Passive acoustic techniques to monitor aggregations of sound producing fish species 2010/004

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1.0 NON-TECHNICAL SUMMARY

2010/004 Passive acoustic techniques to monitor aggregations of sound producing fish species

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Objectives:

This project has focussed on two demersal marine species, one estuarine opportunist and one estuarine species of fish, all of commercial and recreational importance in Western Australia: West Australian dhufish (*Glaucosoma hebraicum*); snapper (*Pagrus auratus*); mulloway (*Argyrosomus japonicus*); and black bream (*Acanthopagrus butcheri*), respectively.

The objectives for this project were:

1. Acquire long-term mulloway vocalisation records and evaluate aggregation boundaries, timings, relative abundance and driving factors.
2. Investigate dhufish/snapper/black bream vocal behaviour and evaluate applicability of acoustic monitoring.
3. Review of passive acoustics as a legitimate tool in fisheries management.

These objectives have remained consistent throughout the duration of the project. An additional objective developed through the analysis of data collected here and through affiliated studies was;

4. Characterisation of fish calls and choruses from unknown sources along the Western Australian coastline.

Outcomes Achieved to Date:

- **Increased understanding and appreciation of the information provided by passive acoustic monitoring of vocal fish species from an ecological and fisheries monitoring perspective.** This project has expanded the application of passive acoustics to detect variations in relative numbers of sound producing fish in an aggregation, as shown by different aggregations of mulloway (*Argyrosomus japonicus*) at particular spawning sites in Western Australia. The confirmation that West Australian dhufish (*Glaucosoma hebraicum*) produce sound, and do so in the wild, with the identification of their call source level (SL), means that passive acoustics could be applied to a new species, such as detecting presence of WA dhufish at a given location.
- **Increased collaboration between research centres within Western Australia.** This collaboration has built on previous FRDC funded partnerships between the CMST and Department of Fisheries WA (DoFWA), including local groups (Department of Parks and Wildlife, Curtin Aquatic Research Laboratory) and international research centres (Florida International University, Shark Bay Ecosystem Research Project) to complete the project.
- **Greater public awareness of the use of sound to communicate by marine animals, particularly fishes.** Several public and scientific seminars around Perth, regional Western Australia and the United Kingdom have greatly increased public knowledge of underwater soundscapes, the use of sound by marine animals and the impacts of sound resulting from human activity on the animals. The work conducted during this project has led to segments on internationally broadcasted television programs, radio interviews and a permanent interactive display in a marine discovery centre.
- **Developing standardised methods for monitoring vocal species with passive acoustic techniques.** The continuation of work conducted in FRDC project 2004/051 and 2010/004 has helped develop and standardise methods for confirming sound production by vocal fish, the identification of call SLs and long-term monitoring of fish choruses, all important steps in monitoring the spatial and temporal presence and abundance of vocal fish species.
- **Application of passive techniques to monitor fisheries.** Techniques, programs and equipment developed and manufactured during this project are to be applied and further developed during planned FRDC and DoFWA projects. Not only will this aid monitoring of vocal fish species, but also species which use soundscapes as a cue for behavioural patterns (for example, the use of particular sounds as a cue for orientation or timing to being migration). A review of the techniques developed here and used elsewhere in the world has highlighted some of the areas where passive acoustic monitoring of vocal fish can aid management and monitoring practices.

The need to optimise spawning success and survival of offspring by fishes has resulted in the evolution of a vast array of reproductive strategies, such as spawning aggregations. A spawning aggregation is defined by Domeier and Colin (1997) as, “a group of con-specific fish gathered for the purpose of spawning with fish densities or numbers significantly higher than those found in the area of aggregation during non-reproductive periods”. However, Mackie *et al*. (2009) noted that this is not always the case, as individuals of a species may aggregate to spawn in numbers lower than those found in schools of the same species, at the same location, outside of spawning times. A more pertinent description of an aggregation from a management perspective is that reproductively active fish are grouped together in a manner which increases their vulnerability to fishing.

Over-fishing of spawning aggregations is often associated with the collapse of the fisheries they supported. Management of fisheries that exploit such aggregations has become a crucial element in sustaining such resources. To effectively assess the biomass, distribution, behaviour and ecological importance of spawning aggregations, techniques are required which are non-invasive, incite as little behavioural bias as possible, can repetitively acquire high-resolution data for periods up to entire spawning seasons and are comparatively easy and cost effective to deploy. Conventional sampling techniques, such as video census (for example, Diver Operated Video surveys or Baited Remote Underwater Video systems), egg tows or catch related sampling often offer only a snapshot-in-time of the aggregation and in some cases suffer from sampling bias induced by the method itself. No sampling method is exempt from bias; however, the integration of a suite of techniques pertinent to the biological and behavioural characteristics of the species can provide complementary data sets that allow a better understanding of their biases.

Although not without limitations, acoustic techniques offer unique, complementary methods to other sampling techniques. Sound waves propagate efficiently through water, allowing acoustic ‘observation’ of sound-producing marine animals over considerably greater distances and ranges of conditions than visual techniques. Over 800 species of fish reportedly produce sound, many during spawning and the recording of these vocalisations is being increasingly used to acquire information on species that aggregate. The lack of human interaction during the recording of fish calls means that passive acoustics offers a non-extractive method of monitoring vocal fish. Sound pressure levels (SPLs) of fish choruses have been shown to be related to the number of calling fish present and provide important information on likely ecological (environmental or anthropogenic) correlates behind the timing, spatial distribution and relative size of aggregations and the behaviours associated with them.

The proposal for this project was developed in liaison with the Department of Fisheries, Western Australia (DoFWA); Aquaculture Development Unit (ADU) at Fremantle Challenger Institute of Technology; the Shark Bay Ecosystem Research Project (SBERP); the Department of Parks and Wildlife (DPaW) and; the Curtin Aquatic Research Laboratory (CARL), who have all provided in-kind support to various areas of the project. Recreational and commercial fishing groups including Recfishwest, Recfishing Research and Western Australia Fishing Industry Council (WAFIC) were consulted for advice and support. The Swan River Trust was also consulted to identify the benefits this project could offer towards their current objectives, and have provided in-kind support in the form of access to a substantial environmental dataset for the Swan River to compare environmental variables with sound production levels.

One of the primary objectives of this project was to quantify the spatial and temporal variations in sound production of mulloway at various aggregation sites. In addition, at the beginning of this project no reports of sound production by WA dhufish, snapper and black bream existed; thus, the project aimed to determine whether these species are vocal and, if so, whether their vocalisations are of use as a fisheries-independent monitoring tool. Deployments have been successfully completed along the WA coastline from Augusta to Shark Bay to record vocalisations by the four target species. In excess of 1.84 Tbytes of data have been collected during the course of the project, comprising a total of 9015 hrs (375 days) of recordings over a total deployment period of 818 days. Analysis from a further nine datasets, comprising 894 days deployment (287 days of recording in total), provided from affiliated projects has helped investigate a variety of fish calls and choruses off Western Australia.

Sea-noise loggers have detected mulloway calls in recordings collected at Shark Bay, Abrolhos Islands, Swan River, Cockburn Sound, Garden Island, Myalup, Geographe Bay and Augusta. Mulloway spawning aggregations have been mapped around the Swan River and at three sites out to the Garden Island channel, by the SPLs of their chorus. The maximum levels were found between Mosman Bay and Blackwall Reach in the Swan River, with a secondary aggregation at the Garden Island channel site. Mulloway calls that make up these choruses have been characterised into three categories (mean source levels in brackets): Category 1 comprised of short calls of 2-5 pulses (163 ±16 dB re 1µPa); Category 2 included long calls of 11-32 pulses (172 ±4 dB re 1µPa); and Category 3 which was a series of successive calls of 1-4 pulses, increasing in call rate (157 ±5 dB re 1µPa). The mean source level (SL) is the SPL at a range of 1m. Analysis of Mosman Bay chorus SPLs over eight spawning seasons, together with concurrent environmental variables, has shown that the fish numbers are related predominantly to temperature, salinity and sunset time with semi-lunar maxima. The commencing of the chorus is associated with temperatures above 19°C and salinity above 34600 mg/L with a positive relationship with both. Over the course of a spawning season the daily timing of the chorus is driven by the time of sunset, but also has a relationship with the time of high tide over shorter time-scales, suggesting that mulloway spawn shortly after high tide in Mosman Bay. Individual calls, while often of consistent fundamental frequency (the frequency which is discerned by humans and likely by fish) have been found to vary by up to 10% of the fundamental frequency (the repetition frequency of swimbladder pulses which humans perceive as the 'pitch' of a sound). Such a variation in frequency can be detected by some species of fish; however, whether mulloway can detect this change and whether it can be detected over the duration of a single call (0.37 s) is unknown. The reasons behind such variations are yet to be determined.

The most likely method of sound production by West Australia dhufish is by the contraction of muscles that are attached to the anterior of a large, waxy swimbladder and to the rear sides of the brain casing. These muscles were identified in both juvenile and mature male WA dhufish. Calls produced by two captive male dhufish confirmed sound production by the species and were recorded at a range of approximately 1 m. These calls comprised 1 to 14 swimbladder pulses at 154 ± 45 Hz mean spectral peak frequency (n = 67 calls) and 3 dB bandwidth of 110 ± 50 Hz. The mean of all call maximum SLs was 124 ± 6 dB re 1µPa at 1 m with the highest level at 137 dB re 1µPa at 1 m. Using spherical spreading as the only transmission loss and excluding the probability of detection and WA dhufish hearing thresholds, a very simple estimate of call propagation predicts that a dhufish call attenuates to a background noise level of 90 dB re 1µPa at around 150 m. Recordings taken at a site in Augusta, known to be inhabited by juvenile (and some mature) WA dhufish, contained similar calls, with a maximum SL of 132 dB re 1µPa at 1 m, suggesting the fish were within 10 m when the calls were produced. In Geographe Bay and off Cape Naturaliste, calls with characteristics similar to those of the captured WA dhufish have been recorded at sites recommended by local fishers as locations where the species is caught during the spawning season. The received levels of these calls were approximately 112 dB re 1µPa at 1 m, suggesting a range of around 100 m. The fact that WA dhufish calls have been recorded *in situ* at a location regularly inhabited by juveniles, as well as at sites and times where mature fish reportedly migrate to spawn means that passive recording of their calls may provide useful information on delimiting times when dhufish are present. While the relatively low SL of their calls results in sample areas of approximately 0.1 km^2, under certain conditions of ambient noise, an array of hydrophones can expand this sample area significantly.

Examination of snapper swimbladders and theoretical modelling of possible sounds show that snapper may be capable of generating sounds at frequencies between 50 and 250 Hz, though no specialised mechanism of sound production could be discerned. Deployments targeting spawning aggregations of snapper in Cockburn Sound and Shark Bay have acquired little evidence of snapper vocalisation. SPLs over the 50-250 Hz frequency band often increased during hours of darkness during the deployments. However, evidence suggests that these increases were due to increases in wind-driven waves during those periods, rather than sound production by the fish. In addition, during rod and line capture of 22 snapper (17 male and 5 female) in Shark Bay by DoFWA, no sounds were detected as the fish were slowly raised to the surface within the detection range of a hydrophone.

Biological examination of black bream did not reveal any clear mechanism for sound production. During the capture of three male black bream, acoustic recordings detected no evidence of sound. Recordings taken in 7 m and 11 m deep holes in the Frankland River, at times when black bream have been captured by recreational fishers and where the species reportedly spawn, have shown evidence of possible fish noise. In the 2010 season, while deployments occurred towards the end of an early spawning season, in the 11 m hole, high-frequency noises were recorded throughout the sampling. These sounds were predominant after sunset and were often accompanied by the sound of moving water (likely generated by fish movement rather than waves). In the 2011 season, fish sounds were detected between 200 and 500 Hz. However, the received levels of these calls were very low (113 dB re 1µPa), indicating either a fish call of low SL, or of long range. Thus black bream were deemed not to produce sounds that could be used in monitoring their presence.

Methods to estimate the number of callers contributing to chorus levels are outlined with specific reference to fish that produce calls of high SL (such as mulloway) and those of lower SL (such as WA dhufish). This has been applied to chorus levels observed in Mosman Bay with confidence limits on the number of callers to provide an estimate of fish numbers in the Mosman Bay aggregation, during periods when individual calls can be counted. Further work is required to extrapolate this method to levels of calling where individual calls can not all be distinguished and the sound pressure levels related to the absolute numbers of fish in the aggregation.

