	0.00514		**

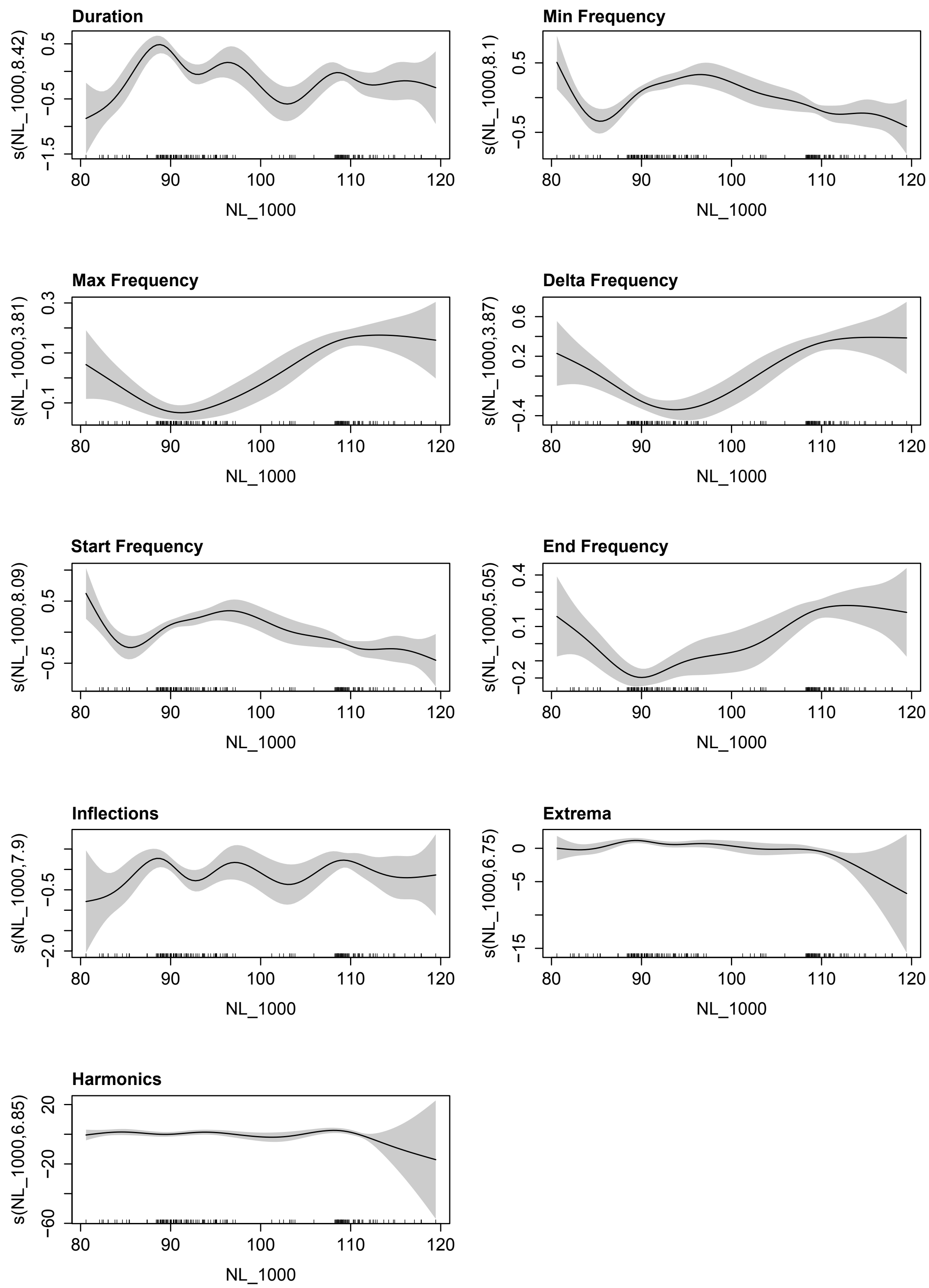

Figure 5.12: Results of the nine whistle characteristic GAMs which selected the 1 kHz octave-band level (NL_1000) as a significant explanatory variable.

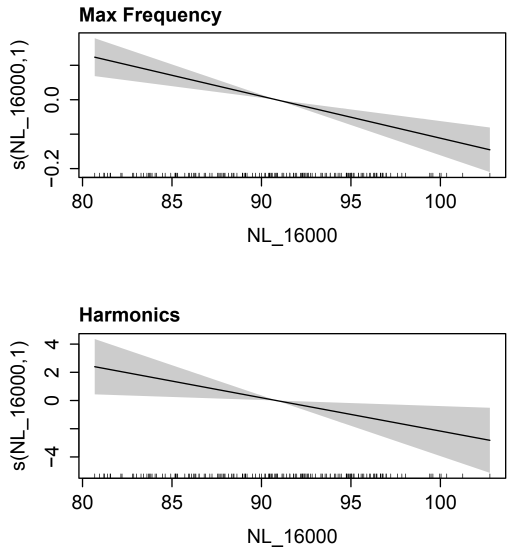

Figure 5.13: Results of the three whistle characteristic GAMs which selected the 16 kHz octave-band level (NL_16000) as a significant explanatory variable.

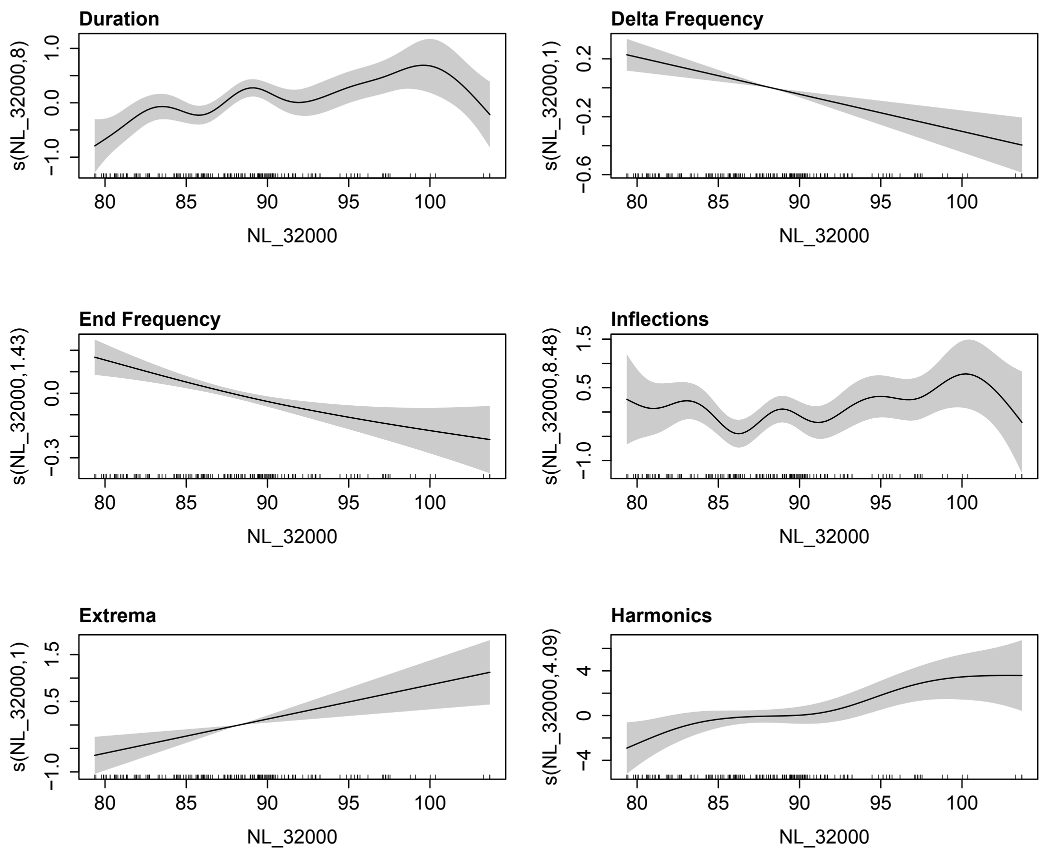

Figure 5.14: Results of the six whistle characteristic GAMs which selected the 32 kHz octave-band level (NL_32000) as a significant explanatory variable.

5.4 Discussion

This study showed significant changes in bottlenose dolphin behaviour in Fremantle Inner Harbour in association with high vessel densities and underwater noise. Animals' responses to stressors can take a variety of forms, such as occupancy in an area or changes to activity budgets. For instance, a previous study on dolphin detections in association with pile-driving conducted in Fremantle Inner Harbour documented reduced visual detection rates during pile-driving activity (Paiva *et al.*, 2015). This contrasts with more recent research at the same site, which found no alteration in the occurrence of dolphins in heavy vessel traffic during theodolite surveys (Marley *et al.*, 2016b). Here, dolphins did appear to change movement speed and activity states in response to vessel density, and whistle characteristics differed in varying underwater noise conditions.

While the average travel rates of dolphin groups were a function of activity state, their movement speed was also affected by vessel traffic. Animals moved fastest during travelling and slowest during resting activities. Resting and socialising groups significantly increased their average speed when vessel density was high. Captive studies suggest that higher swim speeds induce greater metabolic rates (Williams *et al.*, 1992; Yazdi *et al.*, 1999). The risk of impact may be particularly high for resting animals, in that they expend more energy than they would otherwise and their quality of rest is reduced. Resting is important for overall animal health. Disruption to resting activities can induce stress as well as reduce energy reserves, which ultimately affect an animals condition and immune function (Bishop, 1999; Constantine *et al.*, 2004; MacArthur *et al.*, 1979; Meerlo *et al.*, 2008; Tyne *et al.*, 2015). Thus an increase in dolphin movement speed whilst resting could have both physiological and energetic consequences at the individual-level.

Resting and socialising activity states were mainly observed during low vessel densities. While there was an observed increase in resting after high vessel densities, the increase was not statistically significant. This may be ensue from the limited power of the analysis caused by small sample sizes for this behaviour. Resting occurring during low vessel densities could reflect animals that were capitalising on less-busy periods to rest following exposure to high vessel traffic. In addition, female dolphins mainly nurse their calves while resting (Stensland & Berggren, 2007). The slight increase in resting behaviour after exposure to high vessel densities could therefore represent an opportunity for nursing. There were no differences between behavioural budgets during low and decreasing vessel contexts for any of the activity states. Thus, dolphins may make use of low or decreasing vessel density periods to return to their original activities.

Time spent socialising significantly shortened during increasing and high vessel densities. Socialising behaviour is important for the maintenance of conspecific relationships, calf play, and mating opportunities. If these behaviours are repeatedly interrupted there could be long-term population-level consequences (Lusseau & Bejder, 2007). For example, fewer successful mating attempts could result in lower reproduction rates and thus influence population dynamics. Play behaviour has been shown to be important to the development of dolphin calves as a method of learning physical manoeuvres, object manipulation, problem-solving skills, social behaviours, and foraging methods (Kuczaj *et al.*, 2006; Mann & Smuts, 1999; Pace, 2000). But play behaviour is less likely to occur in stressful situations (Pellis, 1991), and could also be disrupted if socialising events become less frequent. Decreased socialising opportunities for calves may therefore impact reproductive or foraging success when they become adults.

Dolphins spent more time travelling whilst vessel density was increasing. Travelling typically occurs at greater average movement speeds than other activity states, so may lead to increased energetic demands. Time spent travelling also leaves fewer opportunities to engage in other vital behaviours such as foraging or resting. Once vessel density was high, dolphins increased the time they spent foraging. Christiansen *et al.* (2010) also reported an increase in foraging when bottlenose dolphins encountered tour boats; yet many other studies have provided evidence to the contrary (Arcangeli & Crosti, 2009; Pirotta *et al.*, 2015; Steckenreuter *et al.*, 2012). Increased foraging activity could be an attempt to compensate for energy lost during disturbance, or could alternatively reflect changes in prey behaviours. For example, fish may scatter in response to vessel transits, making them easier to capture. The observed foraging behaviour may also have been erroneously reported. What was perceived as foraging behaviour could have been an increase in transitions to diving in the presence of tour boats, which has previously been hypothesised to represent vessel avoidance by utilising a different part of the water column (Lusseau, 2003a). Because high vessel densities characterised approximately 28% of the dolphin behavioural samples collected, dolphins could be expected to spend a significant proportion of time expending energy by altering their activities. If these indeed result in increased energy requirements, reduced fitness at both individual and population levels may occur (Lusseau, 2006).

Different vocal behaviours were also observed in contrasting noise conditions associated with presence of vessel traffic (among other sources). When noise levels were relatively high (≥ 110 dB re 1 µPa rms [10 Hz – 48 kHz]), whistles were typically short with a wide frequency range and had multiple inflection points and fewer extrema (similar to 'complex' whistles). At higher noise levels, harmonics were more frequently absent, though this could be the result of masking by noise at overlapping frequencies. Noise at lower frequencies was associated with the broadest differences in whistles, as differences were observed in all characteristics. This shares similarities with other studies. For example, May-Collado & Wartzok (2008) reported that dolphins produced higher frequency whistles in noisy habitats, and when multiple vessels were present dolphins whistled with greater frequency modulation, higher maximum frequency, and longer duration. Similarly, Heiler *et al.* (2016) detected an upward shift in several whistle frequency parameters in the presence of vessels. However, Morisaka *et al.* (2005) found that quieter habitats were associated with dolphins producing whistles at varying frequencies and greater modulation, whilst Buckstaff (2004) found no alteration in whistle duration or frequency as a result of vessel noise.

Whilst whistle characteristics varied with noise levels, they also varied according to activity state, group size and calf presence. This has also been documented in other studies: Hernandez *et al.* (2010) found minimum frequency, inflection points, and duration to be useful for determining dolphin activity states. Heiler *et al.* (2016) found whistles to be longer and contain more inflection points during resting in comparison to when dolphins were feeding or socialising. They also reported a reduction in end frequency and minimum frequency, but an increase in whistle duration, when calves were present in a group. In the present study, the whistles of foraging and socialising groups were typically associated with whistles of short duration and wide frequency range, starting low and ending high, with few inflections and extrema (similar to 'upsweeps'). In contrast, travelling groups exhibited longer-duration whistles that spanned a narrower frequency range but contained the highest numbers of inflections and extrema (similar to 'sine' whistles).

While the whistle sample size was large, the number of unique dolphin groups from which the samples were derived was very limited (n = 11). Merely three of these groups produced the majority of whistles analysed in this study, with remaining groups contributing < 20 whistles each. These three groups were engaged in one of two predominant activities (foraging or socialising), and were of specific group sizes (2 or 3 individuals) and compositions (two groups without calves, one with a calf). In this context, and despite the lack of apparent collinearity between noise levels and activity state, group size or presence of calves, it remains unclear whether noise is ultimately a proximate driver of the observed variation in whistle characteristics. Future research should focus on disentangling the effects of group from activity state, group size and calf presence. Furthermore, it was not possible to identify which individuals were producing the whistles. It is therefore possible that some individuals were re-sampled in this study, and that signature whistles unique to individual dolphins were captured multiple times. In the future, it would be beneficial to examine group composition in terms of which individual dolphins are present with regards to alterations in whistle characteristics in association with noise levels. This will help to clarify the most important drivers of whistle variations.

Bottlenose dolphins' whistles are highly plastic, which facilitates adaptation to dynamic environmental conditions (May-Collado & Wartzok, 2008) and communication requirements. Previous studies have found that dolphin metabolic rates increase during periods of sound production, and may take several minutes to return to resting values (Noren *et al.*, 2013). For example, increases in vocal effort as a result of increases in sound amplitude, repetition rate, or duration can have an energetic impact on individuals (Holt *et al.*, 2015). The types of sounds produced may also bear contrasting energy requirements (Holt *et al.*, 2016), and further work is needed to quantify this. In addition, if increased vessel density causes increases in travelling or foraging behaviours that are associated with greater energy demands for communication, the effects from boat traffic could be potentially magnified. This not only carries implications for dolphin energetic requirements but also highlights the complexity of disturbance responses in this species.

Quantifying the impacts of vessel traffic on dolphin metabolism from a conservation physiology perspective would be further enhanced by obtaining behavioural response information at an even finer resolution, e.g. by monitoring surfacing patterns, dive times, inter-animal spacing, within-site movements, whistle rates and individual behavioural events (Buckstaff, 2004; Guerra *et al.*, 2014; Hastie *et al.*, 2003; Janik & Thompson, 1996; Lusseau, 2003b, 2006; Nowacek *et al.*, 2001; Scarpaci *et al.*, 2000; Stensland & Berggren, 2007). In addition, determining how broadly these responses can be generalised to other sites within this dolphin community's home range and to other dolphin populations is required for effective management. For example, some locations may be mainly used for travelling or foraging, whereas others may act as resting or nursing grounds with an inherently higher risk of disruption. Individuals may even select to use 'quieter' sites for resting or socialising to compensate for decreases in these activity states at busier or noisier sites. Also some populations may be less energetically stressed than others, and are able to cope with greater energy demands at higher impact sites.

Future research to determine which vessel characteristics elicit responses would also improve the knowledge base for management decisions. A range of vessel types have been observed within the Fremantle Inner Harbour, each of which behave differently in terms of manoeuvrability, speed and noise characteristics produced (Marley *et al.*, 2016b). Investigating these variations and their potential influences on dolphin behaviour would allow regulation to include guidelines for boat operations within important dolphin habitats.