This project has built significantly on recent FRDC funded research to further develop passive acoustic techniques as a complementary tool for monitoring and studying sound-producing fish species in Australian waters. Techniques and equipment developed during this project are being applied and developed further for passive acoustic monitoring projects of other type of fauna, such as the Western Rock lobster (*Panulirus cygnus*).

KEYWORDS: Sound production, spawning aggregation, fisheries management, propagation, mulloway, dhufish, snapper, black bream, Western Australia

2.0 ACKNOWLEDGEMENTS

This project has eventuated from the success of FRDC Project 2004/051, 'Management and Monitoring of Fish Spawning Aggregations within the West Coast Bio-region of Western Australia', driven by Dr. Mike Mackie. Dr. Mackie's input has been crucial to the success of the scientific and extension based outcomes of this project. Within the CMST, Frank Thomas and Mal Perry have been immensely helpful in their design, manufacture and maintenance of equipment applied in this study. They have also been intrinsic to a large number of the deployments. Additionally, numerous researchers have provided support during fieldwork, analysis and the review of reports. For their help, grateful thanks go to Alexander Gavrilov, Chandra Salgado, Alec Duncan, Iain Parnum, Kim Klaka, Angela Recalde-Salas and Sarah Marley.

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Communication and extension of this project has required significant promotion through numerous channels, some of which have been less available to the investigators. Staff at the Naturaliste Marine Discovery Centre (Michelle Youngson, Bruce Mackay, Sandy Clarke), Recfishwest (Kane Moyle, Andrew Rowland) and DoFWA (Ben Carlish) have put considerable effort into promoting the project and its outcomes, for which the investigators are very appreciative.

3.0 BACKGROUND

One of the most striking strategies evolved amongst fishes to maximise spawning success is aggregation spawning (Mackie *et al.*, 2009). In many species, large numbers of fish aggregate at the same time and location every year for spawning purposes. Such repetitive, predictable behaviour allows fishers to target otherwise diffuse populations, in some cases systematically reducing the aggregation, and possibly the fishery, to collapse (Colin *et al.*, 2003, Claydon, 2004). These high density spawning aggregations forming at anticipated locations and times can offer the opportunity to observe large numbers of fish at reduced effort. However, such aggregations often form under conditions which bias traditional surveying techniques, for example:

- Low light levels and/or turbid waters can limit the effective range of visual survey techniques (e.g. remote video or diver operated video surveys);
- Strong currents, which may be advantageous to the dispersal of fertilised eggs, can bias egg and larvae sampling techniques;
- Remote and/or inaccessible aggregations logistically reduce the opportunity to replicate sampling;
- Behavioural changes, such as reluctance to feed while spawning can significantly bias catch data;
- An interactive sampling method, such as baited video, induces bias;
- A mobile spawning aggregation requires broad area sampling;

Therefore the monitoring of spawning aggregations needs an adaptive approach to sampling.

No single sampling method is exempt from bias, however, the integration of many techniques allows behavioural characteristics of a species (or individual aggregation) to be matched to a robust set of data, increase understanding of the pertinent biases to facilitate the development of sampling strategies (Mackie *et al.*, 2009). This approach was highlighted by FRDC project 2004/051, which utilised fisher interviews, charter and recreational catch data, active and passive acoustics, underwater video and traditional sampling methods to identify potential implication of fishing aggregations and the risks to sustainability. Passive acoustic techniques employed in that study for mulloway proved to be very successful, often providing unique, robust data, unattainable through any other method. The premise of the technique is simple; listen to the calls produced by the aggregation to census the fish.

Soniferous (sound producing) species of fish such as mulloway have developed vocal cues as an aid to spawning in habitats where communication through visual stimuli is inhibited by turbidity or lack of light (Halford and Thompson, 1994, Rountree *et al*., 2006). The number of species shown to exhibit vocal behaviour is increasing as more research effort is applied (Lobel, 1992, Saucier and Baltz 1993, Luczkovich *et al.*, 1999). Calls can be species-specific, individually characteristic and repeated *ad nauseum* by an individual fish, offering significant information about the caller (Connaughton *et al.*, 2000, McCauley, 2001, Parsons *et al.*, 2009). Calling can be indicative of a spawning aggregation and can facilitate the identification of essential fish habitats, which in turn are often used in determining marine reserve boundaries (Greene *et al.*, 2004). Sound pressure levels (SPLs) produced by fish during aggregating periods have been shown to correlate to egg production in some species and provide a proxy to the spawning aggregation size (Luczkovich *et al.*, 1999). Counting fish calls in low-level choruses where individual calls can be discriminated offers a means to estimate the absolute abundance of calling fish. The spatial extent of fish calling (and spawner movement) can also be determined by measuring chorus levels along transects.

Sound propagates efficiently through water and is only limited by absorption and the sound transmission characteristics of an area, such as the local bathymetry and the sea-bed geo-acoustic properties (Urick, 1983). Depending on ambient noise levels, a vocal fish can be identified *in situ* from upwards of a kilometre away in open water, for some species (Simmonds and MacLennan, 2005, Parsons *et al.*, 2009). Fish calls emanating from large aggregations involving hundreds or thousands of fish can be detected many tens of kilometres away (McCauley, 2001). Such fish choruses are common in Australian waters, with some form of fish chorus recorded at almost every site sampled thus far by R. McCauley (unpublished data). Recent advances in autonomous data processing and increased storage capacity has enabled the Centre for Marine Science and Technology (together with the Defence Science and Technology Organisation) to develop sea-noise noise loggers capable of passively recording sea noise at a desired sampling schedule over monthly to yearly time frames.

The technique of passive acoustic observation offers the opportunity to 'observe' fishes without any negative impact and in a cost-effective manner. The technique holds particular benefit to species: 1) which are susceptible to barotrauma and/or handling stress (such as dhufish and mulloway) and so are not conducive to traditional sampling which require capture and release (such as tagging); 2) for which destructive sampling is not desirable; or 3) which form spawning aggregations in difficult to access areas. Obtaining passive acoustic samples is relatively straightforward and safe; with one or more sea noise loggers deployed on the seabed (typically on sub-sea moorings) that can be left to sample the full spawning season. Continuous records of sound production by aggregating fishes, over an entire spawning season, can provide a complete temporal picture that can be matched to concurrent environmental data, in comparison with ‘snapshot’ results produced by traditional fish sampling methods. These continuous datasets bear particular significance to aggregations which may vary appreciably in numbers over a short period of time (which would create significant bias in short-term surveys). Analysis of the resultant acoustic data is initially complex and requires considerable effort in understanding fish vocalising habits and their transmission characteristics. However, once these parameters are established and the analytical protocols defined, then new data sets can be processed quickly and cost-effectively. This facilitates development of long-term datasets that enable highly informative evaluation of trends over time.

Like any sampling tool, passive acoustic techniques are not without limitations, which require further research. A fish cannot be observed unless it produces sound and therefore the method is predominantly useful for vocal species. In non-vocal species in can be used in conjunction with other sampling methods to provide information on behavioural responses to changes in ambient noise. Additionally, the relationship between calling and non-calling fish requires identification. Ambient noise, such as that generated by vessels or other fish, may mask sounds. Hence, further research is needed to streamline analytical techniques, and to understand animal habits, their effect the data collected by listening to vocalisations and the resulting implications for monitoring.

In certain circumstances passive acoustic techniques can not only provide data on aspects of the biology of a vocal species that otherwise was not known, but offers significant information to fisheries monitoring and stock assessments. Elsewhere in the world passive acoustic techniques have been used to identify unreported spawning aggregation locations, such as the spawning of red drum (*Sciaenops ocellatus*) in estuaries as well as offshore in the U.S., or that haddock (*Melanogrammus aeglefinus*), previously thought to spawn exclusively offshore, also spawn in fjords of Norway. Spatial and temporal delineation of these aggregations can lead to accurate application of temporary fishing closures or sampling used in stock assessments at locations which would have previously been neglected. Passive acoustics are also often used in conjunction with other traditional sampling methods to study biological aspects, such as fecundity, for example, by helping identify the optimum time to acquire egg samples. If this is the case then the information gained may be usable to complement existing monitoring of spawning aggregation biomass

A number of Australian fishes have been reported as vocal or are thought to be vocal. The key species targeted in this project include mulloway (*Argyrosomus japonicus*), West Australian dhufish (*Glaucosoma hebraicum*), snapper (*Pagrus auratus*) and black bream (*Acanthopagrus butcheri*). Each of these species is commercially and/or recreationally important species in Australia. In the eastern states mulloway has been listed as vulnerable due to extensive fishing while it is considered a prized recreational fish in Western Australia. WA dhufish and snapper are employed as indicator species for monitoring demersal fish resources along the west coast of Australia (Brown *et al*., 2011, Fairclough *et al*., 2011), while black bream has become one of the pioneering species for studies of restocking estuaries (Gardner *et al*., 2010). Accurate monitoring of stocks of these three species is of ecological, social and economic importance to Western Australia.

The project has been designed to assess the applicability of passive acoustic sampling to management of these commercially and/or recreationally important species, which may be useful for informing management agencies in their weight of evidence approach to assessing risks to stock of species and stock status. In particular, this project was designed to provide relative spawning aggregation size in mulloway (*Argyrosomus japonicus*) over multi-year scales by monitoring spawning vocalisations, which may be able to provide fishery-independent data useful in assessing their variation. In addition, the study aimed to explore the presence and habits of vocal behaviour in WA dhufish, snapper and black bream to determine whether passive acoustic methods could be used to investigate aspects of spawning aggregation behaviour in those species and thus also possibly fishery-independent monitoring.

3.1 Characteristics of fish relating to sound production

Many species of fish aggregate to spawn in habitats where communication through visual stimuli is greatly inhibited by turbidity or lack of light (for example nocturnal or estuarine spawning). Thus, many species have developed alternative methods of communication, in this case, acoustic cues. In monitoring vocal fish the observer is primarily concerned with the characteristics of the emitted sound. However, to evaluate the importance of underwater sound to a species and whether a fish is likely to utilise sound as a means of communication it is necessary to understand the mechanisms behind both receiving and producing sound.

A brief outline of fish hearing is presented. For a more detailed introduction to this topic see Popper and Coombs (1980), Popper and Fay (1973) and Popper *et al.* (1982).

3.1.1 Auditory system

The inner ears of fish possess three otolithic organs and three semicircular canals, similar to other vertebrates (Popper and Lu, 2000). However, the speed of sound in water and the small separation and coupling between the ears means it is unlikely that fishes use the same binaural cues for sound source localisation as most terrestrial vertebrates (Lu *et al.*, 1996). Fish hearing involves the inner ear, an auditory section of the central nervous system and, in some species, peripheral structures, such as the swimbladder (Popper and Coombs, 1980). Otoliths are calcareous structures, found in the three otolithic organs and have been associated with sound detection functions (Popper and Fay, 1993). The otolithic organs also contain a sensory epithelium which is oriented in three dimensions around the otolith, and which possesses a narrow strip, covered with a large number of sensory hair cells, lying against the inner edge of the otolith. Ciliary bundles comprising stereocilia and kinocilium project from the hair cells, towards the otolith. The hair cells populate the otolithic membrane and are coupled to the otolith by a gel. The sensory cells and the otolith move differentially causing cilia bending. This bending of the ciliary bundle towards, or away from the kinocilium creates polarisation of the hair cell (Popper *et al.*, 1982) and it is this stimulation with which the inner ear detects changes due to a sound source.

Underwater sound comprises two components; directional particle motion and propagating scalar pressure waves (Medwin and Clay, 1998) and these two physically linked components reach the inner ear of a fish in different ways to induce cilia bending (Fay and Popper, 1975, Horodysky *et al.*, 2008). Otoliths are approximately three times denser than water, while a fish's body is of a similar density, thus a fish body may move with a displacement in water mass while the otolith displacement lags behind (Dijkgraaf, 1960). This difference in amplitude and phase between sensory epithelia and otoliths works effectively as a biological accelerometer which directly detects particle motion (Popper *et al.*, 1982, Popper and Fay, 1993, 1999). Such 'direct' detection works primarily at frequencies below 500-600 Hz (Popper and Fay, 1999, Ramcharitar *et al.*, 2006a). However, a swimbladder containing gas of a different density from the body can respond to changes in pressure produced by sound waves. These pressure changes are translated into displacement energy and can be transmitted to the inner ear where hair cells are stimulated. Many fishes have developed accessory structures to maximise this 'indirect' pathway, reradiating sound pressure waves towards the otoliths in the form of particle displacement (Fay and Popper, 1974, Popper and Fay, 1993). The application of these two mechanisms means that several species of fish are capable of detecting acoustic signals via both pressure variation and particle displacement, over a wide range of frequencies.