Recreational vessels are only allowed to transit through the Fremantle Inner Harbour, and cannot fish, mill or anchor for safety reasons. The majority of vessel transits occurred in less than 15 min (Marley *et al.*, 2016b). Dolphin-vessel interactions with recreational boaters were only observed twice in this study; in most cases, vessel occupants seemed unaware of dolphins present within meters of their boat. Boat drivers transiting may not have time to spot dolphins and consider interacting with them. Interactions of short duration such as these could allow vertical avoidance strategies by dolphins to be successful. However, these short-duration interactions within the Fremantle Inner Harbour may not be representative of interaction durations at other locations. Currently, there are no dedicated dolphin-watch tours in the Swan-Canning river system. However, if such tourism operations were introduced in other areas of the river, behavioural responses could occur more frequently, more intensely, and be broader in the types of responses seen here. Finally, the cut-off between 'low' and 'high' vessel traffic levels used in this study was based on the median number of vessels present in 5-min sampling blocks. Assessments of different time intervals for considering vessel densities would provide insight into responses over longer exposure periods.

In conclusion, dolphins within Fremantle Inner Harbour changed their movement speed, activity states, and whistle characteristics in increasing vessel traffic and underwater noise conditions. However, dolphins did not avoid the site altogether in response to high vessel densities (Marley *et al.*, 2016b). The behavioural responses observed in this study may lead to increased energetic demands for dolphins, through increased movement speeds, greater time spent travelling, less time resting/socialising, and increased vocal effort. Some of these energy requirements could be offset by the energy gained foraging at this site. The capture probability of prey responding to vessels transiting may even be improved. Further research is required to examine dolphin target prey species, prey responses to vessel traffic, and the possibility of vertical avoidance strategies by dolphins within the Fremantle Inner Harbour. The complexity of disturbance responses in this species justifies the inclusion of contextual information in future behavioural response studies.

5.5 Acknowledgements

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Chapter 6

A Tale of Two Soundscapes: Comparing the acoustic characteristics of urban versus pristine coastal dolphin habitats in Western Australia

Underwater noise environments are increasingly being considered for marine spatial planning and habitat quality assessments. Although the overall aim of regulation is to quieten anthropogenically noise-rich habitats whilst maintaining pristine habitats free of man-made noise, effective management plans require knowledge upon which to base decisions. Thus, managers of acoustically-specialised species such as dolphins require a categorisation of acoustic habitats and an understanding of how animals use these habitats. Dolphins in waters along the Western Australian coastline inhabit a range of habitats with varying levels of anthropogenic activities. This study aimed to compare the acoustic environment of coastal dolphins in two locations within Western Australia by comparing a 'pristine' habitat (Roebuck Bay in the Kimberley region) with an 'urban' habitat (Fremantle Inner Harbour in the Swan River). Autonomous underwater acoustic recorders were used to collect approximately 940 h of acoustic data from Roebuck Bay. These were compared with 1,080 h from the Fremantle Inner Harbour, gathered as part of a previous study. Additionally, in Roebuck Bay opportunistic *in situ* recordings using a hand-held hydrophone were obtained with concurrent visual observations in the presence of Indo-Pacific bottlenose (*Tursiops aduncus*) and snubfin (*Orcaella heinsohni*) dolphins. Acoustic data were assessed via weekly spectrograms, power spectrum density percentile plots and probability densities, octave-band levels, broadband noise levels, and generalised estimating equations. Sound sources were identified, the variability of soundscapes between and within sites compared, and temporal patterns described. Results indicated that Roebuck Bay and the Fremantle Inner Harbour had highly contrasting acoustic environments. In Roebuck Bay, the local soundscape was dominated by sounds from fish and snapping shrimp, with only sporadic vessel noise. However, in Fremantle Inner Harbour, anthropogenic noise was prevalent due to port operations and high levels of vessel traffic. On average, Roebuck Bay was 20 dB quieter than the Fremantle Inner Harbour over the frequency band 10 Hz – 11 kHz. Dolphin communications had a greater potential to be masked more frequently in Fremantle Inner Harbour than in Roebuck Bay based on

elevated anthropogenic noise levels in the former site. If noise levels were to increase in Roebuck Bay, coastal dolphins may show behavioural and/or acoustical responses as observed at other locations. It is recommended that Roebuck Bay is a prime candidate for management providing protection from human impacts such as acoustic habitat degradation. The bay is relatively pristine with high-quality acoustic habitat, and is inhabited by the largest known population of endemic snubfin dolphins; a species that may be particularly sensitive to impacts given its often highly evasive behaviour in the presence of human activity.

6.1 Introduction

Cetaceans (whales and dolphins) have evolved to become acoustically specialised in order to overcome the challenges of limited light in the ocean. These animals rely on underwater sound for vital life processes such as orientation, communication, predator avoidance, foraging, and reproduction (Tyack & Miller, 2002). However, auditory adaptations also make cetaceans susceptible to the impacts of anthropogenic noise. Many marine habitats have progressively become dominated by anthropogenic sources over the past few decades, altering the acoustic environment experienced by cetacean species (Nowacek *et al.*, 2007). Consequently, in environments with high levels of anthropogenic activities, the use of sound for cetacean life functions may be impeded.

An increasing body of evidence shows that anthropogenic noise may have impacts on cetacean physiology, behaviour and energetics (for reviews, see: NRC, 2003, 2005; Richardson *et al.*, 1995; Weilgart, 2007; Williams *et al.*, 2015b, 2014a). For instance, increases in underwater noise have also been shown to induce a "masking" effect, whereby anthropogenic noise interferes with the detection of signals such as cetacean communication sounds (Erbe *et al.*, 2015a). Therefore, in situations of collective noise from many sources, an animal's ability to perceive sounds may be impeded. Acoustic interference from 'noisy' environments may result in the reduction of individual performance. Noisy environments can even pose a survival threat to a population as a whole if vital functions such as lowered prey detection rates, failure to avoid predators, disturbance of resting activities or ability to communicate with conspecifics is impaired.

However, to implement noise mitigation strategies for cetaceans, there is a need to define, describe and compare 'noisy' and 'quiet' acoustic habitats. By defining acoustic habitats, marine spatial planning based on underwater noise habitat quality assessments can be undertaken effectively (Erbe *et al.*, 2012). Yet underwater noise is difficult to quantify, and its potential effects even more so (Clark *et al.*, 2009). To try and anticipate potential areas of acoustic space conflict, some studies have developed "risk maps" to identify places where acoustically-sensitive species may be vulnerable to masking from anthropogenic noise (Erbe *et al.*, 2014). These analyses integrate marine mammal density maps and information on each species' auditory system with sound propagation model outputs of specific noise sources (Erbe *et al.*, 2014). The results predict hotspots where anthropogenic noise may have an impact on marine mammal habitat, allowing managers to assess the risks associated with various human activities and prioritise conservation efforts. Recently, the concept of "opportunity maps" has also been introduced. Opportunity maps complement risk maps by identifying places where animals are present in high densities but anthropogenic noise levels are low (Williams *et al.*, 2015a). Such areas represent opportunities for zoning conservation areas within high-quality habitat. In contrast, 'noisy' habitats identified in risk maps may require mitigation (Williams *et al.*, 2015a). Ultimately, a prerequisite to both is the identification and categorisation of cetacean acoustic habitats at various spatio-temporal scales.

Of approximately 89 cetacean species occurring worldwide (Society for Marine Mammalogy, 2016), 37 occur in waters off Western Australia. Of these, many are migratory or found offshore, but several dolphin species are coastal and resident within specific locations year-round (Ross, 2006). Due to their range overlap with nearshore human activities, these coastal dolphins are particularly vulnerable to anthropogenic noise-related impacts. The most urbanised dolphin habitat in Western Australia is the Swan-Canning River estuary, which flows through the state capital of Perth (population: over 1.4 million people). A small community of Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) inhabits this system, which is formed by the Swan and Canning Rivers. The estuary is regularly used for recreational and commercial purposes, and has a highly variable anthropogenic acoustic environment (Chapter 4; Marley *et al.*, 2016a,b; Salgado Kent *et al.*, 2012). Yet the small dolphin community (approx. 18 adults; Chabanne *et al.*, 2012) also uses the river system daily, with sightings reported from Fremantle Inner Harbour at the river mouth to over 30 km upstream (Swan River Trust, 2015). Dolphins using the Fremantle Inner Harbour appear to vary their behaviour and whistle characteristics in association with increased levels of underwater noise (Chapter 5). In contrast to this urban environment, the Kimberley region in north-western Australia has some of the most remote, pristine wilderness in the world (Strickland-Munro *et al.*, 2016). The largest town in the Kimberley region is Broome (2,200 km north of Perth) with a small permanent population of approximately 16,000 people; however, this increases to around 45,000 in the austral winter tourism season (Shire of Broome, 2013). Broome sits on the shores of Roebuck Bay, which is regularly visited by bottlenose dolphins and has a relatively large resident population of snubfin dolphins (*Orcaella heinsohni*). Little is known about bottlenose dolphins in Roebuck Bay, but opportunistic photo-ID records have identified the same five individuals present over multiple years (D. Thiele, pers. comm). Snubfin dolphins are endemic to northern Australia, and Roebuck Bay has been identified as critical habitat for the largest reported resident snubfin dolphin population in Australia, with an abundance estimated to range between 130 – 161 individuals (Brown *et al.*, 2016, 2014a; Thiele, 2010). Despite currently limited knowledge on snubfin dolphins, the species is likely particularly vulnerable to human activities as a result of its dependence on near-shore and riverine systems, and its slow reproductive rate

(Cagnazzi *et al.*, 2013; Jefferson *et al.*, 2009; Parra *et al.*, 2006a). While Roebuck Bay may presently have a relatively pristine acoustic environment, several coastal development projects around Broome are planned, including construction of a new marina, boat launch facilities, foreshore redevelopment, and enhancement of beachside precincts (Shire of Broome, 2013). Associated underwater noise from these activities has the potential to change the quality of acoustic habitat within Roebuck Bay.

Underwater noise can interfere with dolphin life functions at both audible and communication frequencies. Dolphin hearing sensitivity varies among species, populations, and even individuals (Brill *et al.*, 2001; Hawkins, 2010; Houser & Finneran, 2006; Houser *et al.*, 2008; Mooney *et al.*, 2012; Popov *et al.*, 2007; Ward *et al.*, 2016). However, as hearing abilities can be difficult to measure in wild animals, frequencies in which animals produce sounds are often used as an indicator of their hearing sensitivities, since these generally overlap (Mooney *et al.*, 2012). Most species of Delphinidae produce sounds which can be classified into three categories: echolocation clicks, burst-pulse sounds, and tonal whistles. Whistles appear to have a communication function, used to maintain group cohesion and facilitate group coordination (Caldwell *et al.*, 1990; Janik *et al.*, 2006; Janik & Slater, 1998). The characteristics of bottlenose dolphin whistles have been previously investigated at several sites around Australia (Hawkins, 2010; Jensen *et al.*, 2012; Ward *et al.*, 2016). These studies suggest that the majority of populations produce whistles within the 2.5 – 19.5 kHz frequency band, but depending upon the location recorded have ranged as low as 1 kHz and high as 22 kHz (Hawkins, 2010). The reason for these geographic differences is unclear, but could be due to varying behavioural contexts, group composition, and levels of ambient noise (Ding *et al.*, 1995; Hawkins, 2010; Ward *et al.*, 2016, Chapter 5). In contrast, snubfin dolphin whistles on the east coast of Australia have been recorded between frequencies of 0.5 – 13 kHz (Berg Soto *et al.*, 2014; Van Parijs *et al.*, 2000). No information has yet been published on the communication repertoire of west coast snubfin populations or bottlenose dolphins within Roebuck Bay. Considering the potential vulnerability of coastal dolphin species to anthropogenic activities and associated noise, there is a need to describe the acoustic habitat of these animals in relation to the frequencies used by dolphins for communication.

This study aims to compare the underwater soundscapes of two differing coastal dolphin habitats in Western Australia in relation to dolphin communication. One habitat is in the relatively pristine waters of Roebuck Bay, and the other is the highly urbanised Fremantle Inner Harbour. The coastal dolphins present in Fremantle Inner Harbour are Indo-Pacific bottlenose dolphins (*T. aduncus*), whilst Roebuck Bay species primarily include bottlenose dolphins (*T. aduncus*) and snubfin dolphins (*O. heinsohni*). To achieve the overall aim of this study, the following objectives were addressed: (1) describe the underwater soundscape within Roebuck Bay and its variability over time; (2) describe the frequency ranges and behavioural contexts of coastal dolphin sounds recorded in Roebuck Bay; and (3) compare the noise levels experienced by dolphins inhabiting

Fremantle Inner Harbour and Roebuck Bay in relation to dolphins' communication space. The results from this study will improve our understanding of dolphin acoustic habitats and provide information essential to the management of these and similar sites.

6.2 Methods

Roebuck Bay (17.9869°S, 122.2928°E) is located off the north-western Australian Kimberley coast and Fremantle Inner Harbour (32.0420°S, 115.7528°E) is located at the mouth of the Swan River, Western Australia (Figure 6.1). Roebuck Bay experiences a semi-arid climate, with cyclones during the wet season. The Swan River is located over 3,000 km south of Roebuck Bay and experiences a Mediterranean climate with warm summers and colder winters.

Roebuck Bay is a large embayment covering an area of approximately 550 km^2. It is bordered by mangroves, sandy beaches, and tidal creeks, with the town of Broome on the north-western side. The bay experiences large semi-diurnal tidal movements with a range of 1.0 to 10.5 m. The Kimberley region is remote and, until recently, has had a relatively small human population of approximately 39,000 permanent residents across 423,517 km^2.

Fremantle Inner Harbour flows through the city of Perth, which has a population of over 1.4 million people. The Fremantle Inner Harbour experiences high levels of underwater anthropogenic noise from vessel traffic, nearby train and vehicle traffic, machinery noise, pile-driving and construction activities (Marley *et al.*, 2016a; Salgado Kent *et al.*, 2012, Chapter 4; Chapter 5). The harbour is Western Australia's largest general cargo port, and is the transit route for recreational vessel traffic travelling between the Swan River and the Indian Ocean. The Inner harbour is also a foraging hotspot for resident bottlenose dolphin communities (Moiler, 2008).

In this study, the underwater acoustic environment and dolphin whistles in Roebuck Bay were measured during 3 months (July and September/October) in 2014, and compared with measurements made during 2 months (May and June) in 2015 in the Swan River (see Chapter 4 for details). While noise measurements lack temporal overlap, they correspond to peak periods of dolphin occupancy at the respective sites. July also represents the peak of the tourism season in Broome, which trails off at the beginning of the wet season in October.

6.2.1 Data Collection

Acoustic recordings were collected in Roebuck Bay using an autonomous logger at a location between Black Ledge and a cyclone mooring area for ships to tie off at in safe waters (Figure 6.1). To cover the two periods (July and September/October 2014) of acoustic recordings, two separate deployments of the same autonomous acoustic logger (henceforth referred to as RB1 and RB2) were undertaken. The same instrument was used in both Roebuck Bay and the Fremantle Inner

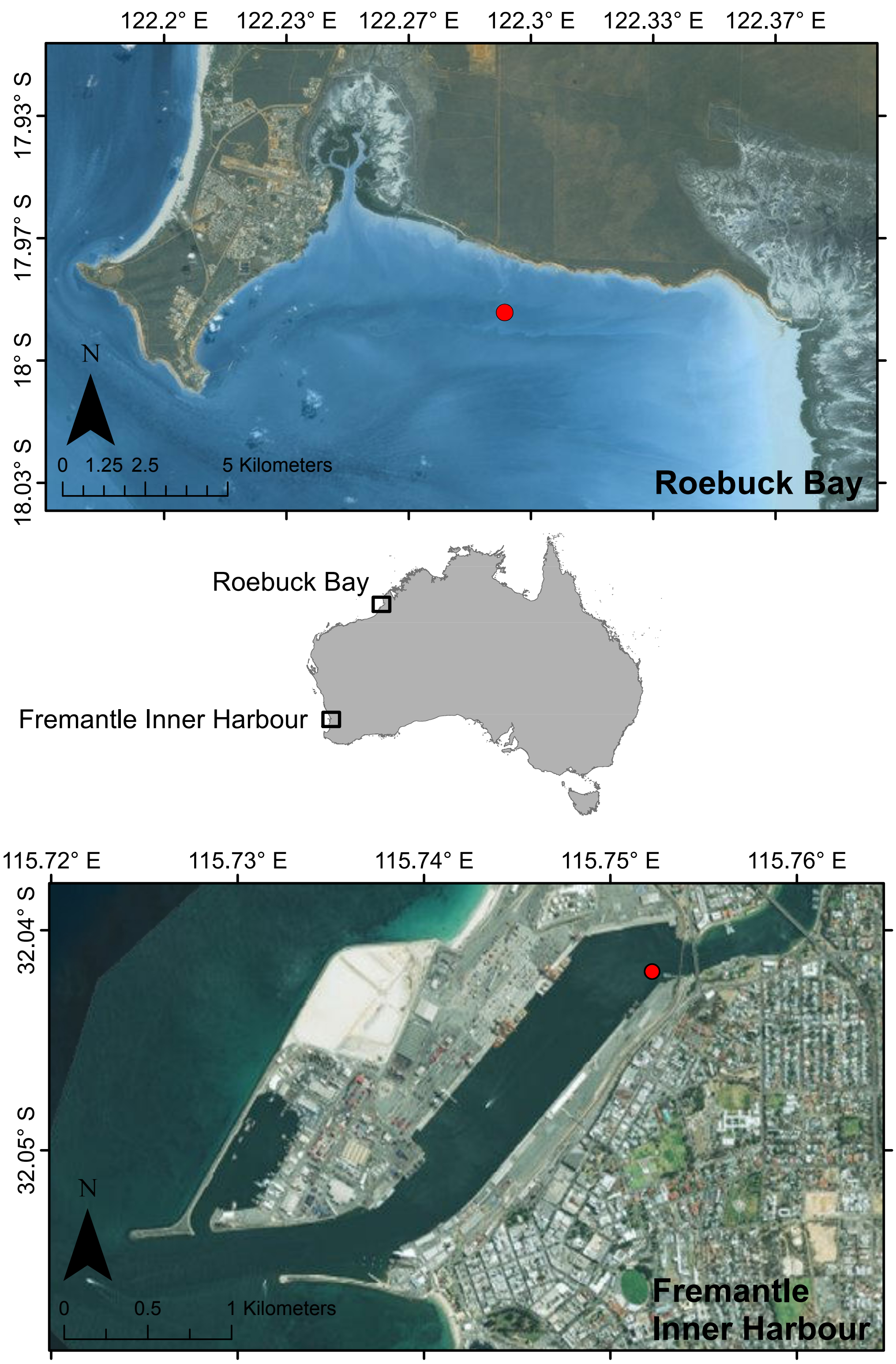

Figure 6.1: Map of Roebuck Bay and Fremantle Inner Harbour study sites in Western Australia. Logger deployment locations are indicated by a red circle.