3.1.1.1 Hearing ‘specialists’ and ‘generalists’

Fishes are often classed as either hearing ‘specialists’ or ‘generalists’ based on their anatomy, ability to detect sound pressure waves, and detectable bandwidth range (Horodysky *et al.*, 2008). Hearing specialists of often unrelated taxa have typically evolved accessory hearing structures to connect the swimbladder to the ear, thereby extending bandwidths to higher frequencies and lower the hearing thresholds. These structures may come in different forms such as the anterior swimbladder diverticulae of the weakfish (*Cynoscion regalis*; Connaughton *et al.*, 2000), the Weberian ossicles (characteristic bones which connect the swimbladder to the inner ear; Popper *et al.*, 1982) of ostariophysines such as the goldfish (*Cassius auratus*; Ladich and Wysocki, 2003) or the suprabranchial chambers (labyrinths) of anabatoids (Wysocki *et al.*, 2009). Fishes without these peripheral structures are described as hearing generalists and typically exhibit higher hearing thresholds and a smaller frequency bandwidth. However, in species where the anterior of the swimbladder terminates closer to the ear lower thresholds over extended frequencies are often observed (Wysocki *et al.*, 2009). If unaided by a swimbladder the inner ear cannot detect indirect transduction of sound pressure, thus species which do not possess a swimbladder are only sensitive to particle motion (Enger and Andersen, 1967, Chapman and Sand, 1974, Wysocki *et al.*, 2009). However, the possession of peripheral hearing structures does not necessarily result in increased frequency bandwidth. The catfish (*Arius felis*), for example, is an ostariophysine (species possessing Weberian ossicles) which can only detect sounds below 1000 Hz. By contrast the squirrelfish (*Holocentrus ascensionus)* is a non-ostariophysine with good sensitivity in excess of 2000 Hz (Popper *et al.*, 1982, Popper and Fay, 1973).

Many species appear to have developed their hearing structures independently and no single fish ‘ear’ can be applied to a taxonomic group. Sciaenidae, for example, display at least three types of swimbladder-ear configurations (Ramcharitar *et al.*, 2006b). Sciaenids such as the spot (*Leoisomtus xanthurus*) and black drum (*Pogonias chromis*) are considered hearing generalists and have swimbladders which terminate some distance from the ear (Ramcharitar and Popper, 2004, Ramcharitar *et al.*, 2006a). By comparison, the weakfish (*Cynoscion regalis*), spotted seatrout (*Cynoscion nebulosus*) and silver perch (*Bairdiella chrysoura*) have developed anterior horns on the swimbladder which project forwards, close to the ear (Ramcharitar, *et al.*, 2006). In between these species, Atlantic croaker (*Micropogonias undulatus*) swimbladders possess anteriorly directed diverticulae which approach, but do not touch the ear (Ramcharitar *et al.*, 2006a).

The mechanism by which a fish hears can determine the levels and frequencies of sounds that it is able to discern and therefore also the range of the source and the level of ambient noise in which it can discern the sound. Given an estimated critical-hearing ratio (Fay, 1974, Tavolga, 1974), McCauley (2001) was able to estimate masking levels for sounds of differing source level (SL; the received level of a call at a reference distance of 1 m) for particular fish. Therefore assessing the auditory mechanism of a species can help identify its hearing sensitivity and frequency. For example, it has been suggested that relative otolith to body-size correlates to species hearing acuity and, as there is a positive relationship between sensitivity and communication, the likelihood of sound production (Gauldie, 1988, Paxton, 2000, Montgomery and Pankhurst 1997, Lychakov and Rebane, 2000, 2002, Ladich and Popper, 2001, Cruz and Lombarte, 2004). The species hearing frequency range illustrates some of the acoustic characteristics a recipient fish should be able to determine and, by inference, those produced by a caller.

3.1.2 Sound production

Fishes have developed numerous methods of sound production, as unsual as the herring, virbrating bubbles at the anal cavity (Wahlberg and Westerberg, 2003). However, the two chief mechanisms of fish sound production are via stridulation (high frequency, wide-bandwidth, usually of short duration), or the vibration of the swimbladder (McCauley, 2001). Stridulation is the rubbing or knocking of body parts together, such as sound of the catfish (*Bagre marinus*; Diogo *et al.,* 2001), creating a noise similar to that of marine invertebrates. This may be from pectoral fins such as sea catfish (*Felichthys felis*) or skeletal bones like the pipefish (*Syngnathus louisanae*) (Burkenroad, 1931, Fish, 1953). Vibration of the swimbladder is often conducted by contracting 'sonic' muscles that create vibrations in the swimbladder chamber. Sonic muscles are not the only method of doing this, but are the most effective. Since the acoustic impedance of the gas inside the swimbladder and the surrounding water differs greatly, the swimbladder is highly effective at generating sound (Simmonds and MacLennan, 2005). Variations in frequency can be created by altering chamber volume or a variation in the force vibrating it, i.e. the tension of the sonic muscles (Sprague, 2000). An example is the variety of calls produced by the grunter (*Terapon theraps)* which has been proposed to vary the frequency of its calls by the opening state of a sphincter allowing gas exchange between the two-chambered swimbladder (McCauley, 2001). Some species, such as the catfish (*Ictalurus punctatus*), generate sound by a combination of stridulation and swimbladder vibration (Vance, 2000).

3.1.3 Reasons for sound production

Fish produce sound for a number of reasons, reportedly associated with; aggressive encounters (usually territorial), reproductive, echolocation, schooling, recognition, feeding, migration, exploration, distress, while some are not-understood (Winn, 1964, Fine *et al.,* 1977). Often species are characterized by their specialisation in acoustic communication. The Sciaenidae family is a prime example, often called drums or croakers, (Fish and Mowbray, 1970) because of their well-developed, fast-acting muscles that they use to vibrate the swimbladder (Moulton, 1963). The most predominant use of vocalisation of sound by fish is during spawning, whether in paired courtship or a spawning aggregation and it is that use of sound on which this project is focussed (Guest, 1978, Mok and Gilmore, 1983, Saucier and Baltz, 1993, Connaughton, 1996, Luczkovich *et al.*, 1999b, Holt, 2002, McCauley, 2001).

Calling by spawning fish has been reported for decades, and recently techniques have been employed which use calling behaviour to locate aggregations (Saucier and Baltz, 1993, Luczkovich *et al.*, 1999a, Holt, 2002), however, sound produced by aggregating fishes may serve several functions and requires elucidation. The male haddock (*Melanogrammus aeglefinus*) and the male Atlantic Cod (*Gadus morhua*) for example, produce sounds of varying characteristics in the lead up to and during courtship (Hawkins and Amorim, 2000, Nilsson, 2004). McCauley (2001) speculated that the habit of fish calling "en masse" in Terapontidae and Sciaenidae choruses in Eastern Australian waters may function as one or more of: increasing the 'catchment area' of the aggregation; to 'prime' nearby fish for spawning; or to assist in mate selection and mediating gamete release.

3.1.4 Ground truthing of species presence and spawning behaviour

Correlations have been shown between calls and spawning related events for species that have been observed by diver or video, with simultaneous acoustic monitoring, either *in situ,* (Lobel, 1992, Gilmore, 2002, Mann and Lobel, 1995, 1998, McCauley, 2001, Sprague and Luczkovich, 2004) or *in aquaria* (Allen and Demer, 2003). However, as spawning in many species is invariably in a dark environment after dusk, specific confirmation is often difficult to obtain.

Two important conditions of the spawning aggregation which require ground truth evidence are the species present within the sampled waters and proof of reproductive behaviour by the surveyed species. Unless ground-truthed by video, reproductive activity within spawning grounds has to be inferred from either the egg distribution or capture of ripe spawners (Hawkins, 2002, Holt, 2002). However, many species migrate immediately before spawning (Holt, 2002), and/or spawn in locations where tidal motion or currents affect egg location subsequent to release (Farmer, 2008, Farmer *et al*., 2005). Thus while the presence of eggs and/or larvae near a soniferous aggregation can be a useful ground truth tool to associate calling with spawning behaviour, lack of them does not necessarily preclude spawning behaviour at that location.

Many fish sounds contain species-specific pulse rates, spectral peak frequencies and structures (Lobel and Macchi, 1995; Mann and Lobel, 1998) and are repeated with little change. This allows the identification of a sound by simple parameters, such as duration, peak frequency, repetition frequency and bandwidth (Mann, 2002). The identification of a single spawning call has been recorded on many occasions (Mok and Gilmore, 1983, Luczkovich *et al.*, 1999a, McCauley, 2001, Hawkins, 2002, Sprague and Luczkovich, 2004). The application of such techniques to estimate absolute biomass has, as yet, not been achieved.

The size of the aggregations of interest in this study are relatively small and numbers are such that ground truthing of species identification and spawning activity have been conducted through video techniques and direct sampling (line fishing). Comparison of waveforms and spectral content of *in situ* passive acoustic recordings with control *in aquaria* calls from individuals of known size and species were used to sufficiently ground truth passive acoustic surveys at locations where inter species vocal diversity was small and animals could be maintained *in aquaria*.

3.1.5 Known biological and behavioural spawning traits of the target species

3.1.5.1 Mulloway (Argyrosomus japonicus, Sciaenidae)

In Australia mulloway are distributed in temperate and sub-tropical waters across the southern coastline, bound approximately by Carnarvon on the west coast and Bundaberg on the east coast at approximately 25º latitude. In Western Australia mulloway is a recreationally and commercially important species which aggregates to spawn in near shore coastal waters or estuaries (Farmer, 2008). The species reportedly reaches spawning maturity at approximately 75 cm while the largest captured fish on record was 75 kg and 1.81 m (Griffiths and Heemstra, 1995, Silberschneider *et al.*, 2009).

Spawning of mulloway occurs on the lower west coast between November and April, when the mean monthly water temperatures typically exceed 19°C, in contrast to the upper west coast, where the mean monthly water temperatures do not fall below 19°C and spawning occurs all year round (Farmer, 2008). Seasonal movement in Perth metropolitan waters has been shown in adult mulloway*,* where near-shore encounters were more common during the summer months with fish moving offshore to *ca.* 100 m depth from May through to southern hemisphere winter (Farmer, 2008).

A comparatively small number of large individual mulloway migrate into the Swan River, Western Australia to spawn, reportedly linked with variations in salinity (Loneragan *et al.*, 1989, Farmer, 2008). In a recent study all samples captured in this area during the spawning period were above the L_{50}, the size at which 50% of the population is sexually mature. The opportunistic biological sampling conducted during spawning months showed a male:female mulloway ratio of approximately 1.3:1 (n = 62) in the Swan River and 1.15:1 (n = 31) across the lower west coast of Western Australia (Farmer, 2008). Spawning typically occurs around dusk or at times of darkness, inferred by the capture of females between 21:00 and 23:30 all of which possessed stage VI ovaries (Farmer, 2008). As many of the females caught immediately prior to the peak of high tide had ovaries containing hydrated oocytes a further link between spawning and high tide was inferred (Farmer, 2008), though this behaviour was not reported in other studies (Ueng *et al.*,1998). The mulloway is an indeterminate spawner, *i.e.* fecundity is not determined prior to the onset of spawning (Hunter and Macewicz, 1985). In Western Australia the species exhibits batch spawning, often releasing and fertilising eggs on a daily basis in a cyclic pattern peaking every few days (Farmer, 2008, Challenger Institute of Technology, unpublished data, author, *pers. obs*.). Although feasible, whether female mulloway return every night to the same location in the Swan River to spawn is unknown.

Mulloway possess large otoliths, bilateral sonic muscles surrounding a large swimbladder (as observed by specimens captured in shallow waters) and have been reported as exhibiting vocal behaviour around the time of spawning (Griffiths and Heemstra, 1995, Ueng *et al.*, 1998, 1999, 2007, Parsons *et al.*, 2006, Farmer, 2008). Although group spawning has been reported in captivity (Ueng *et al*, 2007), individual mulloway in the Swan River are thought to spawn in comparatively small numbers (Farmer, 2008). Vocalisations audible above water are also frequently reported (anecdotal reports by fishers, author, *pers. obs*.). At other locations, around the world, sound production has been reported at times of spawning by aggregations of mulloway (Ueng *et al.*, 1998, 1999, 2007).

3.1.5.2 West Australian dhufish (<u>Glaucosoma hebraicum</u>, Glaucosomatidae)

Endemic to coastal waters of south-western Australia, the WA dhufish is a slow growing, sedentary, demersal species inhabiting reefs and caves to depths of 200 m (Kailola, 1993, McKay, 1997, St John and Syers, 2005, Mackie *et al.*, 2009). This species can live for over 40 years, with the maximum reported WA dhufish being 1.22 m long and weighing approximately 26 kg (Hutchins and Swainston, 1986; Hesp *et al*., 2002).