Table 6.1: Summary of acoustic data collection in Roebuck Bay (RB) and the Fremantle Inner Harbour (FIH).

ID	Start Date	End Date	Days Total	Sampling Frequency (kHz)	Total Gain (dB)	Duty Cycle
RB1	04/07/2014	31/07/2014	27	192	44	10 of 15 min
RB2	24/09/2014	06/10/2014	12	192	44	10 of 15 min
FIH	30/04/2015	14/06/2015	45	96	44	10 of 15 min

Harbour. The Fremantle Inner Harbour dataset was previously described and analysed in Chapter 4.

Recordings were made using a high-frequency acoustic recorder assembled at the Centre for Marine Science and Technology (CMST) and equipped with an external hydrophone. The hydrophone entered the housing via a bulkhead connector to an impedance matching pre-amplifier with 20 dB gain and a programmable 16-bit digital sound recorder made by Wildlife Acoustics Inc. The sampling frequency for recordings in Roebuck Bay was 192 kHz, whilst in the Fremantle Inner Harbour it was 96 kHz (these were down-sampled for comparability during post-processing; see 'Soundscape Analyses' below). Digitised recordings were written to four 128 GB SD cards in the acoustic recorder. The recorder was calibrated by applying white noise of a known power spectral density. High-pass filters (8 Hz) were employed to filter out high levels of low-frequency noise, enhancing the dynamic range of the recorder at the frequencies of interest. At both locations, loggers were set to record 10 min of every 15 min (Table 6.1).

The acoustic recorder was placed on the seabed during all deployments. In Roebuck Bay, the recorder was connected to a weighted ground line leading to a main weight. The main weight was connected via a riser line to a surface float. This mooring was designed to decouple noise from chains on the main mooring and riser line from the recorder. In the Fremantle Inner Harbour, the recorder was deployed from a small jetty and tied off by two surface lines; no chains were used in this mooring design.

6.2.2 Soundscape Analyses

Data were first reviewed in Matlab (Version R2014a, The MathWorks Inc.) to identify prominent sound sources, using the toolbox CHORUS (Gavrilov & Parsons, 2014). To allow comparison with soundscape measurements previously made in Fremantle Inner Harbour (Chapter 4), post-processing used custom-written Matlab code following protocols applied in Marley *et al.*

(2016a) and Chapter 4. To further ensure comparability between locations and reduce computational requirements, data were down-sampled to 22 kHz to include the bandwidth in which the majority of anthropogenic noise overlaps with dolphin communications (whistles). To create weekly spectrograms, recordings were first Fourier transformed in 1 s windows, which produced a time series of power spectral densities (PSDs). Cable noise from the mooring was identified as brief broadband spikes and corresponding 1 s windows discarded from further analysis. The final PSDs were averaged into 10 s windows and the first 10 s PSD average of each minute was plotted into the weekly spectrograms (Mon – Sun).

Broadband noise levels (NL_BB) were calculated as the broadband root-mean-square sound pressure level for each 10-min recording from logger deployments. NL_BB in Roebuck Bay was modelled using hourly ("Hour" of day), weekday or weekend ("DayType"), and different deployment periods ("Deployment"; either RB1 or RB2) as explanatory variables to determine potential temporal predictors. Month as an explanatory variable was not included due to only partial coverage of September and October in RB2. Model terms DayType and Deployment were included as factors, whilst Hour was converted to a cyclical covariate by means of sine and cosine vectors, termed H_s and H_c respectively (Bailey *et al.*, 2013; Zuur *et al.*, 2009):

$$H_s = \sin(\frac{2\pi \times h}{24})$$

$$H_c = \cos(\frac{2\pi \times h}{24})$$

This allowed hours at the start and end of the day to be considered close to each other (e.g. 23:00 hrs and 01:00 hrs). A similar approach has been undertaken in other studies to include circular variables as model terms (Bailey *et al.*, 2013, 2009, 2010; De Boer *et al.*, 2014; Griffin & Griffin, 2003; Marley *et al.*, 2016a; Pirotta *et al.*, 2013).

To account for temporal autocorrelation of noise levels across adjacent hours, generalised estimating equations (GEEs) were used, as these allow for an autocorrelation structure to be included in the model (Bailey *et al.*, 2013; Photopoulou *et al.*, 2011; Zuur *et al.*, 2009). GEEs account for temporal autocorrelation via within-cluster correlations to increase the estimation efficiency, thus allowing maximum use of sequential or repeated measures data (Bailey *et al.*, 2013; Zuur *et al.*, 2009). A Runs Test of model residuals ($p < 0.001$) confirmed that there was autocorrelation in NL_BBs; therefore, a blocking structure was selected to model the correlation. To select clusters for the model blocks (ID), model residual autocorrelation was plotted over time. Correlation of hourly observations declined to approximately zero within a 24-h period. Thus, separate days were treated as independent, and "Date" was selected to define clusters of data points within which residuals were allowed to be autocorrelated. Given that the data were serially correlated and that GEEs are robust in providing consistent estimates of mean parameters even when the correlation structure is mis-specified, an AR-1 correlation structure was selected as the most logical option for the model.

The GEE models used a gamma error distribution with a log-link function. Gamma distributions are appropriate for continuous response variables that have positive values (Zuur *et al.*, 2009). Variance Inflation Factors (VIFs; Zuur *et al.*, 2010) were calculated, but revealed no collinear variables in the model. Selection of the best model was assessed via a quasi-likelihood criterion (QIC; Pan, 2001) and model fit was assessed by plotting observed versus fitted values and fitted values versus scaled Pearson's residuals. Once the final model was selected, repeated Wald's tests were used to assess the significance of each temporal variable, and partial residual plots of significant terms were created.

All statistical analyses were conducted in R (R Core Team, 2015) with the aid of the *geepack* (Højsgaard *et al.*, 2006; Yan, 2002; Yan & Fine, 2004), *MESS* (Ekstrom, 2014), *MRSea* (Scott-Hayward *et al.*, 2014) and *stats* (R Core Team, 2015) packages.

6.2.3 Dolphin Sounds

To avoid mis-classification, only acoustic recordings with concurrent visual observations were used to attribute whistles to species level. Vessel-based acoustic recordings were made opportunistically as part of a separate dolphin study conducting line transects in Roebuck Bay in July 2014 (see Salgado Kent *et al.*, 2015, for survey details). Surveys were undertaken from a 5 m vessel fitted with an outboard engine. As part of the survey methodology, when a dolphin group was sighted, the vessel would break transect and transition into 'closing mode' by approaching the group to collect photographs of the animals for species and individual identification (photo-ID). Information regarding group size and behavioural activity state (foraging, milling, resting, socialising or travelling; Table 6.2) was also collected.

If the animals seemed to be staying in the area, the survey vessel engine was switched off (to reduce background noise) and concurrent hand-held acoustic measurements were made by deploying a hydrophone to approximately 1.5 m depth over the side of the boat. Recordings were made via a SoundDevices 722T, a RESON VP-1000 pre-amplifier with gain settings to suit the environment, and a RESON TC4034 hydrophone (sensitivity -217.3 dB re 1 V/µPa). The SoundDevices 722T digital recorder was set at a sampling frequency of 192 kHz with internal gain of 18 dB. The recording system was calibrated prior to measurements by recording a white noise signal of known level and input in series with the hydrophone; this calibration provided the frequency response of the system. Recordings were continuous and were obtained at different times of the day and different locations within Roebuck Bay, which minimised the likelihood of re-sampling the same dolphin group.

Table 6.2: Definition of dolphin activity states (adapted from Shane *et al.* (1986) and Lusseau (2003a))

Activity State	Definition
Foraging (FO)	Dolphins involved in any effort to capture and consume prey, often involving quick, steep dives of long duration. Diving birds or jumping fish may also be observed.
Milling (MI)	Dolphins show frequent changes in heading, but stay in the same location with no net movement.
Resting (RE)	Dolphins engaged in slow movements or 'logging' at the surface.
Socialising (SO)	Dolphins engaged in a diverse number of interactive behavioural events, including body contact, chasing, leaping, or hitting the water surface with body parts. Groups may split or join.
Travelling (TR)	Dolphins engaged in persistent, directional movement with short, relatively constant dive intervals.

Acoustic recordings were manually reviewed in Adobe Audition (Vr 8.1.0.162) to identify the presence, number and location of dolphin sounds in each file. These recordings were not down-sampled. Whistles were categorised based on the shape of their contours in spectrograms (constant frequency, upsweep, downsweep, convex (up-side-down U), or concave (U-shaped)). Nine whistle features were measured (Chapter 5): (1) Duration, (2) Minimum Frequency, (3) Maximum Frequency, (4) Delta Frequency (Maximum Frequency minus Minimum Frequency), (5) Start Frequency, (6) End Frequency, (7) Number of Inflection Points (where the curvature changes sign, second derivative = 0), (8) Number of Extrema (where the slope changes sign, first derivative = 0), and (9) Presence of Harmonics. Characteristics 1 – 4 were automatically measured using the Raven Pro software, whilst the remaining characteristics were manually measured from visual inspection.

6.2.4 Comparison between Roebuck Bay and Fremantle Inner Harbour

To compare the noise levels between pristine and urban sites, NL_BBs for Roebuck Bay were contrasted with that of the Fremantle Inner Harbour. All three datasets (RB1, RB2, and Fremantle Inner Harbour) were compared using a Kruskal-Wallis test; and, if a significant difference existed, further comparisons were made using Wilcoxon-Mann-Whitney Tests. Statistical analyses were conducted in R using the *stats* package (R Core Team, 2015).

Visual comparisons of acoustic power versus frequency based on PSD percentile plots and OBLs were also made between Roebuck Bay and Fremantle Inner Harbour soundscapes. To achieve this, the first 10 s PSD average of each minute was used to compute PSD percentile plots. To reduce computational effort, the PSD was further averaged into a series of frequency bands, each 10 Hz wide. The n^{th} percentile of each plot gives the level that was exceeded n% of the time, with the 50^{th} percentile representing the median. Thus, these plots illustrate the statistical variability of underwater noise for each deployment, allowing visual comparison of acoustic power versus frequency both within and between sites. Probability densities of how often each percentile level was reached were also calculated from the PSDs as normalised histograms of the decibel levels in each frequency bin (Merchant *et al.*, 2013).

Variation within specific frequency bands between the two sites was examined by comparing octave-band levels (OBLs). First, 1 Hz PSDs of underwater noise were converted to linear units, averaged over 10 min of every acoustic recording, and then integrated into adjacent octave-band levels (OBLs). This resulted in time series of noise levels in each octave band (with one sample corresponding to each acoustic recording), thus allowing comparison of the noise levels in each OBL from both locations.

6.3 Results

At Roebuck Bay, approximately 940 h of acoustic data were collected during the two deployments. Opportunistic *in situ* recordings with concurrent visual observations represented an additional 2 h of acoustic data. Approximately 1,080 h of acoustic data were recorded in the Fremantle Inner Harbour; however, as a detailed description of the Inner Harbour soundscape using this same dataset is provided in Chapter 4, only results required for comparisons are considered here.

6.3.1 Underwater Acoustic Soundscape of Roebuck Bay

Snapping shrimp were the most prevalent sound source observable in Roebuck Bay (Figure 6.2), particularly in the second deployment (RB2). However, the most prominent sound source was from evening fish choruses, which consisted of Call Type I (Figure 6.3a) and covered frequencies between approximately 200 and 1000 Hz. This chorus was also most pronounced in the second deployment (RB2), and also occurred as singular calls during the day. Five additional fish calls were recorded in Roebuck Bay: Call Type II (Figure 6.3b) which was tonal at around 100 Hz; Call Type III (Figure 6.3b) which was a series of impulsive sounds around 300 Hz; Call Type IV (Figure 6.3c) covering frequencies between approximately 100 and 500 Hz; Call Type V (Figure 6.3d) covering frequencies between approximately 50 and 300 Hz; and Call Type VI (Figure 6.3e) which started at approximately 50 Hz and increased to 200 Hz.

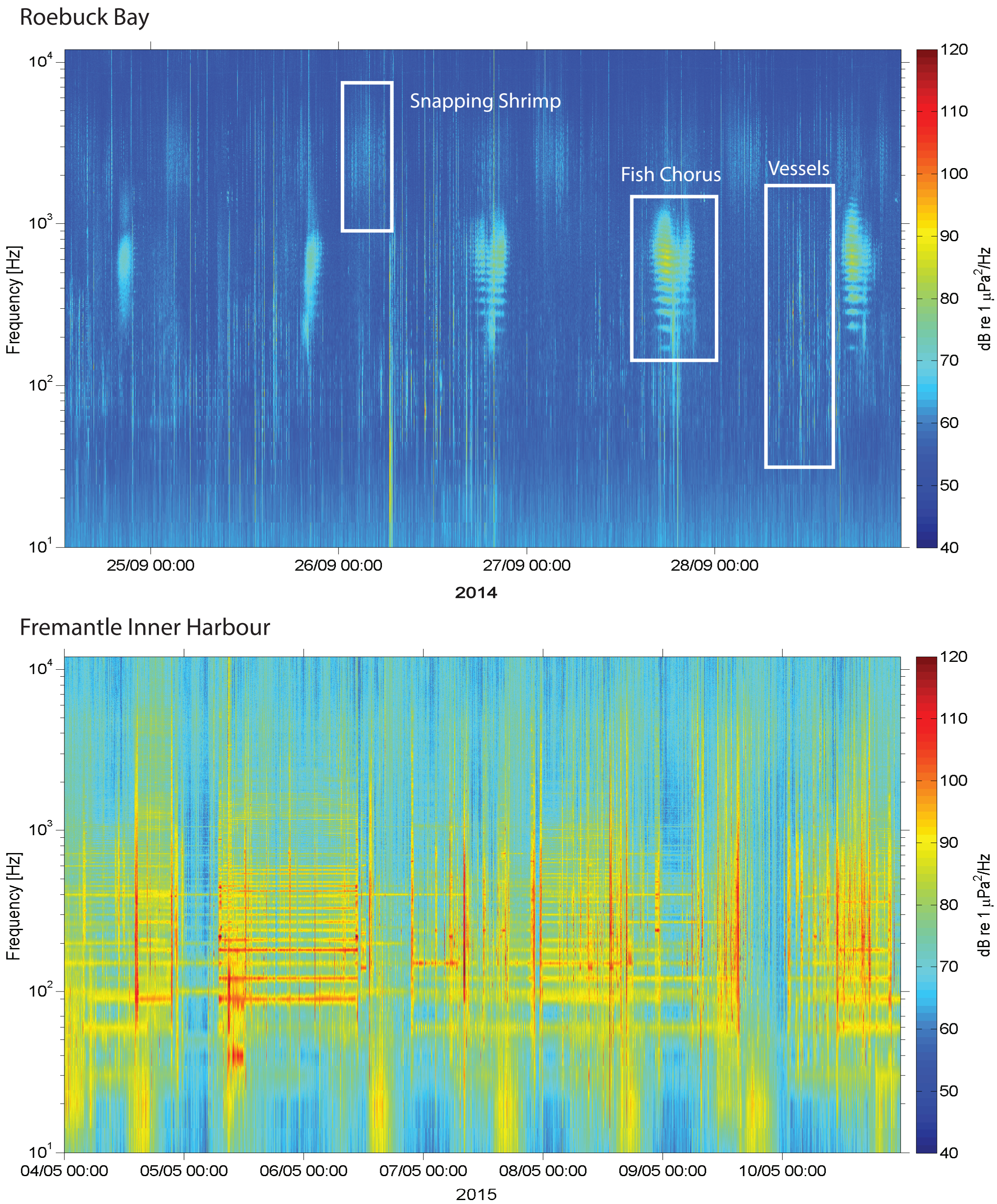

Figure 6.2: Examples of weekly spectrograms from Roebuck Bay (second deployment) and the Fremantle Inner Harbour.

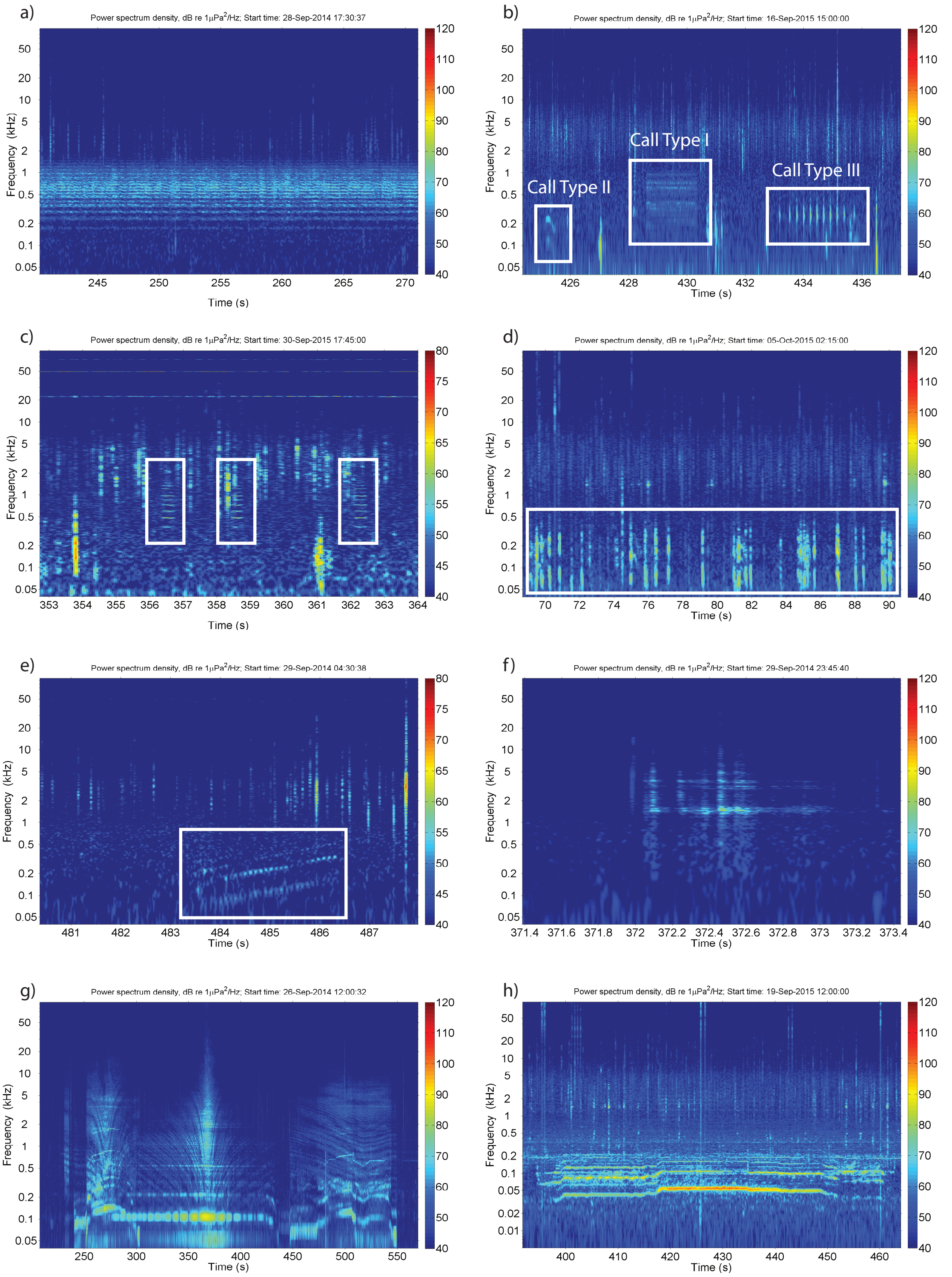

Figure 6.3: Examples of sound sources recorded in Roebuck Bay: (a) fish chorus, (b-e) fish calls, (f) mooring noise, and (g-h) vessel traffic. Note also the presence of snapping shrimp clicks. Fish calls included Call Type I (a and b), Call Type II (b), Call Type III (b), Call Type IV (c), Call Type V (d), and Call Type VI (e).

Table 6.3: Summary of generalised estimating equation (GEE) models investigating temporal patterns within Roebuck Bay by Deployment (RB1-2) and Hour (a cyclical variable, H_s and H_c). Significance level: ≤0.001 ***; ≤0.01 **; ≤0.05 *

Parameter	Coefficient Estimate	Standard Error	Wald	P	
Intercept	4.46626	0.00211	4.47e+06	< 2e-16	***
H_s	-0.00358	0.00127	7.90e+00	0.0049	**
H_c	0.00261	0.00080	1.07e+01	0.0011	**
Deployment RB2	-0.03806	0.00281	1.84e+02	< 2e-16	***

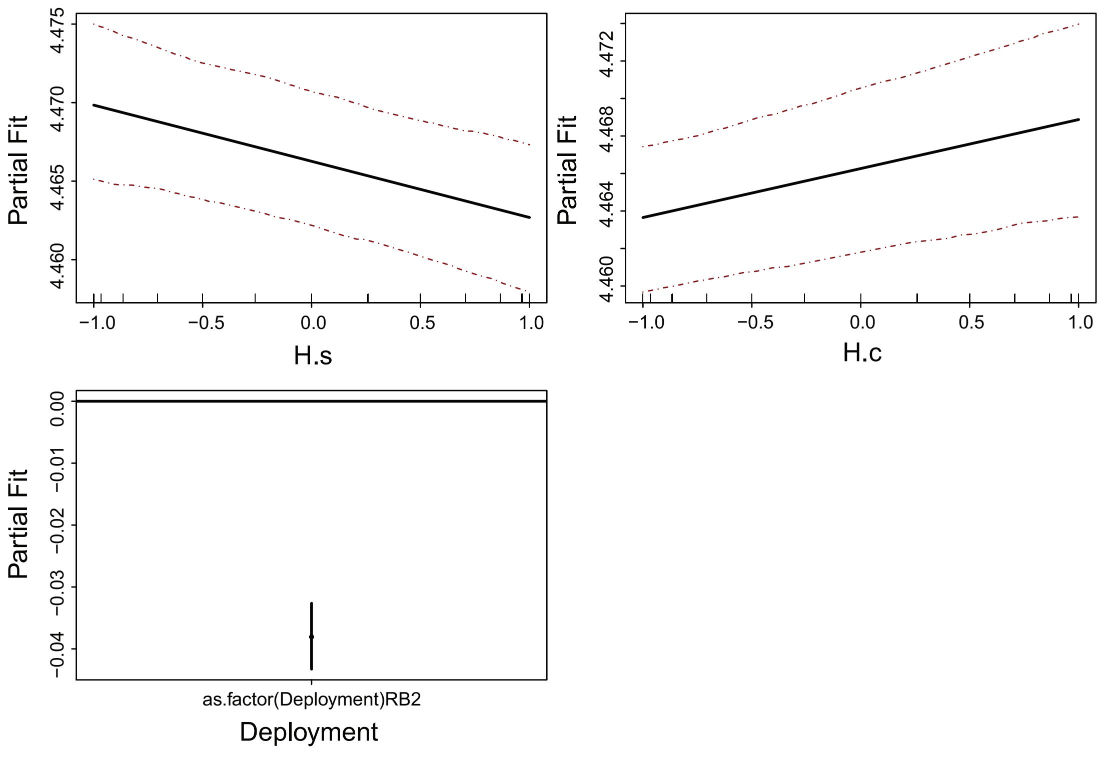

Figure 6.4: Partial residual plots showing temporal modelling of broadband noise levels (NL_BB) in Roebuck Bay. Lines around data points indicate 95% confidence intervals. Note that Hour was included as a cyclical variable (H_s and H_c), whereas Deployment was included as a factor.

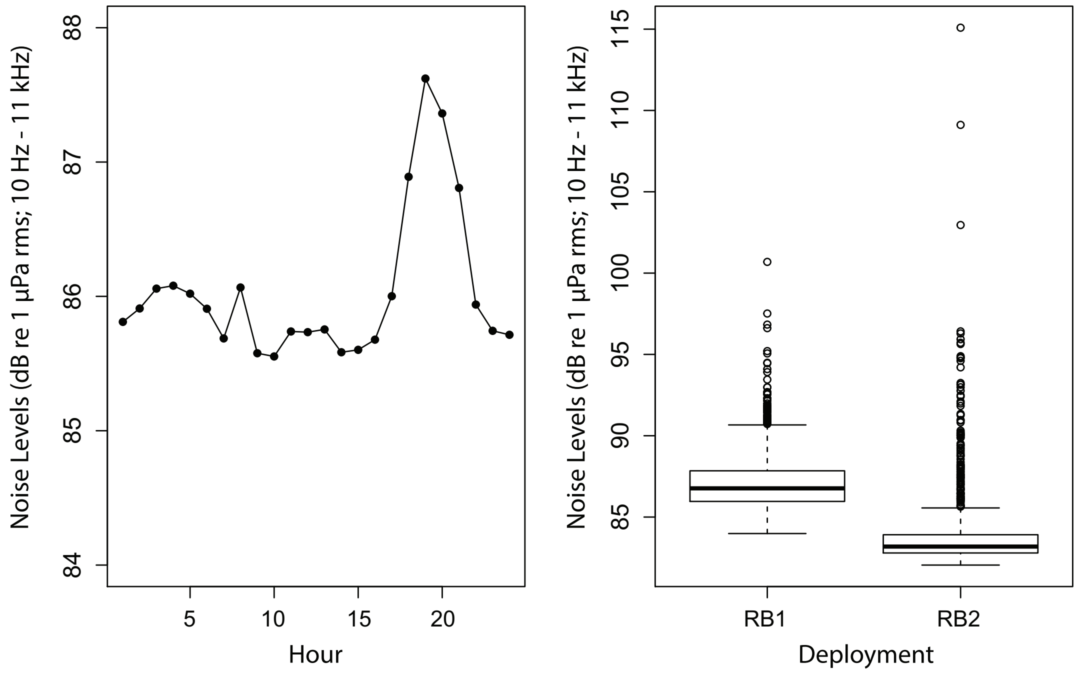

Figure 6.5: Patterns of temporal variability in the Roebuck Bay soundscape, by Hour and Deployment.

Mooring noise resulted from the movement of nearby cyclone mooring chains, causing sporadic but intense sounds around 1.5 kHz (Figure 6.3f). Vessel traffic was relatively infrequent during the entire study period, but was present more often during the first deployment in July (RB1) than the second in September/October (RB2). Vessel noise included broadband propeller cavitation noise (Figure 6.3g) and narrowband tones related to engine and propeller rotation (Figure 6.3a; Erbe *et al.*, 2016).

Temporal variability in broadband noise levels was best explained by Hour and Deployment period (Table 6.3; Figure 6.4; Figure 6.5). Noise levels were typically highest in the early evening, which coincided with the nightly fish choruses present to varying degrees in each deployment. The quietest deployment on average was RB2 (September/October), although it included transient periods of higher noise levels which – at their greatest – surpassed those of the first deployment (RB1 – July). These most likely reflects RB2 having the most intense fish choruses, whilst otherwise experiencing relatively few noise contributors.

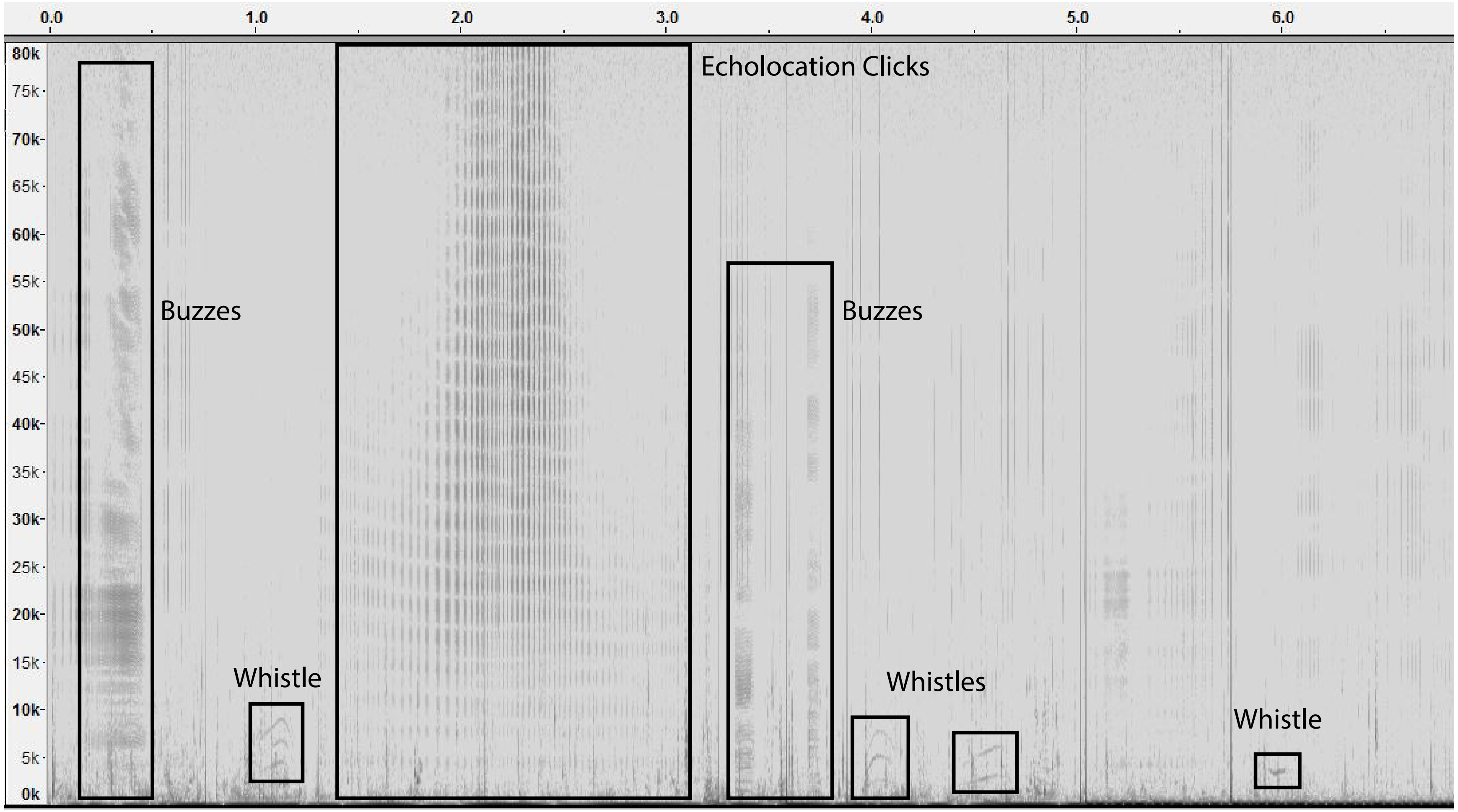

Figure 6.6: Sound types recorded in the presence of snubfin dolphins included broadband echolocation clicks, pulsed 'buzz' sounds, and tonal whistles.

6.3.2 Roebuck Bay Dolphin Sounds

A total of 20 vessel-based *in situ* acoustic recordings (with a mean duration of 6 min and total of 118 min) were made in Roebuck Bay during 19 dolphin encounters in nine days of July 2014. Dolphin encounters included 17 groups with snubfin dolphins, one with bottlenose dolphins, and one with both species. Recordings from the latter encounter (mixed-species group) were not included in analyses since sounds could not be confidently attributed to species level.

Approximately half of the 17 snubfin groups encountered (n = 8) consisted of 4 – 14 socialising animals. Approximately a third of encounters (n = 6) were relatively small groups with 1 – 6 animals slowly travelling. Two encounters were animals engaged in foraging behaviour with group sizes of 1 – 5 individuals. One milling group was encountered consisting of six dolphins. No snubfin dolphin calves were sighted.

Recorded sounds from snubfin dolphins included broadband echolocation clicks (55%), burst-pulse sounds (43%), and whistles (2%) (Figure 6.6; Table 6.4). Clicks were recorded during all activity states. Burst-pulse sounds were mostly recorded in association with socialising, occasionally in travelling groups, once in a foraging group, and never in milling groups. Whistles were mostly recorded in association with travelling groups, occasionally in socialising groups, once in a foraging group, and never in milling groups.

Of the 13 snubfin dolphin whistles recorded, five types were observed: convex (n = 7), upsweep (n = 2), downsweep (n = 1), concave (n = 1), and constant (n = 1). Snubfin whistles ranged in frequency from 1.9 – 9.9 kHz, with a mean duration of 0.24 s and one extremum (Figure 6.7; Table 6.5). Harmonics were recorded as being present in three whistles. No inflection points were recorded for snubfin whistles. These results are similar to those of previous studies on the east coast of Australia, which have recorded snubfin whistles between 0.6 and 13.0 kHz, with mean durations of 0.23 and 0.25 s (Berg Soto *et al.*, 2014; Van Parijs *et al.*, 2000). However, these studies have also reported up to seven extrema (Berg Soto *et al.*, 2014).