Although 100 m across by 10 m deep “ghost patches” of thousands of WA dhufish have been historically reported in the Capes region of Western Australia, the species is now typically found in groups of three and to a lesser extent, up to ten (Mackie *et al.*, 2009). Occasionally groups numbering in the tens of WA dhufish have been observed along the West Coast Bio-region (A. Grochowski; G. Shedrawi, University of Western Australia, *pers. comm*.). WA dhufish exhibits low levels of migration (up to tens of kilometres onshore-offshore), possibly for spawning, and the species is known to vary spawning locations from year to year (Mackie *et al.*, 2009). Histological examination of ovaries showed the species is capable of spawning over several days (Mackie *et al.*, 2009), an observation of possible behaviour which is problematic to confirm in the wild.

Lack of variation in seasonal reproductive timing across the West Coast Bioregion suggests that factors other than environmental variables, such as social cues, influence spawning (Mackie *et al.*, 2009). Male co-habituation of an area, indicative of lekking behaviour, has been observed and the positive relationship between size and spawning frequency corroborates a social structure whereby the largest males spawn with the largest female and presumably fertilise the greatest number of eggs in a single event (Höglund and Alatalo, 1995, Mackie *et al.*, 2009). The influence of social cues is an important trait when considering the possibility of passive acoustic monitoring because it suggests a higher order of communication between individuals.

Prior to this study vocalisation in Glaucosomatidae had not been reported, however, WA dhufish possesses bilateral intrinsic muscles connecting skull and swimbladder (Chiu, 2006, Vu, 2007, Parsons, 2010). Biochemical assessment of Citrate synthase (CS) and L-lactate dehydrogenase (LDH) activity (enzymes associated with energy supply for muscle contraction) in WA dhufish swimbladder muscles suggested their involvement in sound production (Chiu, 2006). These muscles are present in both juvenile and adult WA dhufish. Furthermore, swimbladder vibrations and noise have been heard by scientists when tagging WA dhufish (M. Mackie, DoFWA, *pers. comm*.).

3.1.5.3 Snapper (Pagrus auratus, Sparidae)

Snapper are typically found from shallow coastal lagoons and embayments to depths greater than 200 m on the continental slope, forming dense spawning aggregations in shallow bays such as Cockburn Sound (Moran *et al.*, 1998, Wakefield, 2010; Wakefield *et al*, 2011). The maximum reported length and weight for the species are 130 cm and 20 kg, respectively (Hayes, 1994, Randall *et al*., 1990). In the Perth region, snapper spawn between October and December while in more northern regions spawning occurs during winter (e.g. peaking in June in Shark Bay's eastern Gulf and September in the Western Gulf). Spawning peaks have been observed at new and, to a lesser extent, full moons when tidal ranges are at their greatest (Wakefield, 2010). Within Cockburn Sound, the egg concentrations have shown that an aggregation forms firstly in the northeast area of the sound, moving to the middle and ending in the northwest across the spawning season (Wakefield, 2010), suggesting that the aggregations respond to changing flow dynamics. During spawning, the fish themselves are particularly mobile and form aggregations in shallow waters where they exhibit avoidance behaviour in the presence of vessels (Mackie *et al.*, 2009). Egg release is thought to related to tide, but also occurs predominantly at dusk, and therefore times of low light levels when visual cues at long range are ineffective (Wakefield, 2010).

Although sound production is unreported in snapper some members of the Sparidae family are soniferous (Tavolga, 1974, Cruz and Lombarte, 2004). Paxton (2000) hypothesised that members of the Sparidae family with a relatively large sagitta, such as snapper, ought to be soniferous, similar to other species of the family. Overall the relative sagittal otolith size of Sparidae is between Labridae (few vocal species) and Sciaenidae (a family recognised as ‘drummers’ or ‘croakers’), with the smaller members displaying distinct male/female colour contrasts and no vocal ability (Cruz and Lombarte, 2004).

3.1.5.4 Black Bream (Acanthopagrus butcheri, Sparidae)

As a true estuarine species in Western Australia, black bream almost never leaves the estuary unless flushed into the ocean in extreme flooding (Lenanton, 1977). The species can reportedly reach up to 54 cm total length and 3.6 kg (Steward and Grieve, 1993). Although the types of preferred habitat may vary (Norriss *et al.*, 2002), during spawning the species will often congregate in deep holes, possibly due to advantageous salinity and high dissolved oxygen conditions (Newton, 1996, Sherwood and Blackhouse, 1982, Norriss *et al.*, 2002). In the past, aggregations have been found and targeted in deep holes by fishermen (Norriss, 2002). In southwest Australia, spawning typically occurs between October and January, peaking in November/December (Sarre and Potter, 1999, Lenanton, 1977). Together with aggregations forming in low visibility conditions, the lack of species sexual dimorphism suggests that communication other than visual cues may play a part in spawning.

4.0 NEED

Management of fisheries is a difficult task. This is often because the tools available to study and monitor exploited species and their environment typically have biases and data collected are often limited spatially and/or temporally. Although long-term monitoring may have been conducted over multiple years, it often comprises a number of short surveys i.e. a collection of snapshots-in-time, the number of which are based on the availability of funding and resources. It is therefore not surprising that many fish resources are under threat and why, for instance, it is wise for fisheries assessments to consider multiple data sources (Hilborn and Branch, 2013). The recent 'weight of evidence' approach, used as the basis of an assessment of demersal scalefish in Western Australian waters, is a good example of this (Wise *et al.*, 2007). To complete a species-specific study, novel techniques of observation may be beneficial to elucidate aspects of its biological and/or behavioural characteristics which may not be achieved via more traditional approaches.

Many fish species produce sound, mostly during spawning events. These sounds can be monitored using autonomous underwater sea-noise recorders sampling at regular intervals (typically every 15 min) over extended periods (e.g. up to 1 yr). Once a number of factors pertaining to vocalising habits and local sound transmission are determined, the vocalisations produced by a spawning aggregation can provide information on the relative abundance of the spawning population.

5.0 OBJECTIVES

Three objectives were set at the beginning of this project to develop passive acoustics as a complementary technique to current monitoring methods. These were:

1. Acquire long-term mulloway vocalisation records and evaluate aggregation boundaries, timings, relative abundance and their driving factors.
2. Investigate dhufish/snapper/black bream vocal behaviour and evaluate applicability of acoustic monitoring.
3. Review of passive acoustics as a legitimate tool in fisheries monitoring.

These have remained consistent throughout the duration of the project. An additional objective developed through the analysis of data collected here and through affiliated studies was;

4. Characterisation of fish calls and choruses from unknown sources along the Western Australian coastline.

Sections 7.1, 7.2, 7.3, 7.4 and 7.5, address Objectives 1, 2 and 4, while Section 7.7 addresses Objective 3.

6.0 METHODS

6.1 Possible sound production mechanisms and likely acoustic characteristics

6.1.1 Anatomical investigation

Dissections of donated individuals were conducted either in the field or at the Environmental Biology Department of Curtin University. In each dissection the following characteristics were examined:

- swimbladder size, shape and material - to help estimate the likely volume at depth and possibly damping of vibration by the swimbladder walls. Swimbladder volume was estimated by filling the swimbladder with a known volume of water;
- relationship between swimbladder and body-cavity volume - to help understand how the swimbladder may vibrate and produce sound;
- estimated musculature composition – to determine whether the species has developed specialised muscle structure to vibrate the swimbladder and /or estimate the contractile properties are of any muscles that could feasibly move the swimbladder (for example many species of Sciaenidae have developed varying forms of 'sonic', or super-fast twitch muscles which can be used to vibrate their swimbladders; Griffiths and Heemstra, 1985, Rome, 2005);
- jaws/pharyngeal teeth - to identify whether grinding teeth or snapping jaws may be used to produce sound by the species similar to members of the Sparid and Pomacentrid families respectively (Paxton, 2000, Colleye and Parmentier, 2012) and;
- otolith size relative to overall body size – as Paxton (2000) speculated that the size of the otoliths relative to the overall body size of a species has a relationship with the species' likelihood of being soniferous, the identification of otoliths size could aid in determining whether the target species are vocal.

Theses features aid the identification of a likely mechanism of sound production and acoustic characteristics of any sounds produced.

Where possible males with stage IV (mature) or V (spawning) gonads were examined to ensure sonic muscle mass had been developed. Spawning stage was identified either by a member of DoFWA or CARL. Wild samples were examined to ensure lack of muscle mass was not a result of habituation to captivity. Previous dissections related to the project are also presented as an insight into the possible sound production mechanism.

6.1.2 Theoretical modelling

The chief mechanism used by fishes in sound production associated with spawning behaviour is via vibration of the swimbladder. Classically, the production of sound via a swimbladder has been treated as a resonating gas bubble where acoustic features, such as spectral peak frequency (often called the 'dominant' or 'peak' frequency) are dictated by swimbladder volume, wall stiffness, applied damping and pressure differential between internal swimbladder gas and that of the water surrounding it (Hall, 1981). Individual twitches of the swimbladder produce single sound pulses

(Connaughton *et al.*, 2000). However, for prolonged calls produced by quick, consecutive muscle contractions, the spectral composition differs in that calls contain not only a peak frequency, but also several local spectral frequency peaks of uniform spacing, related to the time between consecutive sonic muscle contractions. Known as the carrier or modulation frequency (and also 'fundamental' or 'pulse repetition' frequency), the spectral peak spacing is dependent on the repetition rate of swimbladder pulses (Watkins, 1967, Nilsson, 2004).

Preliminary models of likely species call characteristics of dhufish, snapper and black bream used two approximations of oscillating bodies; a simple gas filled sphere and a prolate spheroid (Kinsler *et al.*, 2000, Vu, 2007). The resonant frequency f_0 and f_p of the sphere and spheroid bodies respectively are given by:

$$f_0 \approx \frac{1}{2\pi a}\sqrt{\frac{3\gamma p_B}{\rho_w}} \qquad (1)$$

where a is the radius of the sphere, γ is the specific heat ratio, p_B is the pressure within the sphere and ρ_w is the density of water (1026 kgm^{-3}) and;

$$f_p = \sqrt{\frac{3m\gamma P}{\left(\frac{4\pi^2 a^2 \rho_f}{\varphi_s} - 4(m-1)d\right)}} \qquad (2)$$

where P is the pressure, ρ_f is the density of fish tissue (≈1079 kgm^3), a is the radius of a sphere which would have the equivalent volume of the swimbladder, φ is a factor relating to the eccentricity of the swimbladder, m is ratio of swimbladder and fish tissue represented as two spheres, d is a factor relating the two spheres (9.7 x 10^{-4} kgm^{-1}).

Results from the anatomical examination provided broad muscle type and physical dimensions from which contraction rates and therefore the rate of change in swimbladder volume and the pulse repetition frequency could be estimated (Vu, 2007, Parsons, 2010). The pulse repetition rate, muscle contraction rate and swimbladder resonant frequency were then applied in an adapted Matlab program 'SynthCall' (written at the CMST), to predict the acoustic characteristics of a call from the species. Predicted calls were modelled in the form of;

$$e^{\frac{t}{d}} \times \sin(2\pi f_0 t) \qquad (3)$$

where d is the decay constant and t is the time vector. Rate of change in swimbladder volume, system damping characteristics and elasticity of the swimbladder wall all impact the characteristics of individual swimbladder pulses (Feuillade and Nero, 1998). Without *a priori* knowledge of the mechanism it is improbable to model the actual call characteristics precisely. However, these models give a good estimate of what sound can be produced by a species if their swimbladder is vibrated as a mechanism of sound production.

6.2 Passive acoustic data acquisition

A number of configurations were employed conduct underwater recordings (Figure 1). HTI-90U and/or -96min omni-directional hydrophones (Hi-Tech Industries Inc., MS, USA; specifications found in Table 1) located either in mid-water (HTI-90U or -96min) or on the riverbed/seafloor (HTI-90U only) were attached to either a CMST sea-noise logger, Sony DAT recorder or HR5-Jammin Pro recorder.