The encounter with bottlenose dolphins was relatively short, resulting in 5.3 min of acoustic data. The group was foraging and was composed of four adults and one calf. Recorded sounds from bottlenose dolphins included echolocation clicks and ten whistles. Whistles of two types were recorded (Figure 6.7): concave (n = 7) and upsweep (n = 3). These had a frequency range of 9.0 to 17.5 kHz, a mean duration of 0.13 s, and on average one extremum and one inflection point (Table 6.5). Harmonics were present in four of the bottlenose dolphin whistles. In contrast, bottlenose dolphin whistles recorded in the Fremantle Inner Harbour have a fundamental frequency range of 1.2 – 17.5 kHz and a mean duration of 0.59 s (Chapter 5). Whilst the Fremantle Inner Harbour maximum whistle frequency concurs with that in Roebuck Bay, bottlenose dolphin whistles in Roebuck Bay had a higher minimum frequency. Whistles recorded from Roebuck Bay bottlenose

Table 6.4: Recordings of snubfin dolphin sounds in association with different activity states. No resting activity was observed.

Activity State	Total Acoustic Data (min)	Total No. Individuals	Clicks		Burst Pulses		Whistles	
			Count	Min^{-1}Indv^{-1}	Count	Min^{-1}Indv^{-1}	Count	Min^{-1}Indv^{-1}
Travelling	35.60	19	96	0.142	6	0.009	8	0.012
Foraging	12.87	5	67	1.041	1	0.016	1	0.016
Socialising	47.20	60	188	0.066	302	0.107	4	0.001
Milling	3.05	5	43	2.820	0	-	0	-

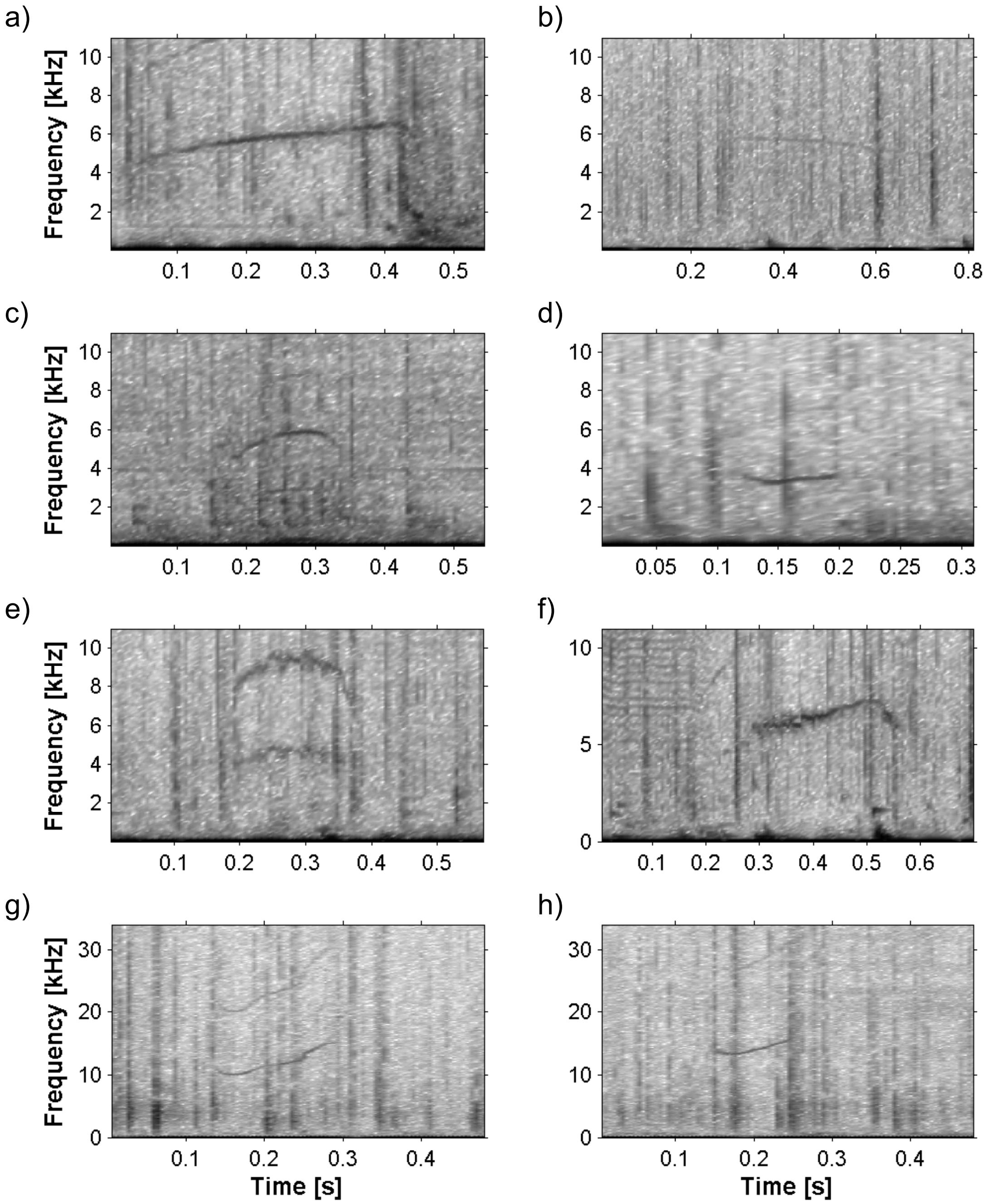

Figure 6.7: Examples of whistles from snubfin dolphins (a – f) and bottlenose dolphins (g – h) recorded in Roebuck Bay.

Table 6.5: Summary of whistle characteristics recorded in association with snubfin (n = 13) and bottlenose dolphins (n = 10) within Roebuck Bay.

	Duration (s)	Min Freq (Hz)	Max Freq (Hz)	Delta Freq (Hz)	Start Freq (Hz)	End Freq (Hz)	Inflections	Extrema
Snubfin Dolphins								
Minimum	0.10	1.9	3.2	0.7	1.9	2.7	0	0
Mean	0.24	4.1	5.7	1.7	4.4	4.6	0	1
Maximum	0.45	6.6	9.9	3.3	6.6	6.6	0	1
Bottlenose Dolphins								
Minimum	0.05	9.0	13.6	2.2	9.9	13.6	0	0
Mean	0.13	11.8	15.7	3.9	12.4	15.7	1	1
Maximum	0.19	14.5	17.5	5.5	15.4	17.5	3	1

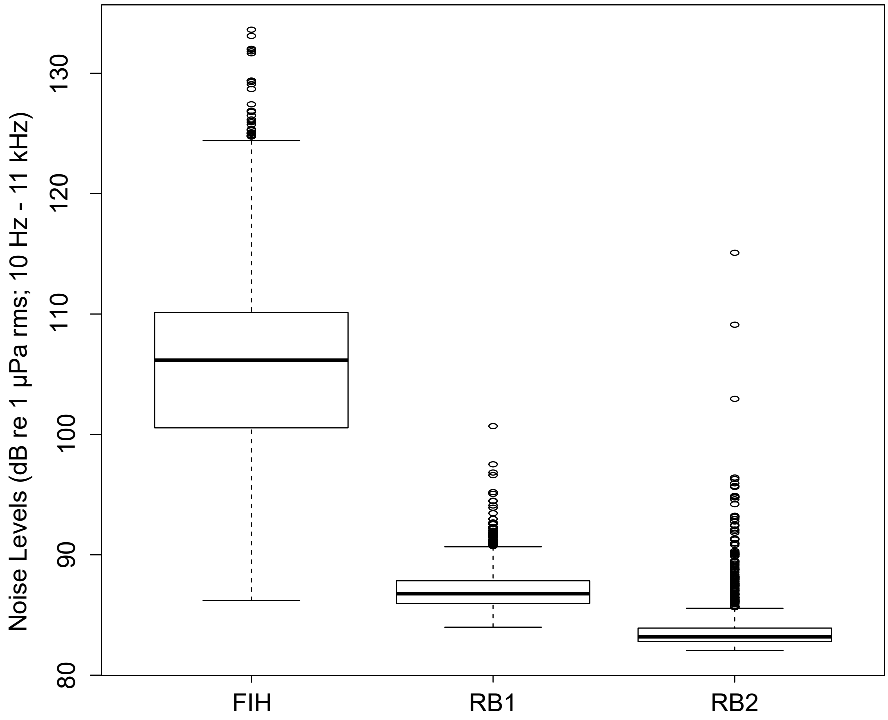

Figure 6.8: Comparison of overall broadband noise levels between Roebuck Bay (RB1-2) and the Fremantle Inner Harbour (FIH). All three datasets were significantly different from each other.

dolphins were also considerably shorter than their counterparts in Fremantle Inner Harbour (Chapter 5). Although the fundamental frequency of bottlenose dolphin whistles can reach minimum frequencies of 1 kHz (Hawkins, 2010), such whistles were not observed in this study.

The whistles recorded here showed very little inter-species overlap. In contrast with snubfin dolphin whistles, bottlenose dolphin whistles were typically of higher frequency and shorter duration. The mean lowest frequency recorded for snubfin and bottlenose whistles were 4.1 ±1.2 kHz and 11.8 ± 1.7 kHz, the mean highest frequencies were 5.7 ± 1.7 kHz and 15.7 ± 1.2 kHz, and the mean durations were 0.24 ±0.12 s and 0.13 ± 0.04 s, respectively.

6.3.3 Comparison of Pristine and Urban Sites

Roebuck Bay and the Fremantle Inner Harbour were different in their underwater acoustic environments at the times measured. The most prominent sound source in Roebuck Bay was the evening fish chorus, whereas the Fremantle Inner Harbour weekly spectrograms were dominated by anthropogenic noise from vessel traffic and port operations (Figure 6.2). There were significant differences in NL_BBs between Roebuck Bay and the Fremantle Inner Harbour (Kruskall-Wallis X^2 = 6180.8, df = 2, $p < 0.001$; Wilcoxon-Mann-Whitney Tests for all three datasets had $p < 0.01$; Figure 6.8). The Fremantle Inner Harbour experienced a mean NL_BB of 106 dB re 1 µPa rms (10 Hz – 11 kHz) in May/June, whereas Roebuck Bay had lower mean NL_BB's of 87 and 84 dB re 1 µPa rms (10 Hz – 11 kHz) in July and September/October, respectively.

The PSD percentiles indicated that the underwater noise environment in September/October in Roebuck Bay was the quietest of those being compared, but the presence of the evening fish chorus (peaking at 0.6 kHz) considerably increased noise levels (Figure 6.9). Underwater noise in Roebuck Bay in July and September/October had peaks at 1.5 kHz, representing the presence of noise from movement of adjacent cyclone moorings. Snapping shrimp noise was more prevalent in Roebuck Bay than in the Fremantle Inner Harbour; the latter being particularly well characterised by vessel noise between 0.1 – 1 kHz. The PSD plots show that Roebuck Bay was mostly quiet, with the most frequent occurrences of PSD levels falling below the median. However, in the Fremantle Inner Harbour, the probability density was spread out relatively evenly over a 40 dB range, meaning that very loud periods were as common as the very quiet ones; although 'quiet' is a relative term, since quiet periods in Fremantle Inner Harbour were still approximately 10 – 25 dB higher than in Roebuck Bay.

Discrepancies between sites were also visible in the OBLs, where the largest differences between Fremantle Inner Harbour and Roebuck Bay were in the low and mid frequencies (Figure 6.10). Noise in the 640 Hz-centred OBLs in Roebuck Bay generally represented the evening fish chorus and other fish calls. Roebuck Bay had increased noise at higher frequencies, likely attributable to snapping shrimp and mooring noise, although these were still surpassed by the noise levels in Fremantle Inner Harbour. Occasionally, noise in Fremantle Inner Harbour centred on 640, 1280, 2560 and 5120 Hz OBLs dropped to levels lower than those in Roebuck Bay.

6.3.4 Relevance to Dolphins

This study recorded coastal dolphin whistles in Roebuck Bay which ranged between 1.9 and 17.5 kHz. However, studies of other populations of bottlenose and snubfin dolphins around Australia indicate that whistles might range as low as 1.0 and 0.5 kHz, respectively (Berg Soto *et al.*, 2014; Hawkins, 2010; Van Parijs *et al.*, 2000). Based on this and previous research, coastal dolphin whistles could be expected to overlap with received noise from sound sources with acoustic energy between 0.5 – 22 kHz and OBLs centred on 640, 1280, 2560 and 5120 Hz.

Roebuck Bay experienced relatively low levels of noise in these OBLs, with means ranging from approximately 85 – 95 dB re 1 µPa. The September/October Roebuck Bay deployment generally had lower mean values than the July deployment, likely reflecting the higher levels of vessel traffic in July. When present, vessel noise often dominated the Roebuck Bay soundscape (e.g. Figure 6.10). However, the relatively infrequent nature of vessel noise at the acoustic logger location in Roebuck Bay indicates that it is likely to cause only short-lived, localised disruption in dolphin

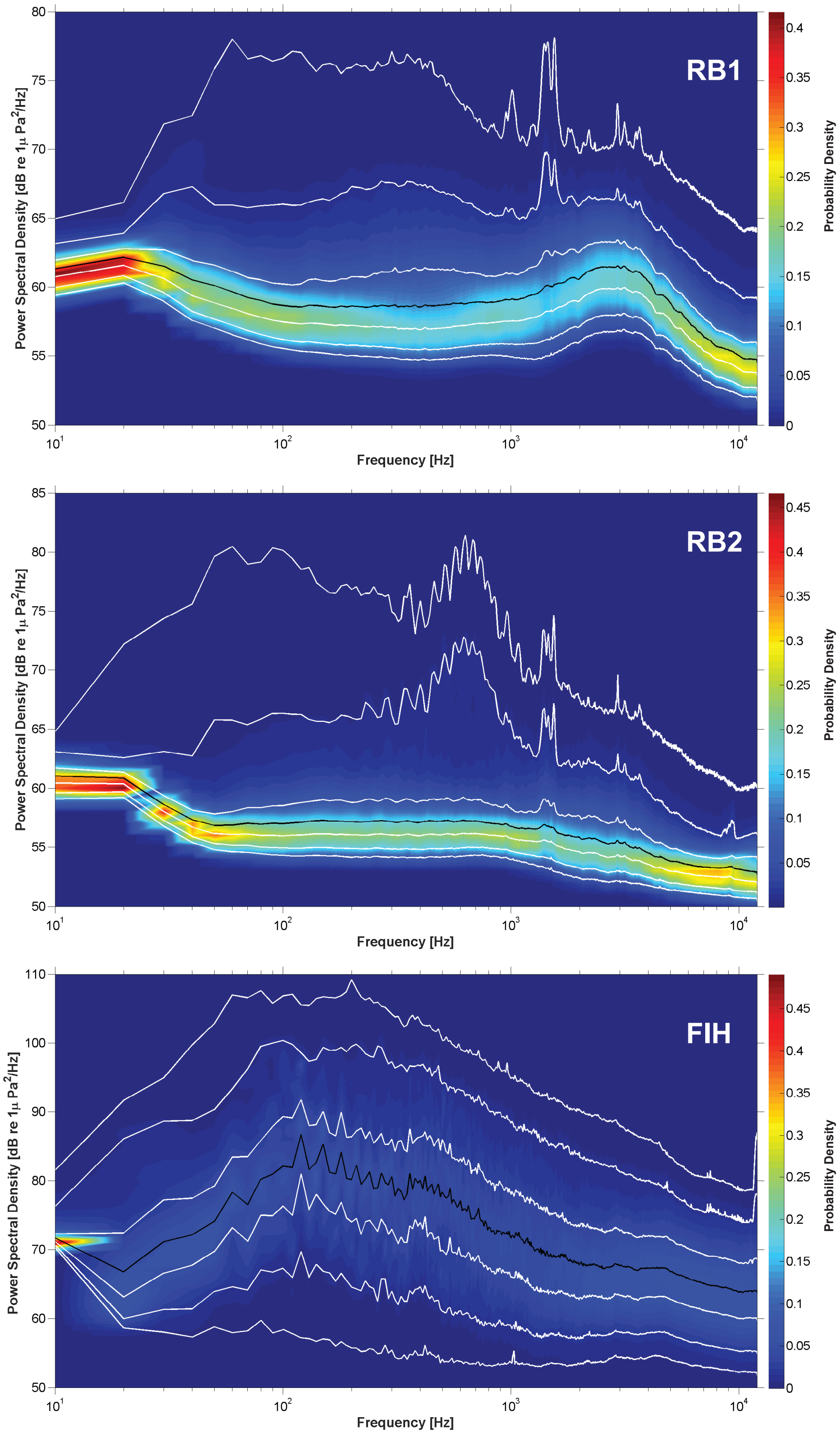

Figure 6.9: Power Spectrum Density (PSD) percentile plots comparing the soundscape at Roebuck Bay (RB1-2) with that of the Fremantle Inner Harbour (FIH). Probability densities of PSD levels are shown in colour.