Mid-water recordings were conducted from moored or drifting vessels with hydrophones lowered to 4, 5 or 10 m depth with an attached fishing 'sinker' to ensure negative buoyancy.
Riverbed, "bottomed" recordings were acquired by attaching hydrophones to sea-noise loggers developed by the CMST and Defence Science and Technology Organisation (DSTO) in steel housings. During short-term deployments (single evening) housings were connected to a surface buoy and retrieved by pulling up all equipment (Figure 1c). Over long-term deployments (up to 6 months), additional dump weights where added to the housing (Figure 1d). A 5 m chain, followed by a 30 m rope connected the housing to a secondary dump weight. In some cases (generally waters deeper than 15 m, or of complex topography, such as kelp, seagrass or sponge gardens) a Sonardyne 7986 Lightweight Release Transponder with release canister and small sub-surface buoy were attached to the dump weight. Equipment retrieval was conducted by acoustic message sent to the transponder which released the sub-surface buoy and attached rope to the surface, from which all equipment was retrieved. Unfortunately, on occasion heavy fouling caused the release to fail and equipment was recovered by grappling or diving.

Specifications of hydrophones, noise loggers and digital recorders can be found in Table 1. Calibration coefficients were calculated from:

$$C = |hyds| - gain \tag{4}$$

where *hyds* = hydrophone sensitivity (dB re V/µPa) and *gain* = total system recording gain in dB (McCauley, 2001). As V and Pa are root mean squared values the sensitivity is actually dB re 1 $V^2/\mu Pa^2$. Once the system response was added to correctly scaled FFT values the spectral level was given in dB re 1 $\mu Pa^2/Hz$ (McCauley, 2001).

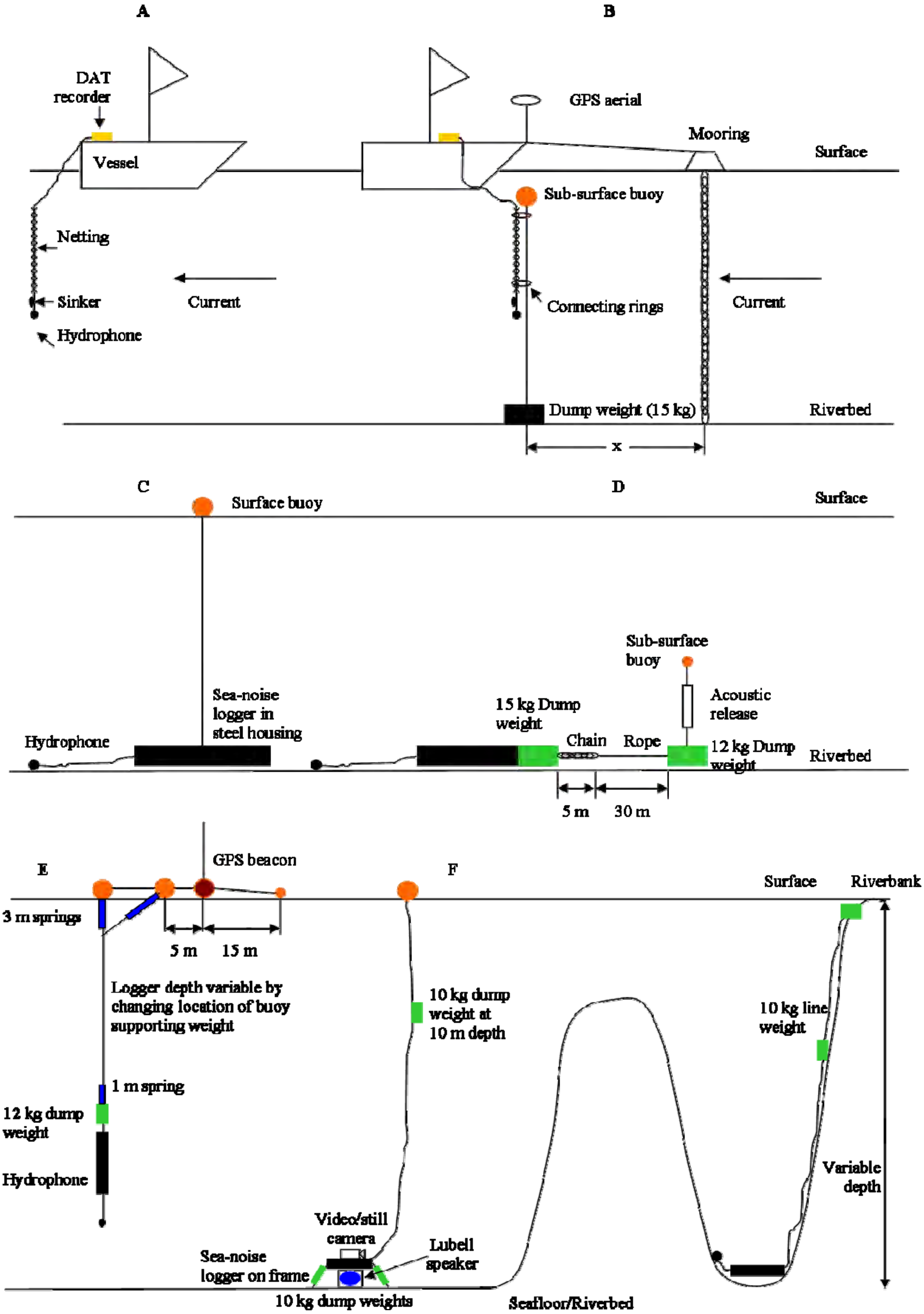

Figure 1. *Hydrophone deployment configurations from drifting vessel (A), moored vessel (B), short-term bottomed sea-noise logger (C), long-term bottomed sea-noise logger (D), drifting mid-water (E), frame attached with speaker and camera (F) and positioned on the riverbed in a hole near the riverbank (G).*

Table 1. Specifications and calibration coefficients for various combinations of hydrophones, noise loggers and Sony DAT recorders.

Item	Model/parts	Characteristics
Hydrophones	HTI-90U (3)	Cable length 10 m; sensitivity -197.7, -198.1, -198.1, dB re 1 V/µPa respectively; hydrophone capacitance 14.09, 14.31, 14.10 nF
	HTI-96min (2)	Cable length 10 m; sensitivity -164.1 dB re 1 V/µPa; pre- amplifier required
	GEC Marconi S11101X (1)	Cable length 45 m; sensitivity -203.5 dB re 1 V/µPa; hydrophone capacitance 9.4 nF
DAT Recorders	Sony D100 (2)	Digital Audio Tape deck, 16-bit; frequency response quoted as 20-14,500 Hz (± 1.0 dB) at Fs 32 kHz; dynamic range quoted as >87 dB
	Sony D8 (1)	Digital Audio Tape deck, 16-bit; frequency response quoted as 20-14,500 Hz (± 1.0 dB) at Fs 32 kHz; dynamic range quoted as >87 dB
Portable digital recorder	HR5-Jammin Pro	Digital recorder to SD cards, 24-bit; frequency response quoted as 20-46,000 Hz (± 3.0 dB) at Fs 96 kHz; dynamic range quoted as >87 dB
Sea-noise loggers	Sir Gawain, Sir Tristan, Sir Galahad, SNR20, SNR29	Hydrophone pre-amplifier, 20 dB gain with 0-20 dB pre filter gain, giving maximum 40 dB gain, 16-bit; low frequency cut-off 8 Hz, high frequency cut-off ranging 1-15 kHz, survey dependent
Pre-amplifiers	CMST design	20 or 40 dB gain; 4 Hz ->20 kHz; impedance 1 MΩ
Noise generator	White noise	-70, -90, -110 dB re 1 V^2/Hz output

6.2.1 Sea noise loggers

The CMST acoustic Sea-Noise Recorders are autonomous recording units designed for medium to long-term deployment. During the term of this study the sea noise loggers were deployed in 30 kg stainless steel housing units of 114 mm outer diameter and 900 mm length powered by two 9 V battery packs (one to power the hydrophones pre amplifier and one to power the recorder). The loggers were configured to interface with one hydrophone (though two are possible) via a Subconn LBH3F connector. An integral hydrophone pre-amplifier (20 dB gain with user selectable lower frequency cut-off filter at 8 Hz or 160 Hz) and an integral anti-aliasing filter (0-20 dB pre filter gain with a 6th order Butterworth filter and high-frequency cut off from 1 kHz to 15 kHz) provide a maximum 40 dB gain. The system employs 16 bit Analogue to Digital Conversion with RMS noise of A/D at 3 quantisation levels (total recorded noise level depends on hydrophone capacitance, amplifier gain, cut-off frequency). Data was stored on one 2.5" hard disk drive using FAT32 format and standard IEEE file structure, buffered by a Type 1 Compact Flash Card. Recording intervals were set to bear in mind the time taken between recordings to download files from the flash card to hard disk drives. A RS232 interface allowed user configuration of sampling rate (up to 26 kHz), bandwidth, gain, sampling durations, record intervals) with support for multiple user configured sampling schedules. At maximum sampling rate the system draws 75 mA, in comparison with sleeping and dozing rates of 20 uA and 8 mA respectively.

6.2.2 Study sites

Primary locations for acoustic recording sites were selected based on interviews with commercial and recreational fishers, results from previous CMST research and local knowledge from the DoFWA. Study sites were prioritised based on the likelihood of aggregation presence, accessibility, budget and characteristics of acoustic propagation. Approximate locations of study sites for all target species are shown in Figure 2 and Figure 3.

6.2.2.1 Mulloway

Previous research projects have focussed on the mulloway found in Mosman Bay, Swan River (Figure 2), showing movements of fish and relative sound production over three years. This project has enabled the analysis of data from three subsequent spawning seasons. Within the Swan River this has been expanded to include recordings taken at Fremantle Port, Blackwall Reach and around the Swan and Canning Rivers (Figure 2, black and orange dots).

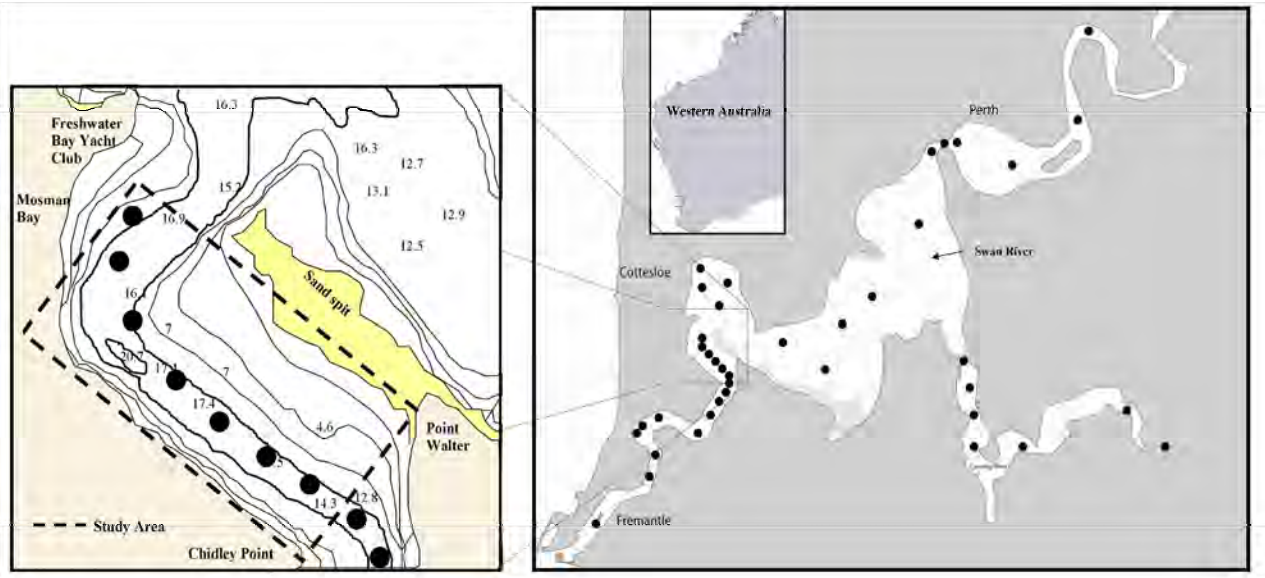

Figure 2. Map of Western Australia, Swan River and Mosman Bay (inset) highlighting the primary passive acoustic study area of mulloway surveys (dashed box). Depths at various locations are shown in metres. Black dots around the Swan River illustrate locations spot recordings targeting mulloway vocalisations. Orange dot represents location of acoustic dataset from an associated project.

6.2.2.2 West Australian dhufish

Interviews with various recreational and commercial fishers and DoFWA scientists, allowed the selection of sampling sites along the west Australian coast (Figure 3). Within Geographe Bay and metropolitan waters these locations comprise small reef 'lumps', often surrounded by patches of seagrass, where fishers have captured small numbers of dhufish over several years. By contrast, reports from the Canal Rocks area off Cowaramup (sampling sites near Cape Naturaliste, bottom left locations in Figure 3) suggest significantly larger numbers of spawning dhufish (Mackie *et al.*, 2009, Anon, 2010, 2011, Berry *et al*., 2012). Sites at the Abrolhos Islands were recommended by members of the DoFWA and the Centre for Marine Futures (UWA) as locations where schools/aggregations of tens of dhufish have been observed on multiple occasions during previous research projects. Consultation with recreational fishers, members of the CARL and DoFWA have led to targeting waters off Perth. The targeted sites vary in depth between 12 and 45 m, often comprising seagrass habitat with associated reef, and in some cases large overhanging reefs. Additional datasets have been analysed from recordings taken approximately 500 m from the HMAS Swan wreck off Dunsborough (Figure 3, orange dot), in 27 m of water, as well as waters near Garden Island and off Myalup.

6.2.2.3 Snapper

Study sites of snapper were recommended by researchers at the DoFWA. Aggregations have been targeted concurrently with sampling conducted by the DoFWA. In Shark Bay recordings have been acquired at 'The Patch' in the Eastern Gulf and at various locations in the Western Gulf. The Patch comprises approximately one square kilometre of comparatively flat sand substrate in around 8 m of water. The Patch has been shown to be one of the main spawning aggregation sites in the Eastern Gulf (Jackson, 2007). The area is in open water and subject to prevailing winds and tidal patterns. Various sites in the Western Gulf were recommended by charter fishers and the DoFWA researchers. Mid-water recordings (Figure 1a) were taken at several sites in depths varying between 6 and 15 m during the capture of 17 mature snapper by recreational fishers.

Two sites in Cockburn Sound were targeted; each located approximately 50-100 m west of a wreck and sandbars. The snapper aggregate here over sand substrate with little vegetation and are mobile around the site. Water depths vary from 5-15 m. Mid-water recordings were acquired in October and November, 2010 from the DoFWA *RV Gannet,* during sampling conducted for a DoFWA monitoring project. Underwater noise loggers were also deployed during this period at both sites.

6.2.2.4 Black bream

Aggregations of black bream reportedly form in deep holes in the Frankland and Blackwood Rivers (Norriss *et al*., 2002). Recordings have been acquired from two holes (7 and 11 m deep) in the Frankland River, where silt substrate riverbed descends rapidly from around 3-4 m to the bottom of the hole. Each hole comprises a rocky bottom with little silt substrate and a layer of debris which has been presumably taken from upstream and deposited in the hole by the current. The holes measured between 10 and 15 m in diameter, and therefore typical CMST mooring configurations were adapted for deployment. The loggers were positioned in the middle of each hole from which a weighted line ran along the riverbed out to the riverbank, where the line was moored underwater with a 50 kg dump weight (Figure 1g).

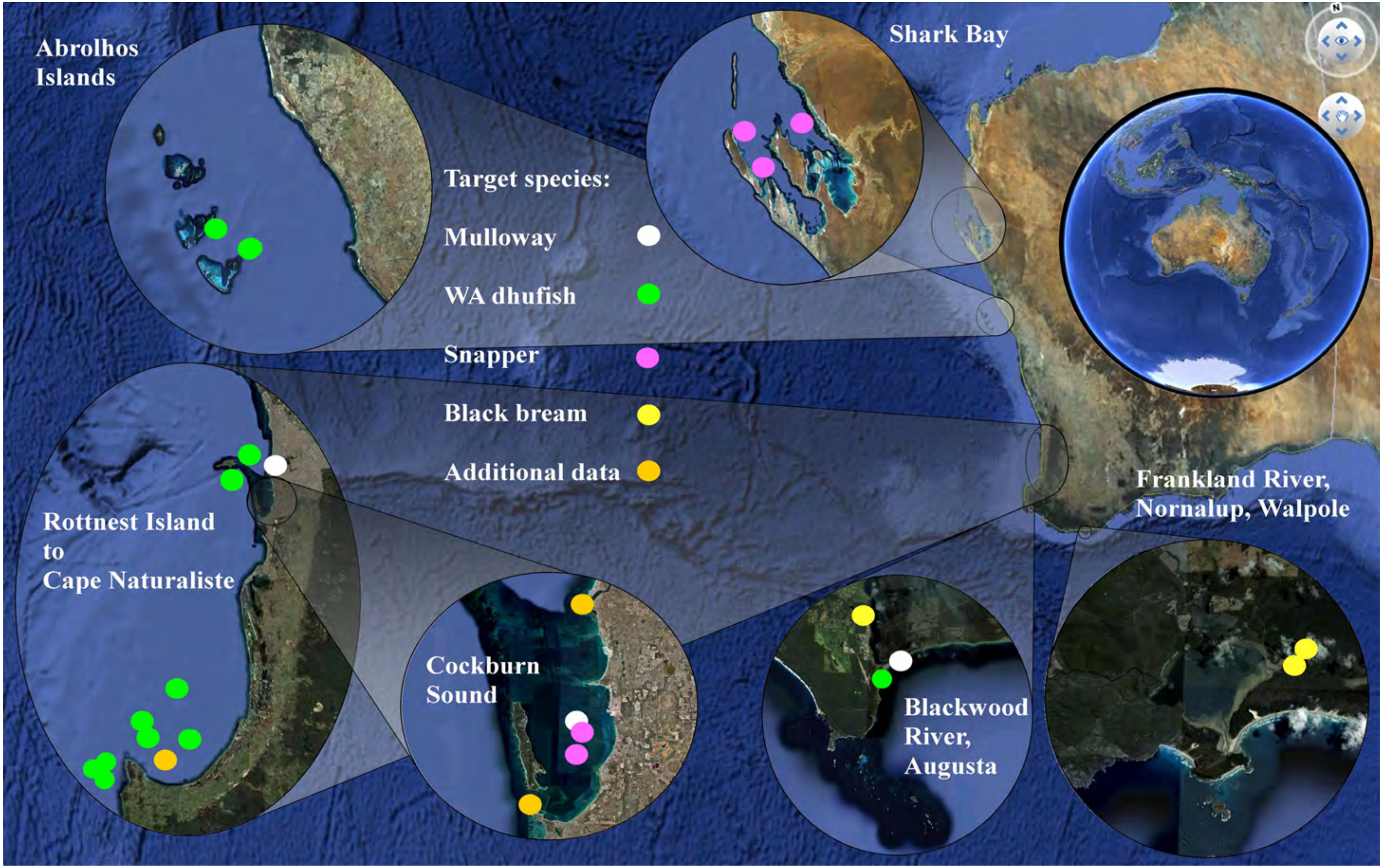

Figure 3. Map of study sites across Western Australia. Coloured circles represent approximate locations of recordings targeting mulloway, dhufish, snapper and black bream (white, green, pink and yellow dots, respectively). Maps provided by Google Earth.

6.2.2.5 Deployments

Details of acquired acoustic recordings can be found in Table 2, Table 3 and Table 4. The sampling schedules used in recordings varied according to duration and sampling rates (Table 3). To date, only one deployment has failed to acquire data (Table 3), due to the failure of a connector. Numerous datasets collected by the CMST during alternate projects have been made available for analysis in this study (Table 4).

Table 2. Sampling settings and schedules used

Schedule number	Sample rate	Low-frequency roll-off	Anti-aliasing filter	Total gain	Sampling schedule
1	8 kHz	8 Hz	2.8 kHz	40 dB	780 s every 900 s
2	8 kHz	8 Hz	2.8 kHz	40 dB	380 s every 900 s
3	20 kHz	8 Hz	10 kHz	40 dB	120 s every 900 s
4	32 kHz	--	--	30 dB	Periodic DAT recordings

Table 3. Times, locations, settings and sampling schedules of acquired datasets.

Location	GPS	Target species	Deployment Date	Retrieval Date	Collaborator support	Schedule number	No. datasets	Data collected?
Shark Bay	25°42.667'S 113°49.489'E	Snapper	11/07/10	14/07/10	DEC, DoF, SBERP	1	1	Y
Shark Bay Western Gulf	Numerous	Snapper	13/07/10	13/07/10	DoF	4	7	Y
Cockburn Sound †	32° 11.694'S 115° 44.478'E	Snapper	8/10/10	16/10/10	DoF	1+4	1	Y
Cockburn Sound †	32° 10.062'S 115° 44.120'E	Snapper	8/10/10	16/10/10	DoF	1+4	1	Y
Cockburn Sound	Two above sites	Snapper	8/10/10	8/10/10	DoF	4	4	Y
Frankland River	34° 59.180'S 116° 49.164'E	Black bream	20/10/10	26/10/10	DEC	1	1	Y
Frankland River	34° 58.848'S 116° 49.369'E	Black bream	20/10/10	26/10/10	DEC	1	1	Y
Swan River	32° 00.460'S 115° 46.470'E	Mulloway	22/10/10	6/2/11	--	2+3	2	Y
Cockburn Sound (D9)	32° 11.694'S 115° 44.478'E	Snapper	9/11/10	17/11/10	DoF	1	1	Y
Geographe Bay	33°27.456'S 115° 6.909'E	Dhufish	13/12/10	17/01/11	Sea Rescue	1	1	N*
Geographe Bay	33° 30.176'S 115° 20.101'E	Dhufish	13/12/10	26/01/11	Sea Rescue	1	1	Y
Mosman Bay, Swan	Numerous	Mulloway	31/01/11	--	--	4	14	Y
Horseshoe Reef,	33° 39.954'S 114° 50.612'E	Dhufish	08/02/11	11/02/11	DoF	1	1	Y

Cowaramup								
Swan River	32° 00.460'S 115° 46.470'E	Mulloway	6/2/11	14/4/11	--	2+3	1	Y
Swan River	32° 00.460'S 115° 46.470'E	Mulloway	6/2/11	14/4/11	--	2+3	1	Y
Swan River	32° 00.460'S 115° 46.470'E	Mulloway	6/2/11	14/4/11	--	4	1	Y
Swan River	Numerous	Mulloway	16/2/11	16/2/11	--	4	16	Y
Rat Island, Abrolhos	28° 46.460'S 113° 48.430'E	Dhufish	21/2/11	26/2/11	DoF	1	1	Y
CARL	Curtin University	Dhufish	Various	Various	CARL	4	6	Y
Swan River	32° 00.460'S 115° 46.470'E	Mulloway	3/10/11	01/08/12	---	1	1	Y
Augusta	Numerous	Dhufish	22/11/11	23/11/11	DoF	1	1	Y
Cape Naturaliste	Numerous	Dhufish	21/12/11	16/02/12	DoF/Sea Rescue	1	2	Y
CARL	Curtin University	Dhufish, black bream	numerous	numerous	CARL	1	1	Y
Swan River	32° 00.460'S 115° 46.470'E	Mulloway	18/04/12	18/04/12	---	2†	3	Y
Rottnest Island	31°59'4"S 115°33'2"E	Dhufish	13/11/11	13/11/11	DoF	1	1	Y
Augusta	Numerous	Dhufish	22/11/11	23/11/11	DoF	1	1	Y
Rottnest Island	31°59.083'S 115°33.035'E	Dhufish	30/11/11	30/11/11	DoF/CARL	1	1	Y
Frankland River	Numerous	Black bream	28/11/11	--	DEC	1	2	Y
Swan River	32° 00.460'S 115° 46.470'E	Mulloway	1/12/12	TBC	---	1	1	Y
Augusta	Numerous	Dhufish	4/12/12	15/01/13	CARL	2	1	Y
Cape Naturaliste	Numerous	Dhufish	21/12/12	07/02/13	Sea Rescue	1	3	Y
Total number of datasets (excluding schedule 4 portable recordings)							33	

† Mid-water vessel based recordings were also taken at this site during the deployment of the long-term logger

* Due to a connector failure this deployment only recorded the electrical noise of the logger

Table 4. Details of additional acoustic datasets from affiliated research projects.