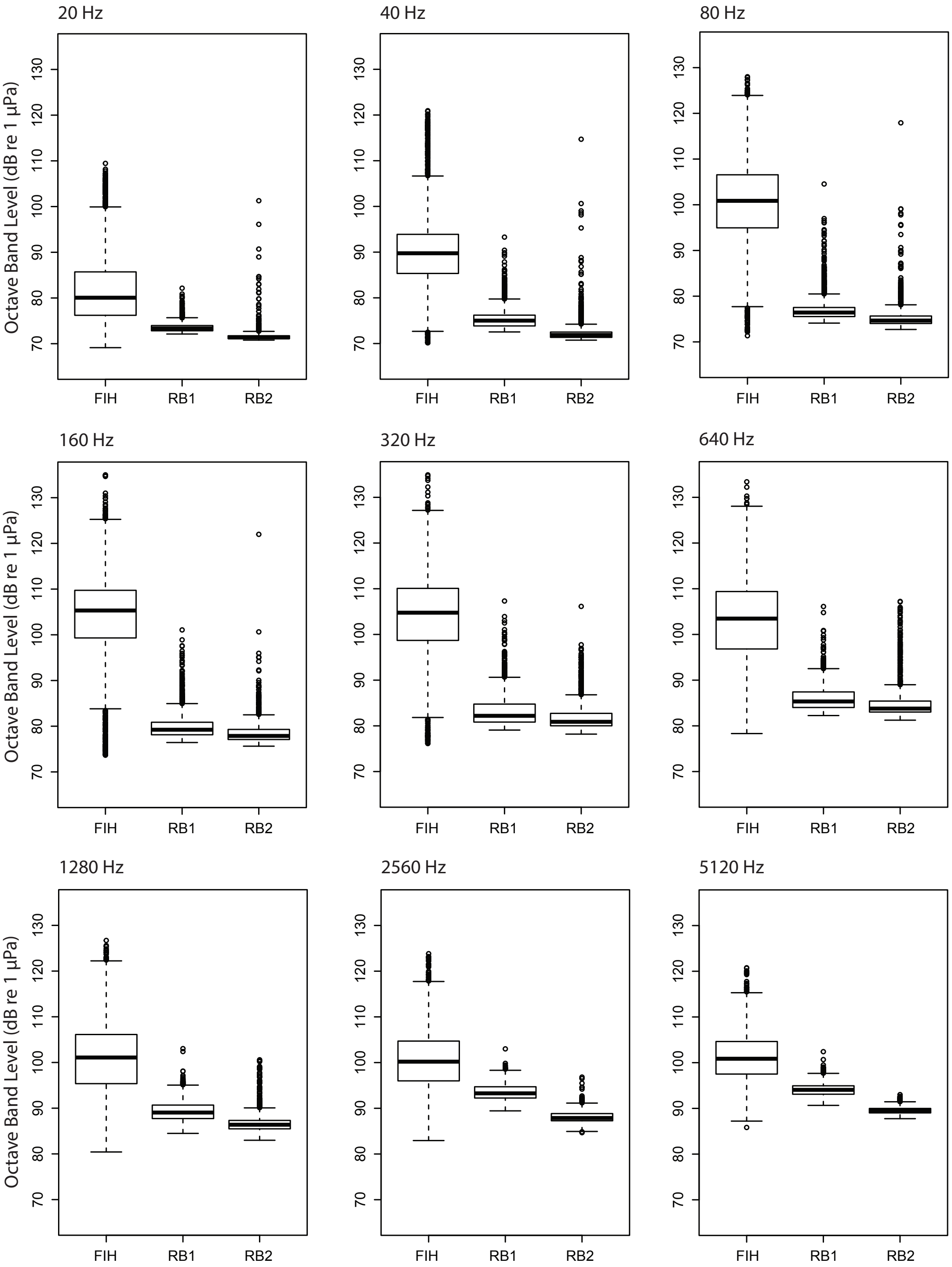

Figure 6.10: Whisker plots of octave-band levels (OBLs) from Roebuck Bay (RB – two deployments) and the Fremantle Inner Harbour (FIH – one deployment).

communication. Fish choruses had a greater risk of competing for acoustic space than vessel noise.

Although several fish calls were recorded, one type produced considerably long and intense evening choruses. However, all fish calls were typically below 1 kHz, thus represented relatively little overlap with snubfin dolphin whistles and potentially no overlap with bottlenose dolphin whistles. The most prevalent sound source was snapping shrimp clicks. Although these occur at frequencies which overlap with coastal dolphins, the brief, transient and intermittent nature of these impulsive clicks reduces their potential for masking.

In contrast to Roebuck Bay, the Fremantle Inner Harbour experienced means of 100 – 110 dB re 1 μPa in these four OBLs of interest (centred on 640, 1280, 2560 and 5120 Hz) due to the presence of vessel traffic and port operations. These activities produce the most prominent and prevalent sounds in the Fremantle Inner Harbour. Their potential effects are discussed in Chapter 4 and Chapter 5. Since anthropogenic noise is persistent at this site, considerably increasing soundscape noise levels across frequencies relevant to dolphins, the Fremantle Inner Harbour contrasts strongly to Roebuck Bay in its acoustic habitat quality.

6.4 Discussion

Roebuck Bay and the Fremantle Inner Harbour represent two highly contrasting acoustic environments for coastal dolphins. In this study, the local soundscape in the former was dominated by biotic sound sources, such as fish calls and snapping shrimp clicks. Sound from anthropogenic sources was from short-lived, sporadic vessel traffic and frequent movement of cyclone mooring chains. In contrast, the soundscape in the latter was dominated by anthropogenic noise. Predominant sources were vessel traffic and activities associated with port operations.

On average, hourly broadband noise levels in Roebuck Bay were 20 dB quieter than those of Fremantle Inner Harbour. The differences in noise levels were particularly pronounced in the 80 and 160 Hz octave bands. In Fremantle Inner Harbour, these octave bands contained low-frequency anthropogenic noise from port operations, which dominated the soundscape. While there is a Port in Roebuck Bay (Port of Broome), it is located at the far north-west of the bay, several kilometres from the study site. In addition, the Port of Broome is not as developed as the Fremantle Port nor does it have high levels of shipping traffic. The Fremantle Inner Harbour also experiences high levels of recreational vessel traffic (Marley *et al.*, 2016b). Roebuck Bay has boat ramps at Entrance Point and Town Beach (both located north-west of the acoustic logger deployment site), which are used by recreational boaters. Additionally, the bay has popular fishing spots in Dampier and Crab Creeks (east of the acoustic logger deployment sites). Thus, vessels departing Broome or Entrance Point travelling to key fishing spots often transited through the area where the acoustic logger was deployed (authors' pers. obs.). Despite this, the acoustic energy in Roebuck Bay in octave-band levels corresponding to vessel traffic was much lower than in Fremantle Inner Harbour. Future underwater noise recordings in closer proximity to the Port of Broome, boat ramps and fishing spots could give additional insight into the acoustic conditions experienced by coastal dolphins in high human-use sites in Roebuck Bay. In addition, the soundscape description provided here only represents a snapshot of the bigger acoustic picture of Roebuck Bay. Therefore, future research extending the spatial and temporal expanse, by collecting recordings from other sites throughout the bay and monitoring across several months/seasons over multiple years, is recommended. Broader-scale spatio-temporal patterns within the Roebuck Bay soundscape could then be ascertained for comparative soundscape analysis with other sites. This could potentially allow predictions to be made regarding the response of coastal dolphins to changes in the Roebuck Bay soundscape.

In Roebuck Bay, the maximum noise level reached in octave-bands overlapping with dolphin communication bandwidths was 115 dB re 1 µPa rms (10 Hz – 11 kHz), with an average of 86 dB re 1 µPa rms. In Fremantle Inner Harbour the maximum level reached in these octave bands was 134 dB re 1 µPa rms, with an average of 106 dB re 1 µPa rms. In a previous study, vessel densities associated with these elevated underwater noise levels in Fremantle Inner Harbour resulted in responses by bottlenose dolphins (Chapter 5). While dolphins remained present in the harbour during busy periods, they displayed behavioural changes during increasing and high vessel densities. In addition, when underwater noise levels were above 115 dB re 1 µPa rms (10 Hz – 48 kHz), dolphin whistles were shorter and covered a wider frequency range (Chapter 5). These behavioural alterations may come at an energetic cost, which could accumulate over the long-term and contribute to reduced body condition and health (Holt *et al.*, 2015, 2016; Noren *et al.*, 2013). While such responses can be used to guide our understanding of dolphin acoustical behaviour at other sites, ultimately responses are site- and species-specific. For instance, while dolphins were not displaced as a result of increased vessel traffic in the Fremantle Inner Harbour, displacement could occur for animals not previously habituated or for species that are evasive of human activities (such as snubfin dolphins). Studies of dolphins in other communities have indeed shown evidence of area avoidance in response to vessel traffic and underwater noise (Bejder *et al.*, 2006; Lusseau, 2005; Pérez-Jorge *et al.*, 2016; Pirotta *et al.*, 2013; Rako *et al.*, 2013). Given the relatively limited exposure to anthropogenic activities and associated noise, dolphins faced with increased vessel traffic in Roebuck Bay could avoid or spend less time within areas currently occupied. Potential consequences could include reduced access to important foraging or resting sites, increased susceptibility to predation, increased inter-specific competition resulting from forced habitat cohabitation, and increased energetic costs from the physical act of relocating to potentially poorer-quality habitat. Even if animals stay within the bay, additional energetic demands could result from behavioural responses to anthropogenic stressors, such as changes in movement speed, behavioural budgets and/or acoustic behaviour (Au & Perryman, 1982; Buckstaff, 2004; Stensland & Berggren, 2007; Constantine *et al.*, 2004; Guerra *et al.*, 2014; Heiler *et al.*, 2016; Lemon *et al.*, 2006; Lusseau, 2003a, 2006; Mattson *et al.*, 2005; Nowacek *et al.*, 2001, Chapter 5). Impacts from vessels to numerous snubfin dolphins are already evident. In recent years, a number of direct propeller strikes and fishing net/line entanglements have been documented (Thiele, 2010). Vessel-related threats will increase with growing human activity within the bay, and if not carefully managed have the potential to impose serious consequences for the bay's dolphin communities. As yet, there is no published information describing the baseline behaviours of dolphins in Roebuck Bay and there is no way to predict the consequences of increased vessel traffic and/or underwater noise. Thus, future work on the occurrence, movement patterns, habitat use, behavioural budgets, and whistle characteristics of bottlenose and snubfin dolphins in Roebuck Bay is recommended.

An important part of assessing the potential impacts of underwater noise on dolphins in an area lies in quantifying the potential for masking dolphin communications. In this study, whistles had a greater potential to be masked more frequently in Fremantle Inner Harbour than in Roebuck Bay based on elevated anthropogenic noise levels in frequencies overlapping dolphin communications in the former site. Foraging bottlenose dolphins in the Fremantle Inner Harbour displayed whistles ranging between approximately 1.2 kHz and ending at 17.5 kHz, with a mean duration of 0.59 s (Chapter 5). Whistles recorded from bottlenose dolphin populations elsewhere around Australia have reported absolute minimum frequencies comparable to Fremantle Inner Harbour in the range of 1 kHz; with mean minimum and maximum frequencies of 4.9 kHz and 11.7 kHz for dolphin populations in Moreton Bay, 5.3 kHz and 13.1 kHz in Byron Bay, 4.6 kHz and 10.9 kHz in Bunbury, and 3.9 kHz and 12.0 kHz in Monkey Mia (Hawkins, 2010). In contrast, whistles from foraging bottlenose dolphins in Roebuck Bay ranged considerably higher in frequencies, starting at around 9 kHz and ending at 17.5 kHz (with an average duration of 0.13 s). Mean minimum and maximum frequencies of 11.8 kHz and 15.7 kHz (respectively) recorded for Roebuck Bay bottlenose dolphins were also considerably higher than those reported elsewhere. While the frequency range was narrower and duration shorter for bottlenose dolphin whistles recorded in Roebuck Bay than in Fremantle Inner Harbour (and other Australian sites), the lower frequencies of whistles in Fremantle Inner Harbour overlapped more often with frequencies of anthropogenic noise energy. Although these results could be a function of the underwater noise environment, they could equally be a function of the limited whistle sample obtained from Roebuck Bay, as data from this species were limited to recordings from one foraging group. In contrast, whistles from snubfin dolphins in Roebuck Bay, while still limited, were from a larger number of groups engaged in a range of activities (travelling, foraging, socialising and milling). In Roebuck Bay, snubfin dolphin whistles ranged between 1.9 – 9.9 kHz. This range was slightly narrower than that reported for snubfin dolphins on the east coast of Australia, where whistles occurred between an absolute minimum of 0.6 and maximum of 13 kHz (Berg Soto *et al.*, 2014; Van Parijs *et al.*, 2000). Whistle measurements from dolphins along the east coast were from larger sample sizes than the present study (n = 13 present study, n = 34 Berg Soto *et al.*, 2014, n = 51 Van Parijs *et al.* 2000). Analyses of a larger sample size from Roebuck Bay could result in reduced differences between whistle characteristics from Roebuck Bay and the east coast. Snubfin whistles reported in this and other studies were similar in their lower frequency range (beginning at around 1.9 kHz) to bottlenose dolphins, but did not range as high as bottlenose dolphins in the Fremantle Inner Harbour or elsewhere. If anthropogenic noise were as intense in Roebuck Bay as in the Fremantle Inner Harbour, snubfin whistles would have a greater risk of masking than bottlenose dolphins due to their relatively limited and low frequency ranges.

Alternative explanations for differences in whistles between species and in different soundscapes include geographic variation, acoustic niche partitioning, and activity states. Geographic variation in whistles produced by the same dolphin species have been documented in various areas. The geographic scale can range from islands in the same state (e.g. Hawaii; Bazúa-Durán & Au, 2004), to sites along a country's coastline (e.g. Australia, Japan, Brazil; Hawkins, 2010; Morisaka *et al.*, 2005; Rossi-santos & Podos, 2005), or different regions within a larger body of ocean (e.g. Mediterranean Sea, Atlantic Ocean; Azzolin *et al.*, 2013; May-Collado & Wartzok, 2008). This variation could reflect geographic distance or genetic differences between populations of the same species. With regard to inter-species differences, bottlenose and snubfin dolphins in Roebuck Bay could be partitioning their acoustic niche by vocalising in different frequency ranges to reduce communication competition within the same frequency bands. Acoustic niche partitioning has been observed in several terrestrial species (Azar & Bell, 2016; Both & Grant, 2012; Pijanowski *et al.*, 2011; Sinsch *et al.*, 2012; Tennessen *et al.*, 2016), and suggested to occur in sympatric marine mammal species (Kyhn *et al.*, 2013; Miksis-Olds, 2013; Mossbridge & Thomas, 1999; Van Opzeeland *et al.*, 2010). Verification of acoustic niche partitioning in an attempt to avoid whistle overlap in Roebuck Bay would require detailed repertoire descriptions for both species and dedicated research on masking probabilities. Finally, differences in whistle characteristics associated with different species and soundscapes in this study could be a function of the activity state in which most whistles were recorded in Roebuck Bay. A range of studies show evidence for bottlenose dolphins using different sounds in different behavioural contexts. Hernandez *et al.* (2010) found duration, minimum frequency and number of inflections to be useful characteristics for determining dolphin activity state. Similarly, Díaz López (2011) suggest that peak frequency and duration may be good predictors of behaviour. Heiler *et al.* (2016) also found a strong effect of surface behaviour on whistle parameters, with resting showing the greatest difference to other activity. Changes in whistle production rate have also been reported in association with different activity states (Jones & Sayigh, 2002; Quick & Janik, 2008; Acevedo-Gutiérrez &

Stienessen, 2004). Only one study has related snubfin dolphin sounds to behaviours. Research in Queensland, Australia, found associations between foraging activity and the production of broadband clicks, 'creaks' and 'buzz' sounds; socialising activity and 'squeaks'; and whistles with both contexts (Van Parijs *et al.*, 2000). Similarly, in this study recordings from socialising groups of snubfins included 302 burst-pulse 'squeak' sounds, but only four whistles. Unlike in Queensland, burst-pulse 'squeaks' and whistles were documented in association with snubfins that were travelling and foraging. Only echolocation clicks were recorded from milling snubfins. Overall, whistles in this study accounted for only 2% of the sounds recorded in association with snubfin dolphins. Determining whether the results are a function of limited or biased sampling or are a true indicator of repertoire composition requires further research.

In conclusion, Roebuck Bay represents a relatively pristine acoustic environment for coastal dolphins. It is likely that dolphins in Roebuck Bay differ from other populations in their whistle characteristics. Human-induced alterations to this soundscape have the potential to change the way dolphins use their environment and exert certain impacts given dolphins' limited prior exposure to intense levels of chronic anthropogenic noise. There are suggestions that Roebuck Bay be developed in coming years to include a marina (Shire of Broome, 2013) which, in addition to short-term intense noise produced during construction, could increase recreational vessel noise within the bay over the longer term. Managers of marine areas are charged with the responsibility of minimising human impacts on wildlife to acceptable levels, which are often in the face of severe data deficiency. However, acoustic habitat quality is increasingly included in habitat protection plans. Thus, conservation and management decisions must increasingly be made on whether to reduce anthropogenic noise in 'noisy' environments or to preserve pristine, 'quiet' environments. Animal populations which display extreme site fidelity and are negatively impacted by noise will require noise reduction efforts to achieve successful area-based management (Williams *et al.*, 2015a). Given the challenges associated with reducing anthropogenic noise in areas where human activities are already firmly established, identifying and protecting existing quiet areas may be an easier, more pragmatic option. Roebuck Bay is a relatively pristine area with high-quality acoustic habitat. The location is also where the largest known population of endemic snubfin dolphins occurs (Brown *et al.*, 2016; Thiele, 2010); a species which has been observed to be evasive of human activity (authors' pers. obs.). To ensure the longevity of the snubfin population in Roebuck Bay, protection from human impacts such as degradation of acoustic habitat is recommended.

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Chapter 7

General discussion

This thesis aimed to examine the behavioural and acoustical responses of coastal dolphins to noisy environments. The aim was achieved by investigating acoustic habitat in relation to dolphin behaviour in the urbanised environment of the Swan River in south-western Australia, and comparing it to the relatively pristine environment of Roebuck Bay in north-western Australia. The Swan River falls within the home range of the Swan River Indo-Pacific bottlenose dolphin community of approximately 18 adults and their calves. Roebuck Bay hosts a relatively large population of approximately 150 snubfin dolphins, in addition to a small number of bottlenose dolphins that range within the bay. To define and compare the two locations, the following objectives were addressed:

1. Within the Swan River:
    (a) Quantify prominent underwater sound sources
    (b) Identify temporal and spatial patterns in the underwater soundscape
    (c) Investigate bottlenose dolphin occupancy in relation to vessel traffic in key habitats
    (d) Examine bottlenose dolphin behavioural and acoustical responses to vessel traffic and associated underwater noise, and
2. Compare urban Swan River and pristine Roebuck Bay underwater soundscapes in relation to coastal dolphin communication

The most prominent contributor of underwater noise to the Swan River soundscape was vessel noise, which was present in over 50% of the hourly recordings assessed (Objective 1a). The Swan River environment was comprised of multiple acoustic habitats, each with its own characteristic soundscape and temporal patterns in underwater noise (Objective 1b). Although Perth Waters was the noisiest Swan River site (mean broadband noise level 112 dB re 1 µPa rms [10 Hz – 11 kHz]) due to dominant snapping shrimp clicks, vessel noise had the greatest potential to mask dolphin whistles. As a result, the 'noisiest' site from an anthropogenic perspective and in relation to dolphin communications was the Fremantle Inner Harbour. With a mean broadband noise level of 106 dB re 1 µPa rms (10 Hz – 11 kHz), this site was dominated by noise from activities associated with port operations and vessel traffic. Bottlenose dolphins used Perth Waters and the Fremantle Inner Harbour differentially, with animals occupying the Fremantle Inner Harbour more frequently and for longer periods than Perth Waters despite the heavier vessel traffic at this site (Objective

1c). Finer-scale behavioural observations of dolphins at Fremantle Inner Harbour indicated that, despite remaining present in the harbour during busy periods, dolphins displayed responses to vessel traffic and associated underwater noise at this site (Objective 1d). At high vessel densities, dolphin movement speeds increased and behavioural budgets changed. In addition, whistle characteristics were different when broadband noise levels were above approximately 115 dB re 1 µPa rms (10 Hz – 48 kHz), although whistle characteristics could have been associated with individuals or their specific behaviours at the time. The Fremantle Inner Harbour is considerably noisier than Roebuck Bay; the example site of a relatively pristine acoustic habitat within the range of bottlenose dolphins (Objective 2). Mean noise levels in Roebuck Bay are approximately 20 dB quieter than those of the Fremantle Inner Harbour. Noise that did occur in Roebuck Bay was primarily biotic in nature rather than emanating from anthropogenic sources.

In summary, although the Swan River dolphins have long been exposed to vessel traffic throughout their range, these animals still respond to high vessel densities associated with underwater noise. These responses may be strategies for coping with life in a noisy environment, but could also come with an energetic cost. Increased swim speeds, more time spent travelling, less time resting or socialising, and greater vocal effort can alter the metabolism and energy budgets of these animals. This is particularly true for mother-calf pairs, as females already face greater energetic demands required for lactation whilst calves need adequate resting and nursing times. If habituated dolphin communities such as that in the Swan River show responses to vessel traffic, this raises the question of how relatively inexperienced dolphins in quiet areas would respond to increased noise levels. This study takes the first step in identifying dolphin acoustic habitats in Western Australia and how coastal dolphins respond to anthropogenic activities and noise in those habitats. This study also makes recommendations for future research.

7.1 Dolphin Acoustic Habitats in Western Australia

Without knowledge regarding the underwater soundscape experienced by acoustically-specialised fauna, it is difficult to assess how these animals may be impacted by an increasingly urbanised acoustic environment. Prediction of potential impacts is particularly important for sensitive faunal species that are long-lived and slow-reproducing, such as dolphins. Yet the characteristics of most marine soundscapes inhabited by dolphins remain unknown. Sound sources remain unidentified, the spatio-temporal patterns of noise levels unknown, and the extent to which animals are exposed to anthropogenic noise undetermined. To understand the impacts of underwater noise on coastal dolphins, the marine environment needs to be understood from an acoustic perspective. Prominent soundscape contributors must be identified and quantified, and dolphin responses and potential communication masking assessed. The magnitude of responses and compromised ability to sense the environment can then be used to determine the potential effects on dolphin body condition and overall health from increased energy demands. Applied to the development of management and regulations, this knowledge ultimately improves species conservation outcomes.

This study identified numerous underwater sound sources in the Swan River, from abiotic, biotic, and anthropogenic origins. Dolphins were not the only biotic sound sources present in the Swan River; snapping shrimp clicks and fish calls were also recorded. Snapping shrimp are likely of little interest to dolphins – they are too small to be prey items and, although shrimp clicks overlap in frequency with dolphin whistles, the impulsive nature of these clicks makes them unlikely to cause whistle masking. However, some studies have suggested that snapping shrimp clicks could act as indicators of underwater structures such as reefs, and reef noise could attract fish and crustacean larvae (Montgomery *et al.*, 2006; Simpson *et al.*, 2008; Stanley *et al.*, 2010; Vermeij *et al.*, 2010). When foraging, Swan River dolphins have been observed moving among structures within the river, such as boat pens, jetties, rocky cliff faces, and other features (Swan River Trust, 2015). These structures are often used by fish as refuges, and provide good foraging opportunities for dolphins, with the additional benefit that the solid structures can be used to herd fish schools against for easier prey capture. If snapping shrimp clicks provide acoustic cues identifying settlement locations for planktonic larvae, it is also possible they could serve as 'acoustic prey location identifiers' for dolphins. Snapping shrimp were particularly prevalent in recordings from Perth Waters and Matilda Bay, both of which are areas with numerous jetties and boat pens. Heirisson Island contained none of these structures, and recordings had few snapping shrimp clicks. Surprisingly, despite its proximity to the ocean and the presence of bridge foundations, harbour walls, and a jetty, the Fremantle Inner Harbour had relatively low occurrence of snapping shrimp. In some recordings, such as in Matilda Bay, there were changes in snapping shrimp presence over time. More detailed temporal or seasonal patterns of snapping shrimp clicks could be examined in future analyses to determine fine-scale and long-term changes. Fish calls were prominent at Heirisson Island, where mulloway fish (*Argyrosomus japonicus*) gathered to create loud evening choruses. Such fish choruses are typically seasonal in nature; thus the Heirisson Island soundscape is likely very different during other months not included in this study. Dolphins have not been recorded feeding on mulloway in the Swan River, likely due to the relatively large size of these fish (which reach a maximum length of 2 meters). However, several other fish sounds were also recorded in the river, although these could not be identified to species-level. As with the snapping shrimp clicks, it is possible that fish calls could act as 'acoustic prey location indicators' to dolphins. There have been no studies investigating dolphin foraging or prey relationships in the Swan River; further investigations on this topic would benefit scientists responsible for informing management, and managers implementing regulation.

Although there were intense biotic sound sources spread throughout the Swan River, none of these dominated the measured acoustic environment to the same degree as vessel traffic. Noise from vessels ranged in its characteristics, but was typically broadband and of much longer duration than biotic sounds. When present, vessel noise had the potential to mask almost all other sound sources within the same frequency bands. Fish calls were typically lower in frequency than dolphin sounds, whilst snapping shrimp clicks were too impulsive and intermittent to mask whistles. In comparison, much of the Swan River anthropogenic noise overlapped with the same frequency bands as dolphin whistles, and could consequently mask these communication signals. With few areas of the Swan River closed to vessel traffic, masking has the potential to occur through much of the dolphins' range, particularly during daylight hours when vessel traffic is high. Of all locations monitored in the Swan River, Fremantle Inner Harbour was the 'noisiest' site. There was a distinct increase in noise during the day as a result of vessel traffic and port operations as verified during visual monitoring shifts at this site, which typically overlapped with both 'quiet' and 'noisy' times. Future research investigating diurnal patterns in masking and dolphin behaviour would provide further insight regarding the implications of heavy traffic conditions on dolphins' daily activities. In summary, the prevalence of man-made sound, including vessel noise, in the river confirms that the Swan River is a noisy, underwater urban environment.

This study also investigated the differences between an urban and pristine acoustic habitat in Western Australia. The Fremantle Inner Harbour in the state capital and Roebuck Bay in the pristine Kimberley region had 20 dB difference in mean broadband noise levels. However, at some times the Fremantle Inner Harbour was just as quiet as Roebuck Bay. Thus noisy habitats can have quiet periods of 'acoustic refuge'. The most prominent soundscape contributors in Roebuck Bay were biotic in nature. Snapping shrimp were present and, as the acoustic logger was deployed between a rocky ledge and permanent cyclone moorings, the shrimp were most likely settled on these structures. Several distinct fish call types were also recorded in Roebuck Bay, one of which formed a prominent evening chorus. Many of the Roebuck Bay fish calls have been recorded at other sites along the northern coast of Australia such as Port Headland and Darwin Harbour (Parsons *et al.*, 2016a,b). However, Roebuck Bay fish calls were different from those recorded in the Swan River, likely reflecting the different species compositions at these sites (tropical versus temperate). It is unknown whether any fish calls recorded originated from bottlenose or snubfin dolphin prey species. Future research examining how dolphins use fish sounds as acoustic cues in their environment would provide insight on the importance of detecting fish calls in the soundscape for dolphin foraging. Regardless, Roebuck Bay was typically noisy as a result of fish choruses, whilst Fremantle Inner Harbour was noisy due to anthropogenic activities. Overall, noise levels were much higher in Fremantle Inner Harbour than in Roebuck Bay.

In summary, this study confirms differences between soundscapes in two areas; one location where coastal dolphins experience high and the other where they experience low anthropogenic underwater noise levels. Such knowledge can be used to create 'opportunity maps', identifying locations where habitats low in underwater anthropogenic noise coincide with high marine mammal densities (Williams *et al.*, 2015a). Thus managers can mitigate underwater noise impacts through prevention at a lower economic cost than in areas already heavily affected by anthropogenic activities and noise. By this logic, it would be substantially easier to keep Roebuck Bay quiet than it would be to remove anthropogenic noise sources from the Swan River to achieve acoustic habitat of equal quality. Roebuck Bay and the Swan River are known to be important locations for coastal dolphins. In particular, Roebuck Bay supports the largest known population of snubfin dolphins (endemic to Australian waters). Additional research is recommended to identify key locations and sensitivities of snubfin dolphins to underwater noise, and to determine the significance of Roebuck Bay to other species (such as bottlenose dolphins). It is likely that increases in anthropogenic noise within Roebuck Bay would result in habitat degradation that could compromise the acoustic integrity of this site. The implications of long-term exposure to noise as a chronic stressor to Swan River dolphins also requires further investigation. In particular, chronic stress is known to lower immune system function and body condition. Underwater noise impacts can work synergistically with reduced water quality to render dolphins more prone to disease and illness. In addition, long-term passive acoustic monitoring would allow the detection of changes in animal occurrence and the presence of anthropogenic activities, as well as detecting trends in the overall acoustic quality of dolphin habitats. There is a lack of historic baseline acoustic records for many marine areas, making it difficult to determine how the acoustic habitat of these sites may have changed over time. Pristine acoustic areas can help inform decision making at locations where historic noise levels are unknown, by allowing comparisons between marine environments relatively free from human activities with environments rich in man-made noise. Finally, this thesis illustrates the importance of using a range of acoustic analytical techniques to determine noise levels of these habitats and the sources of such noise.

7.2 Behavioural and Acoustical Responses of Coastal Dolphins

This study investigated a range of behavioural responses to determine whether bottlenose dolphins experienced disturbance from vessel traffic and noise. Behavioural responses included changes in presence/absence, number of sightings, time spent in the study area, average movement speeds, activity state transitions, behavioural budgets, and whistle characteristics. While there are other responses dolphins can display to disturbance, these illustrate several of the wide range of behaviours animals can employ. Future studies could include finer-scale measures, such as individual behavioural events (e.g. side flops, leaps, tail slaps), inter-animal distances, dive patterns, surfacing rates, fine-scale movement patterns, vocalisation rates, call amplitudes, among many other behaviours. In this study, multiple measures were used to obtain a broader picture of the magnitude of behavioural changes occurring.

While a single response type can occur without cascading effects to other behaviours, many behaviours are linked. For example, while dolphins did not leave Fremantle Inner Harbour, they spent more time travelling when vessel densities were high. At the same time, dolphins' average travelling speeds also increased at high vessel densities. Combined with less time spent resting, the consequences of these changes in behaviours are an increased energetic burden. Whether increased energy demand is the reason for the observed increased time spent foraging at high vessel densities, or whether foraging conditions are somehow improved in high vessel density conditions, or foraging behaviour was confused with vertical avoidance in this study, is yet to be ascertained.

Complexities in measuring behaviours and determining their cause illustrate the complicated nature of animal behaviour in disturbance studies. However, the results presented here can be built-upon in future research. In particular, information on dolphin movement speeds and their energy demands during different activity states and at varying vessel densities is missing in the literature. This knowledge gap hinders progress in energetic studies. For instance, metabolic data obtained from captive animals could be applied to dolphins in conditions experienced in the wild. There are several existing studies which document dolphin movement speeds, but typically these only refer to general observations of travelling animals or only mention disturbance contexts and not activity states. All mean speed values were included in this study to make the detailed data available to other researchers. Dolphin travel speeds recorded here are slightly slower than those in some other studies (Williams *et al.*, 1992), but this may be because the area is used mainly for foraging rather than to transit through. The Fremantle Inner Harbour is approximately 400 m wide, and the boundaries of the core foraging site within are only seconds to minutes away for a dolphin traveling at slow to medium speed. Thus the core foraging area can be covered quickly at relatively slow travel speeds, reserving higher energy-demanding behaviours, such as chasing, for capturing prey or socialising. In fact, maximum speeds recorded in this study were typically used by dolphins covering short distances to join other dolphins foraging or socialising. A comparison of travel speeds at other sites within the Swan River, such as transiting locations, would help clarify the cause of the discrepancy in travel speeds measured here and in other studies.

Activity states and behavioural budgets measured in this study broadly matched those reported in the literature. In periods of high vessel traffic, dolphins tended to increase time spent travelling and reduce time spent resting or socialising. However, in contrast to several other studies dolphins increased time spent foraging when vessel densities were high. This suggests either a true increase in foraging behaviour or an increase in diving behaviour similar to that used when foraging (as discussed in Chapter 5 and above). If the former, it may be that increased foraging opportunities outweighed the energetic costs of disturbance. Different locations within the river are likely to have different ecological 'values' to dolphins, based on prey availability, suitability for resting, etc. The Fremantle Inner Harbour was a site worth staying in because of its foraging value despite it being a busy, noisy environment, as opposed to less valuable areas for foraging such as Perth Waters (Chapter 3). Tolerance of high vessel densities may also change seasonally within a site, if for example high quality and/or density prey are seasonal. However, the physical environment may also play a role, with deeper areas like the Fremantle Inner Harbour (dredged to 13 m depth) offering more 'escape routes' than shallower areas such as Perth Waters (average 1 m depth). The use of vertical avoidance strategies would be limited to areas with sufficient depth, such as Fremantle Inner Harbour. Further research on dolphin foraging behaviours and vessel avoidance techniques in the Swan River would clarify whether diving was associated with foraging or vertical avoidance of vessels.

Most previous studies investigating dolphins' behavioural transitions in response to vessel traffic have used the presence/absence of tour boats, with corresponding impact (boats present) and control (no boats) treatments for which to apply Markov chains. However, the current study not only included 'low' and 'high' vessel density categories as impact and control, but also included periods when vessel traffic was 'increasing' or 'decreasing'. Inclusion of these categories revealed that dolphin behavioural budgets differed when vessel traffic was low, increasing, and high. Low and decreasing categories showed no difference in their behaviour budgets, indicating that dolphins quickly resumed their original activities after disturbance. This rapid transition back to baseline behaviour likely reflects the habituated nature of Swan River dolphins. However, the dolphin community is only habituated up until a certain point, and changes its behaviour beyond a threshold. Whether this threshold is exactly 3 vessels transiting the area per 5-min period used as a sample period in this study or some other value requires further investigation.