Location	GPS	Data expected on target species	Deployment Date	Retrieval Date	Collaborator support	Schedule number
Mosman Bay, Swan	32° 00.460'S 115° 46.470'E	Mulloway	07/12/05	13/03/06	--	1
Mosman Bay, Swan	32° 00.460'S 115° 46.470'E	Mulloway	12/10/06	21/05/07	--	1
Mosman Bay, Swan	32° 00.460'S 115° 46.470'E	Mulloway	19/10/07	14/03/08	--	1
Mosman Bay, Swan	32° 00.460'S 115° 46.470'E	Mulloway	08/11/08	04/04/09	--	1
Mosman Bay, Swan	32° 00.460'S 115° 46.470'E	Mulloway	29/10/09	21/02/10	--	1
Mosman Bay, Swan	32° 00.460'S 115° 46.470'E	Mulloway	10/03/10	23/04/10	--	3
Blackwall Reach, Swan	32° 01.105'S 115° 47.047'E	Mulloway	10/03/10	23/04/10	--	3

Fremantle Port	32° 11.694'S 115° 44.478'E	Mulloway	29/03/10	25/06/10	--	1+4
Geographe Bay	32° 10.062'S 115° 44.120'E	Dhufish	23/11/09	26/07/10	Sea Rescue	1
Geographe Bay	32° 10.062'S 115° 44.120'E	Dhufish	07/11/10	13/12/10	Sea Rescue	1
Garden Island	------	Mulloway	31/04/11	12/05/11	Carnegie	1

6.2.3 Processing

System frequency response in each case was confirmed with a white noise source set at either -70 or -90 dB re 1 V^2/Hz (Table 1). Digital files acquired with sea noise loggers were read into Matlab® using programs written by the CMST. Acoustic data from Digital Audio Tape (DAT) recorders were transferred from tapes to digital files by means of a 486 PC based FFT signal analysis package with a DP430 signal processing card (Data Physics Corporation) at one or more sample frequencies (rates) from 2,604 (38.4 ms), 5,208 (19.2 ms), 10,416 (9.6 ms) and 20,833 Hz (4.8 ms). The waveforms were stored on hard disk drive at the CMST, Curtin University. HR-5 Jammin pro recorded data, in the form of wav files, were saved directly to hard drives.

Data were processed using Matlab® programs developed by the CMST, and passed through high (20 Hz) and low (2000 Hz) pass filters to limit noise effects, such as hydrophone movement and shrimp clicks. Analyses of data were then conducted from spectrograms (produced with a 0.7 FFT overlap and typically a 1024 point ‘Hanning’ window) and waveform plots, each produced in Matlab.

6.2.3.1 Analysis of call temporal characteristics

For analysis the start of each call (and each pulse) was taken as the first detected voltage amplitude peak in the waveform, referred to as the Call Initiation Peak (CIP). The end of a call was noted as the point at which the final pulse had decayed below background noise. The duration of the call was also taken as the time over which 90% of the energy from the call was detected on the recording system. A variety of call characteristics were recorded: call duration; pulse period; number of pulses in a call; modulation frequency and; call carrier frequency or spectral peak frequency (frequency peak of the power spectrum of an entire call). Time between calls possibly originating from the same source provided an estimate of call rates, and variations in amplitude between different calls were also noted. Specific functions used in call analysis are described below where pertinent.

6.2.3.2 Analysis of acoustic levels

Passive acoustic units are often reported in a variety of formats. To help compare results in this study with other past, present and future reports characteristics such as SLs are often shown in all formats (Southall *et al.*, 2007);

- Broadband SPLs (dB re 1 µPa);
- Spectral levels (the sound pressure over a specified bandwidth, dB re 1 µPa^2/Hz);
- Sound exposure levels (SEL, the integral of the pressure squared over the duration of the signal, dB re 1 µPa^2.s) and;
- Peak-peak pressure levels (the algebraic difference between the maximum positive and maximum negative instantaneous peak pressure, (dB re 1µPa)

Statistics here have been applied in the logarithmic scale (rather than in the linear domain) as this is the scale in which they are perceived. All SLs were estimated to the reference pressure at a range of 1 m from the source.

The sound pressure level (SPL) L_p is a logarithmic measure of the effective sound pressure of a sound relative to a reference value. It is measured in decibels (dB) above a standard reference level:

$$L_p = 10\log_{10}\left(\frac{p_{rms}^{\ 2}}{p_{ref}^{\ 2}}\right) = 20\log_{10}\left(\frac{p_{rms}}{p_{ref}}\right) \quad \text{dB} \qquad (5)$$

where p_{rms} is the root-mean-square pressure and p_{ref} is the reference pressure.

To accurately determine fish call SL it is necessary to first remove the background noise. For this purpose fish calls and background noise were considered as incoherent signals. By Parseval's Theorem, the time-averaged squared total pressure recorded by the logger was equal to the sum of the time-averaged squared partial pressure of each constituent signal (Sprague and Luczkovich, 2004). The level of fish call (C_f), once background noise was removed, is given as:

$$C_f = 10\log_{10}(10^{\frac{L_{s+n}}{10}} - 10^{\frac{L_n}{10}}) \qquad (6)$$

where L_{s+n} was the level in dB re 1 µPa of the overall signal and was the background noise level (McCauley, 2001).

The method of call energy level analysis in this study is based on theory protocols from McCauley (2001) and outlined in Parsons *et al*. (2012b). Figure 4 displays three of the steps involved in both analyzing the acoustic pressure attributable to a call and determining the frequency band over which the majority of call energy occurs. A digitized segment of the recording, including the call and encompassing a minimum of 500 sample points, containing energy from noise only, either side of the call, was converted to pressure wave form (Figure 4a). The cumulative energy is the total energy throughout the duration of the call and pressure levels within the 5% and 95% region of the total cumulative energy curve (Figure 4b) were calculated (Malme *et al.*, 1986) thus standardizing the averaging time to that at which 90% of the energy from the entire signal (less noise) had passed. The call length was therefore taken as the time for 90% of the signal energy to pass. A power spectral density of each call was produced to observe spectral peak frequencies compared with each calculated energy level (Figure 4c).

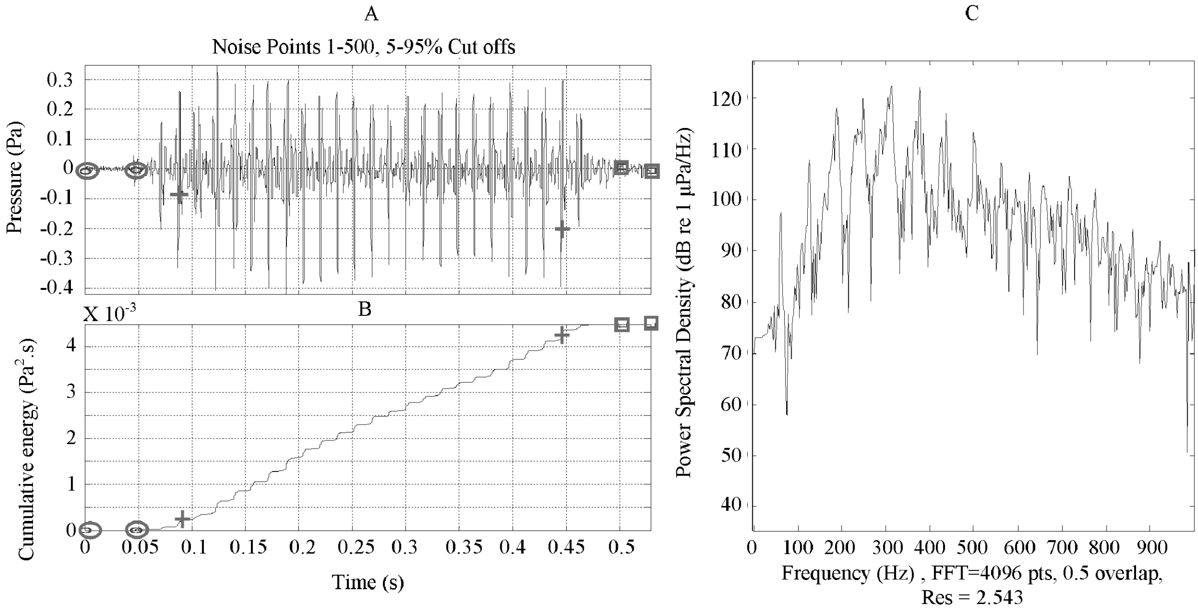

Figure 4. Example sound pressure level (dB re 1μPa) calculation of an mulloway Category 2 long call. a) Waveform of example call with noise removal zone 500 samples before (circles) and after (squares) shown. Crosshairs mark the points at which 5 and 95% of the total energy occurs within the analyzed region. b) Cumulative energy of the call showing pressure squared per second with 5 and 95% region markers shown. c) Power spectral density of call. (Coates, 1980, Image taken from Parsons et al., 2012b).

The received level (RL) can be related to the SL and simple transmission loss (TL) in the form of:

$$RL = A\log_{10} r + SL \qquad (7)$$

where *A* is the transmission loss constant and *r* is the slant range (the shortest range between two points of differing altitude; Urick, 1983) between the caller and the hydrophone. RL is then a linear function of $\log_{10}r$. In datasets where multiple calls at known ranges could be analysed linear regression of RL against $\log_{10}r$ (Walpole and Myers, 1985) provided estimates of the TL constant (*A*) and the SL. The 95% confidence intervals for the estimates of *A* and SL were calculated using the methods described by Walpole and Myers (1985), as were 95% confidence intervals for predictions of received levels from sources at any given range along the regression curve andare shown as the 95% confidence interval boundaries on the transmission loss plots in this report.

Geometrical spreading provides a minimum loss on which to base initial calculations (Sprague and Luczkovich, 2004). Surface reflections were observed in the reported data, however, in the context of SL calculation spherical spreading was considered as a minimum estimate for transmission losses for calls in 20 m depth water, at ranges of less than 100 m (Cato, 1980). The estimated transmission loss trends were compared to spherical ($20\log_{10}r$) and cylindrical ($10\log_{10}r$) spreading losses, where *r* is measured in metres (Urick, 1983), to help validate the regression models.

6.2.3.3 Modelling long-term trends in SPLs/Spectral levels with environmental drivers

Circadian rhythm of sound production by fish can be species characteristic and related to the local environment (Ueng *et al.*, 1998). However, in many species captivity has resulted in restricted vocal behaviour and consequently, disparities between observed calling trends in captivity and the wild (Midling et al., 2002).

Passive acoustic recordings were acquired from Mosman Bay in the Swan River, over eight spawning seasons with the loggers positioned in the middle of the river in approximately the same location each year (Table 5).

Analysis of spectral levels was carried out using CMST developed Matlab® algorithms. Marine fauna respond on a daily basis to the sun elevation thus analysis has zeroed the daily clock time base to the time of sunset (upper limb hitting the horizon). The time of local sunset was retrieved from the Geoscience Australia website for each day and used as the zero hour point. Thus time each day is often given as hours prior (-ve) or post (+ve) local sunset. The 250 Hz one-third octave band spans the frequency range of most energy in mulloway calls and measured choruses (Section 7.2) and so has been used as indicative of their vocalisation behaviour or calling intensity in spectral level units (dB re $1\mu Pa^2/Hz$).

Recording samples which were significantly affected by vessel noise were removed. During daily vocalisation, the spectral levels of each five-minute sample were calculated and if the preceding and succeeding samples displayed a greater than 3 dB re 1 μPa drop (Figure 5, right hand evening spectral levels), the sample was tested for vessel noise. Spectral analysis and visual scrutiny of the individual sample confirmed or rejected the presence of vessel noise. Figure 5 shows how spectral levels within the 250 Hz centred, one-third octave varied throughout the day, and which portions can be attributed to vessel noise or fish calls.

Table 5. Mosman Bay hydrophone specifications and deployments

Season	No. of samples/days	Start Date	End Date	Sample rate (Hz)	Sample schedule
2004-5	3608 / 25	11/01/2005	5/02/2005	6 kHz	300 s every 10 mins
2005-6	9409 / 98	6/12/2005	14/03/2006	6 kHz	300 s every 10 mins
2006-7	21597 / 223	11/10/2006	22/05/2007	4 kHz	300 s every 15 mins
2007-8	14381 / 151	19/10/2007	13/03/2008	4 kHz	300 s every 15 mins
2008-9	14251/151	08/11/2008	04/04/2009	6 kHz	300 s every 15 mins
2009-10	82015/228	19/10/2009	05/06/2010	6 kHz	300 s every 15 mins
2010-11	59674/166	30/10/2010	14/04/2011	6 kHz	300 s every 15 mins
2011-12	20198/210	04/10/2011	10/05/2012	6 kHz	300 s every 15 mins

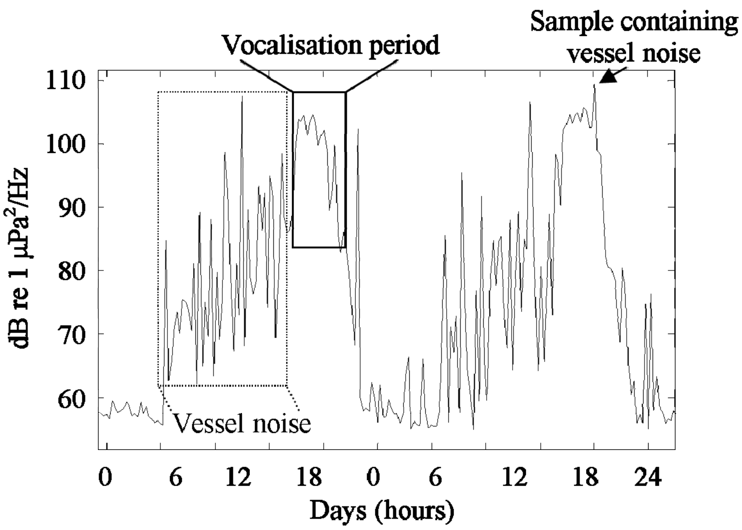

Figure 5. Five-minute averaged sample spectral levels of the 250 Hz, one-third octave for two days of the spawning period. Areas of vessel noise and fish vocalisation are shown.