Whilst in previous research in the Fremantle Inner Harbour whistle characteristics were not related to octave-band noise levels (Ward *et al.*, 2016), in this study they were. Dolphin whistle characteristics were most different in the presence of increased levels of low-frequency noise (octave-band level centred on 1 kHz). While dolphins are acoustically-specialised for communication at higher frequencies, broadband noise levels that coincide with the lower frequency range of dolphin whistles may reduce the effectiveness of communication. In the study by Ward *et al.* (2016), a 10 s window immediately prior to dolphin whistles was used to calculate noise levels, while in this study a 2 s window was used. There is no available information describing how quickly animals alter their vocalisations following noise exposure. However, alterations in vocalisations may be neural and reflexive, resulting in a fast response (Gillam *et al.*, 2007; Hase *et al.*, 2016). If responses are rapid, Ward *et al.* (2016) may have used too large a window for calculating noise levels. Alternatively, it may be that both studies were confounded by limited groups of dolphins sampled. In addition to whistle characteristics being related to noise levels in this study, they were also related to activity state, group size, and calf presence. A sample originating from limited numbers of groups engaged in certain behaviours and in certain noise conditions could have caused biased results. Hence, differences may relate to the groups present in the studies and their whistle repertoire. The difficulty in obtaining a large, representative, random sample is reflected in differences in the datasets from the two studies. While Ward *et al.*

(2016) used a considerably larger sample size of whistles (n = 477 vs n = 164 here), the current study found several whistles unrecorded by Ward *et al.* (2016). Obtaining random samples of dolphin whistles is virtually impossible. However, future studies could aim to include individual identification of dolphins within proximity of the acoustic recording system, in addition to a suite of explanatory variables including group composition, group size, activity state and noise levels to disentangle their interacting effects. Furthermore, a greater range of broadband noise scenarios than those able to be obtained in this study would improve our understanding of dolphin whistle responses to noise. Average broadband noise levels in the Fremantle Inner Harbour were 110 dB re 1 µPa rms (10 Hz – 48 kHz), and dolphin whistles were recorded in conditions ranging from approximately 96 to 125 dB re 1 µPa rms (10 Hz – 48 kHz). However, there was a sparsity of samples between 111 and 118 dB re 1 µPa rms (10 Hz – 48 kHz), causing a gap in the upper-intermediate noise levels. The change in dolphin whistle characteristics occurred at some point in this range. Extending the collection of whistle samples to other Swan River locations with different soundscapes would provide for a greater range of noise levels in addition to expanding the spatial applicability of results. For instance, the average broadband noise levels of Perth Waters was 112 dB re 1 µPa rms (10 Hz – 11 kHz). Further data within this range, in conjunction with contextual information, could aid in progressing knowledge obtained from this study.

Broadband noise levels in Roebuck Bay and Fremantle Inner Harbour on average differed by 20 dB. The higher levels recorded in Fremantle Inner Harbour are considerable in their implications on effective communication ranges, sensory stimulation, and stress experienced by coastal dolphins. Levels of exposure to man-made noise in Roebuck Bay were far below those associated with changes in Swan River dolphins' behaviours. Due to a lack of prior exposure, Roebuck Bay dolphins may differ in their behavioural responses to dolphins in the Swan River. Given that they are unhabituated to high levels of man-made noise, Roebuck Bay dolphins may have a lower tolerance for anthropogenic activities and noise. This could potentially make them more sensitive to disturbance and more prone to altering behaviour at lower noise levels. Furthermore, the dolphin communities in Roebuck Bay and Fremantle Inner Harbour may differ in how they perceive sound. Hearing sensitivity varies both between and within species. Information on snubfin dolphin sensitivities is required, as there is currently no information available for this species. In bottlenose dolphins hearing sensitivity can vary by up to at least 10 dB (based on audiograms of 14 bottlenose dolphins; Houser & Finneran, 2006; Popov *et al.*, 2007). Hearing can also vary according to age and sex (Brill *et al.*, 2001; Houser *et al.*, 2008). Further research on dolphins' hearing abilities in quiet and noisy environments is required to determine how hearing sensitivities are altered with chronic man-made noise exposure. Research in multiple Western Australian dolphin environments would test whether similar changes occur in whistle characteristics in association with underwater noise across dolphin communities, regardless of location. Other studies have reported a variety of ways in which dolphins can alter their vocal behaviour in response to vessel noise. Energetic consequences of vocal repertoire alterations, such as elongating whistles or increasing vocal rate to improve communication in noisy environments would allow energy costs of alterations to be compared. The nature of noise in a 'noisy' environment may render some alterations more effective for communication than others. Thus selecting a more cost-effective alteration may not be an option.

If Roebuck Bay and Swan River dolphins are comparable in their sensitivities and responses, then dolphins in Roebuck Bay could experience significant energetic savings. Given the relatively low levels of vessel traffic and noise in Roebuck Bay, levels eliciting dolphin responses in the Fremantle Inner Harbour are likely rarely reached. The energy dolphins in Roebuck Bay do not expend in regular responses to vessel traffic could translate to healthier individuals, leading to increased survivorship and reproduction rates. However, for snubfin dolphins in Roebuck Bay, either due to species-specific behaviour, sensitivity, or relative inexperience with vessels, a greater proportion of animals have vessel strike injuries and scars than bottlenose dolphins in the Swan River (author pers. obs.; Thiele, 2010). Future studies on health differences among snubfin dolphins and the two bottlenose dolphin communities at these two study sites would benefit future protection of coastal dolphin populations.

7.3 Implications for Management and Future Research

To determine the impact of human activities on coastal dolphins, knowledge on the effects of human impacts and the extent of overlap with dolphins' home range is required. The Swan River dolphin community has a home range that covers the lower, middle and upper reaches of this river, and also extends into the Canning River (which feeds into the Swan River middle reaches) and parts of Cockburn Sound (within proximity of the Swan River mouth). This home range covers an area greater than 72 km^2 (the extent of the Swan-Canning). Swan River dolphins use the range of habitats within the Swan-Canning River estuary on a near-daily basis, for a range of life functions including foraging, resting, transiting, and socialising. Dolphins spend varying times at different locations depending upon the benefits gained and losses incurred at each site. While some sites may be optimal foraging or safe resting locations, others may be poor in prey, expose dolphins to predation or serve mainly for transiting from one preferred site to another. The use of these locations likely varies as their relative benefits change with the seasons. In addition, stressors such as human activities may change the cost-to-benefit ratio, rendering some preferred sites less attractive at certain times.

Human use varied at different locations within the Swan River in this study. While there was no published information on vessel use in the Swan River, the present study quantified vessel densities and movement using theodolite-tracking at two river locations. In addition, acoustic monitoring to define the soundscape experienced by dolphins and measure human noise sources including vessels was undertaken at five sites. Results from visual and acoustic monitoring revealed localised underwater acoustic habitat within the Swan River, with each site displaying a unique soundscape. Soundscape variations at other locations within the Swan River are likely. To map the entire Swan River soundscape, broader spatio-temporal coverage of acoustic monitoring is required. Extending monitoring into the Canning River would provide soundscape information within an area of the dolphins' home range which likely receives less anthropogenic noise than the Swan River as a result of different management zoning and vessel restrictions. As the primary source of vessel traffic in the Swan River involves small recreational boats not fitted with AIS (Automatic Identification Systems), this type of data were not examined since they would not have provided representative vessel traffic information in this area. Theodolite-tracking worked well, as Perth Waters and Fremantle Inner Harbour were overlooked by high vantage points. This method could be implemented at strategic locations in future studies within the Swan-Canning River estuary for monitoring. In addition, acoustic measurements offer an alternative method to monitor vessel presence throughout the river system. Acoustic monitoring is more cost-effective over longer periods than employing theodolite tracking teams. Other methods for monitoring vessel traffic in the Swan-Canning Rivers could include monitoring of boat-ramp usage or conducting shore-based vessel counts at target locations. Monitoring at multiple locations over time would allow the extent of human-dolphin habitat overlap to be documented throughout the river system over different seasons. Information on the acoustic quality of dolphin habitats, together with information on water quality, ecological processes, species biodiversity, and wildlife health, contributes to the overall knowledge required by managers to successfully balance ecological health with human requirements.

Dolphins tracked at the Fremantle Inner Harbour and Perth Waters indicated disproportionate overlap with vessel traffic at these two locations. Swan River dolphins occupied Fremantle Inner Harbour more frequently and for longer periods than Perth Waters despite the similarly high levels of vessel traffic. Thus, the Fremantle Inner Harbour is one location where benefits during study season likely outweighed the costs of an anthropogenically noisy environment. The fact that dolphins show differential site use (Chapter 3) means that a threshold from one location cannot be generalised for mitigation across locations. In addition, habitat that is critical during one season may not be critical at other times of the year. Hence, response thresholds would be expected to vary within a particular site during different seasons. These complexities pose challenges for managers designing protection zones based on dolphin critical habitats and thresholds for mitigation. For example, anthropogenic construction activities which produce intense noise (e.g. pile-driving in the Fremantle Inner Harbour; Paiva *et al.*, 2015) typically require cessation of activities when dolphins are within recommended threshold range to mitigate noise-induced injury. However, implementing effective management of dolphin behavioural responses to chronic low-level noise requires a long-term monitoring approach to define thresholds based on behavioural trends and changes in health.

While determining these thresholds may take time to become available, there are a range of measures that can be implemented to reduce man-made underwater noise levels in the environment. For instance, noise will most likely increase with increasing vessel speed due to increased propeller cavitation (Erbe *et al.*, 2016), hence implementation of speed limits that significantly reduce cavitation would likely reduce noise produced. Noise levels are also associated with factors such as propeller trim angle, number and diameter of propeller blades, engine model, vessel course, boat length, and hull displacement. By characterising vessel noise based on engine/vessel features, navigation modes and manoeuvres, low-noise options could be identified or new low-noise designs could be made available. Furthermore, restricting access by particular vessel types or manoeuvres in critical areas could reduce impacts. Some techniques for reducing engine noise can also improve engine or fuel efficiency that benefit boat owners. Several speed restriction zones are already in place within the Swan River, yet in this study frequent speed violations in Perth Waters and the Fremantle Inner Harbour were observed. This was particularly true for some vessel types, such as jet skis. Knowledge of vessel acoustic signatures could potentially provide additional information regarding vessel speeds in the river system. While the Water Police regularly patrol the river system and can issue fines for speed violations in speed-restricted zones, this study illustrates at least two areas that would benefit from increased awareness regarding vessel safety and additional enforcement of speed restrictions in the Swan River.

For bottlenose dolphins that occur in Australian coastal waters, many different conditions are available to assess responses to underwater noise in quiet 'control' sites versus noisy 'impacted' sites, and the effectiveness of mitigation approaches. In this study, Roebuck Bay provided a relatively quiet and the Swan River a relatively noisy acoustic habitat for coastal dolphins in Western Australia. However, this study was limited to the two locations. A greater depth of knowledge is required to extrapolate results beyond these two sites. In contrast, snubfin dolphins are limited to the northern, tropical coast of Australia. Little is known about their exact distribution and occurrence (Beasley *et al.*, 2005; Bejder *et al.*, 2012; Parra *et al.*, 2006b; Palmer *et al.*, 2014a,b; Parra *et al.*, 2002; Allen *et al.*, 2012; Parra *et al.*, 2006b). These areas are typically remote and sparsely populated by humans, so there may well be quieter acoustic habitats in existence for snubfin dolphins than that of Roebuck Bay. However, Roebuck Bay hosts the largest known population of snubfin dolphins in Australia (Brown *et al.*, 2016, 2014b; Thiele, 2010). Even if quieter environments exist, they may not overlap with large, resident populations of snubfin dolphins. Identification of 'quiet' and 'noisy' coastal dolphin habitats and their overlap with high animal densities is required for marine spatial planning in relation to species using sound for life functions. The maintenance of acoustic habitats relatively free from anthropogenic noise in locations with high dolphin occupancy will reduce stressors and have conservation benefits to populations such as snubfin dolphins in Roebuck Bay.

The Australian Government has plans to implement a marine protected area (MPA) in Roebuck Bay. Recently, there has been much debate regarding zoning of the MPA, as stakeholders discuss which activities should be allowed within the park boundaries. These discussions have not extensively considered the implications of underwater noise on Roebuck Bay's marine life, but the Yawuru Nagulagun / Roebuck Bay Marine Park Joint Management Plan states an intention to manage physical disturbance to marine mammals from vessel traffic and boat strike, coastal development, industrial activities, inappropriate human interaction, and acoustic disturbance (DPaW & Wildlife, 2016). Chapter 6 highlights the pristine acoustic environment of Roebuck Bay as a feature worth preserving given the sensitive nature of snubfin dolphins. There are numerous approaches that can be used to regulate underwater noise. These include implementing speed restrictions on vessel traffic, regulating which noise-producing activities can occur in certain areas, a requirement for implementing noise mitigation during construction (e.g. bubble curtains for pile-driving activities), and spatial or temporal restrictions to human activities. Future discussions regarding the MPA now have the additional benefit of this preliminary description of the Roebuck Bay soundscape and its relevance to coastal dolphins.

The information in this study is based measurements made at one site within Roebuck Bay frequented by bottlenose and snubfin dolphins over two months. Roebuck Bay in its entirety covers approximately 550 km^2 and is visited by many other cetacean species, such as humpback dolphins (*Sousa sahulensis*) and humpback whales (*Megaptera novaeangliae*). The bay is also home to dugong (*Dugong dugon*), green turtles (*Chelonia mydas*), flatback turtles (*Natator depressus*), hawksbill turtles (*Eretmochelys imbricata*), loggerhead turtles (*Caretta caretta*), and olive ridley turtles (*Lepidochelys olivacea*), in addition to numerous species of sharks, rays, mantas, sea snakes, fish, and invertebrates. This leaves a large proportion of the bay acoustically undescribed and the effects of noise on many marine species at locations such as the Port of Broome unconsidered. Additional acoustic measurements over a broader spatio-temporal scale, sound propagation modelling to account for the variable environmental conditions within the bay, and further research on the hearing abilities and behavioural responses of several marine species to noise is recommended. This will allow assessment of variability in the sound environment and its relationship to marine fauna within Roebuck Bay.

7.4 Conclusions

Overall, this thesis highlights the importance of considering acoustic habitats with regard to acoustically-specialised species, and advocates examining a range of behavioural response types when investigating potential disturbance from anthropogenic activities and underwater noise.

The two study areas considered here represented contrasting acoustic environments for coastal dolphins. The Swan River included a series of busy, noisy, urban acoustic habitats dominated by anthropogenic noise, whereas Roebuck Bay was a quiet area characterised by biotic sound sources. Within the Swan River, dolphins had strategies for dealing with noisy environments, and the foraging opportunities found in one noisy focal site likely outweighed the energetic costs of disturbance. The geographically distinct study areas considered here were separated by over 3,000 km of coastline. There are likely multiple 'low', 'high, and 'intermediate' acoustic habitats in between, representing soundscapes of varying noise levels and different sound sources. There are also dozens of other dolphin populations and communities (not to mention species) scattered around the coastal waters of Western Australia. How these dolphins respond to sound sources encountered in their acoustic environment may well differ from the findings presented here. Such responses will depend on the sound sources in question, habituation of animals to those sounds, hearing abilities and whistle characteristics of the dolphin communities, and various other contextual factors. Consideration of a range of response and contextual explanatory variables in behavioural response studies is critical. Whilst this outcome may suggest a seemingly never-ending quest to determine the behavioural and acoustical responses of coastal dolphins to noisy environments in Western Australia, it also represents countless numbers of scientific discoveries yet to be made.

Appendix A

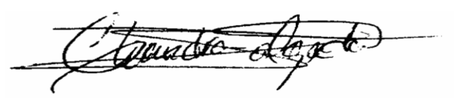
Co-Author Contribution Statements

By signing below, co-authors agree to the listed publication being included in the candidate's thesis and acknowledge that the candidate is the primary author, i.e. contributed greater than 50% of the content and was primarily responsible for the planning, execution and preparation of the work for publication, unless indicated otherwise.

Publication title: Underwater Sound in an Urban Estuarine River: Sound Sources, Soundscape Contribution, and Temporal Variability.

Co-authors:

Dr Christine Erbe



Dr Chandra Salgado Kent

Publication title: Occupancy of bottlenose dolphins (*Tursiops aduncus*) in relation to vessel traffic, dredging and environmental variables within a highly-urbanised estuary.

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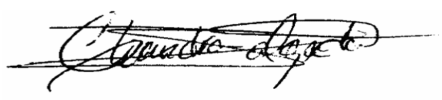

Dr Chandra Salgado Kent

Dr Christine Erbe

Publication title: Spatial and temporal variation in the acoustic habitat of bottlenose dolphins (*Tursiops aduncus*) within a highly-urbanised estuary.

Co-authors:

Dr Christine Erbe

Dr Chandra Salgado Kent

Dr Miles Parsons

Dr Iain Parnum

Publication title: Effects of vessel traffic and underwater noise on the movement, behaviour and vocalisations of bottlenose dolphins (*Tursiops aduncus*) in a highly-urbanised estuary.

Co-authors:

Dr Chandra Salgado Kent

Dr Christine Erbe

Dr Iain Parnum

Publication title: A Tale of Two Soundscapes: Comparing the acoustic characteristics of urban versus pristine habitats for coastal dolphins in Western Australia.

Co-authors:

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Appendix B

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