Solar, lunar (Geoscience Australia), tidal (Department of Planning and Infrastructure - DPI), water temperature, salinity, and pH level (Swan River Trust) data were obtained for correlation against chorus levels and times. DPI tidal data were sampled every five minutes at the Barrack Street jetty, approximately 8.5 km upstream, and Swan River

Trust data originated weekly at approximately 9 am from a sampling station in Blackwall Reach, 600 m downstream from the hydrophone location.
The environmental data was modelled against three characteristics of sound production to determine spawning drivers or correlates. These sound production variables were: mean spectral levels of the 250 Hz centred one-third octave, taken between one hour prior and three hours post local sunset; the peak spectral levels during the chorus period; and the time of the peak sound production. The environmental variables tested were as follows: time of sunset; water temperature at 14 m depth; salinity at 14 m depth; maximum level of peak high tide; time of high tide; tidal range; lunar phase; pH levels; and the time difference between high tide and sunset.

Generalized Additive Models (GAMs) were produced in S-Plus and Matlab to model trends in sound production (the response variable) in relation to trends in environmental conditions (the descriptor or predictor variables). GAMs are a method of analysing data responses which may be non-normal distributed with non-linear smooths of the predictor variables (Embling, 2007).

Overfitting can often cause a variable to be incorrectly considered significant when modelling responses to autocorrelated variables (Lennon, 2000). A prime example is that in the river, as water temperatures increase through summer and lower rainfall brings little freshwater, salinity also increase. Therefore pair tests were conducted between descriptor variables and the least significant of the pair rejected if an R^2 value greater than 0.7 was observed. To minimise model overfitting the smooths for each variable were limited to five degrees of freedom and confidence in fit was conducted using five-fold cross validation (Hastie and Tibshirani, 1990, Chambers and Hastie, 1993).Variables were selected using Akaike's Information Criterion (AIC) method and backwards stepwise regression conducted to detect the model exhibiting the least variance. GAMs were produced for all seasons except the 2004-5 spawning season which was considered to contain too few samples to accurately model the data.

The correlation between sunset and temperature was higher than the 0.7 threshold in the 2004-5, 2006-7, 2009-10 and 2011-12 seasons (0.767, 0.769, 0.762 and 0.774 respectively), though lower in the remaining seasons. However, temperature and light levels have been shown separately to be significant in characteristics of sound production and spawning behaviour of some soniferous fishes (Ueng *et al.,* 1998, 1999, Connaughton *et al.*, 2000). Therefore both temperature and sunset time were included in the GAMs.

The sound production datasets in this study were of varying sample sizes. When comparing similar models of differing sample size, adjusted D^2 (also referred to as adjusted R^2) establishes the deviance in the response variables accounted for by the model. A model with no residual deviance has an adjusted D^2 of 1. As such, the adjusted D^2 was considered a statistically sound measure to compare different models with different sample sizes and was calculated as per Guisan and Zimmermann (2000).

It should be noted that the recording taken from the 2005-6 season requires a further calibration constant due to a recording system fault (i.e. water leaking down the wires changing the effective hydrophone capacitance). This fault was due to an insidious failure of the underwater connector. As a result, illustrated spectral levels of the season appeared lower than in reality. This fault was not expected to affect the recorded trends in sound production, as the problem was constant.

6.2.3.4 Estimating numbers of calling fish from sound pressure levels recorded by a single hydrophone

A number of factors need to be considered when estimating the number of callers in a mulloway aggregation. If calls do not overlap, call counting techniques can provide estimates of fish callers using determined consistent calling rates. This has currently been conducted up to a maximum of 15 individual callers over any individual minute. Parsons *et al.* (2010) illustrated the ability to range short mulloway calls with a single hydrophone using surface reflection techniques. However, with multiple over lapping calls, this is not possible as the surface reflection cannot always be identified.

During one evening's chorus Parsons (2010) identified up to approximately 300 calls per minute for mulloway Category 1 calls alone, and 150 for combinations of Category 1 and 2 calls using call counting techniques. Calls were discriminated based on call separation, amplitude and duration. Calling rates of approximately 2 and 4 seconds between calls were estimated respectively for Category 1 and 2 mulloway calls, equating to approximately 10 individual callers in both cases. Parsons (2010) illustrated that some calls can be individually characteristic and that call pressure amplitude is related to caller range. The comparison of spectral content and waveform amplitude was able to estimate up to a maximum 15 callers in an individual two minute segment (Figure 6). In this example nine callers were identified. During the early evening, when Category 2 long calls were prevalent, a maximum of 15 individual fish were determined to be calling during any 10 second interval. However, once the aggregation reaches a point when calls consistently overlap discrimination between callers becomes significantly more problematic. At times of chorus level calling, where calls overlap, it was speculated that more than 15 callers were present, though this could not be confirmed.

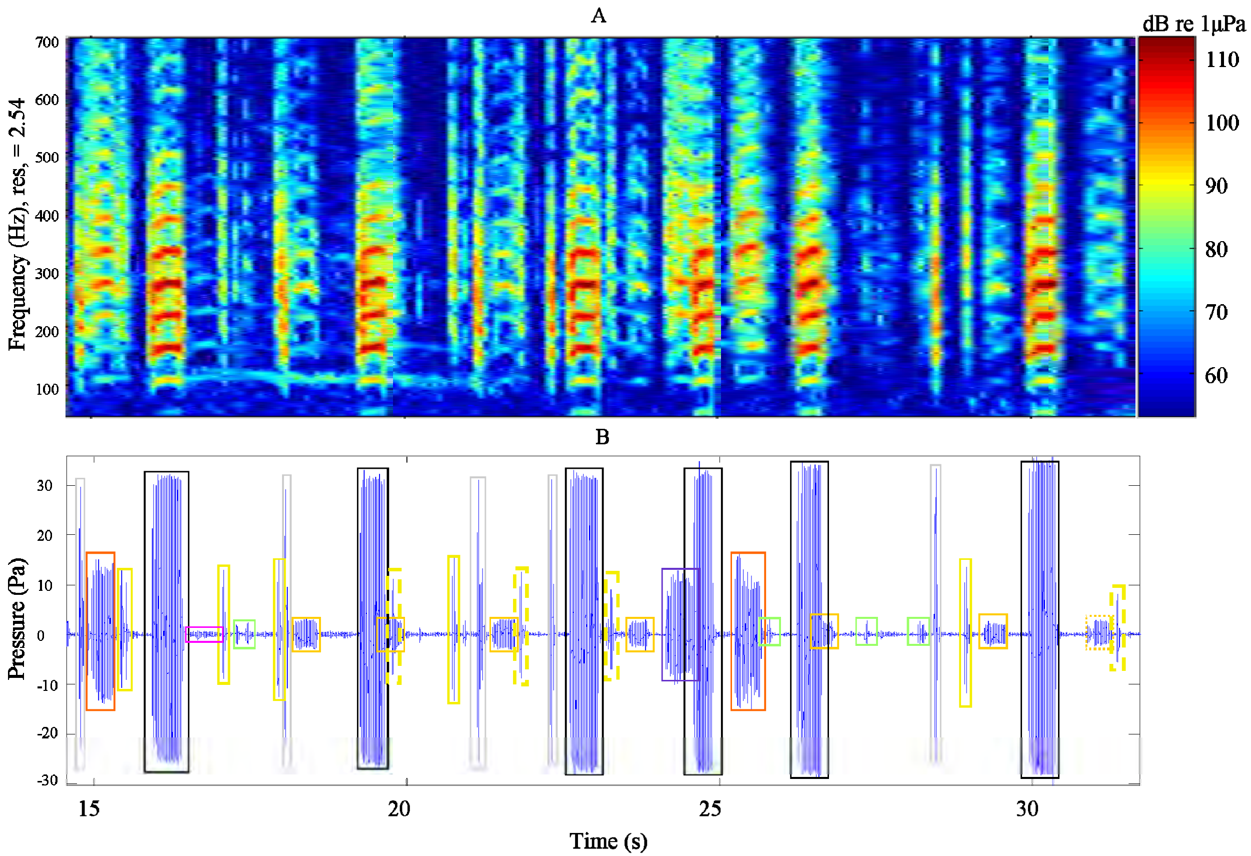

Figure 6. Spectrogram (A) and waveform (B) of 30 seconds of calling, as recorded by a bottomed hydrophone in 18.5 m of flat water. Coloured continuous lines surrounding Category 1 and 2 calls in waveform highlight individual fish calling repetitively. Dotted lines represent calls from fish speculated to be the same fish as the equivalent coloured lines. Spectrogram frequency resolution was 2.54 Hz.

SPLs of fish choruses have been related to increases in collected eggs (Luczkovich et al., 1999b), providing an idea of the relative increase of calling fish and, by proxy, spawning numbers. However, transferring this to absolute numbers requires the identification of the transmission losses; the SL of calls; quantification of ambient noise; call rates; caller position in the water column; and an estimate fish spatial distribution. Additionally, in many species of Sciaenidae, it is only the male which possesses functional sonic muscles, with which it produces sounds (Griffiths and Heemstra, 1995, Connaughton *et al.,* 2000). Thus an estimate of the sex ratio of the population is needed. Then, while the relationship is complex, if call rates are maintained by individual fish and their spatial distribution is random, then the total number of species characteristic calls recorded within an area should correlate to the number of fish calling. Therefore, if the call rate is known, and the percentage of males within the population that call at any given time can be estimated, then the total number of calling males can be determined. However, these ratios of callers to total population become more complex if both sexes of the species are soniferous, as the ratio between males and females emitting calls must be assessed.

To make the model more complex, background noise and temperature affect the ambient SPLs and fish SLs (Connaughton *et al.*, 2000). Asboth have been shown to vary throughout the spawning season in Mosman Bay, estimates of spawning numbers could only been made from the evening when call SLs and TLs were determined. Each five minute recording was separated into two minute segments to maximise recording of the highest number of fish calling within the area, while limiting likelihood of a vessel passing. Segments containing excessive vessel noise, masking calls, were rejected. The analysed segments encompassed periods of few callers, several callers where individual calls could be distinguished, and periods where calls overlapped sufficiently to significantly increase background noise levels during the two minute period. As mulloway Category 3 calls are rare and sporadic (Parsons *et al*., 2013d), analysis was conducted only on Category 1 and 2 calls. Where possible, individual calls were counted from both waveforms and spectrograms for that segment. Segments where calls overlapped to produce a constant background noise (such as during times of peak chorus calling) were not analysed using call counting techniques.

SPLs attributable to fish calls were calculated as per Section 6.2.3.2 (Parsons et al., 2012c). However, during chorus periods, where calls merged, it was not always possible to locate a sample period containing a minimum of 500 points without calling present. To compensate for the absence of clear ambient noise with no fish calling present, periods free of calls were identified throughout the evening and those considered to most closely resemble the noise present in the segment being analysed were taken as an appropriate estimate of the ambient noise.

Figure 7 highlights the incremental growth of cumulative energy with time, in particular, the variation in gradient of the energy curve due to near consistent noise such as a vessel at constant range (Figure 7a), changing noise such as a passing vessel (Figure 7b) and mulloway calls (Figure 7c, expanded inset). Figure 7b highlights the complexity of accounting for SPL contribution from passing vessels or vessels which started engines during the two minute segment (Figure 7c). For example, the first 15 seconds of the recording shown in Figure 7c, where noise from a distant vessel has been removed, displayed several distant calls. However, once a vessel at closer range started up, such calls were masked on the waveform and barely visible on the cumulative energy curve as they contributed comparatively lower energy, (Figure 7c, black ovals). The spectral content of the two sections of this recording are shown in Figure 7ci, and ii where the vessel contribution around 100 Hz in the first 15 seconds (i) has been accounted for by noise removal, but additional noise from the second vessel in the latter section has not (ii). Vessel noise spectra were often centred between 200 and 300 Hz, at similar frequencies to calls of mulloway and so could not easily be filtered out.

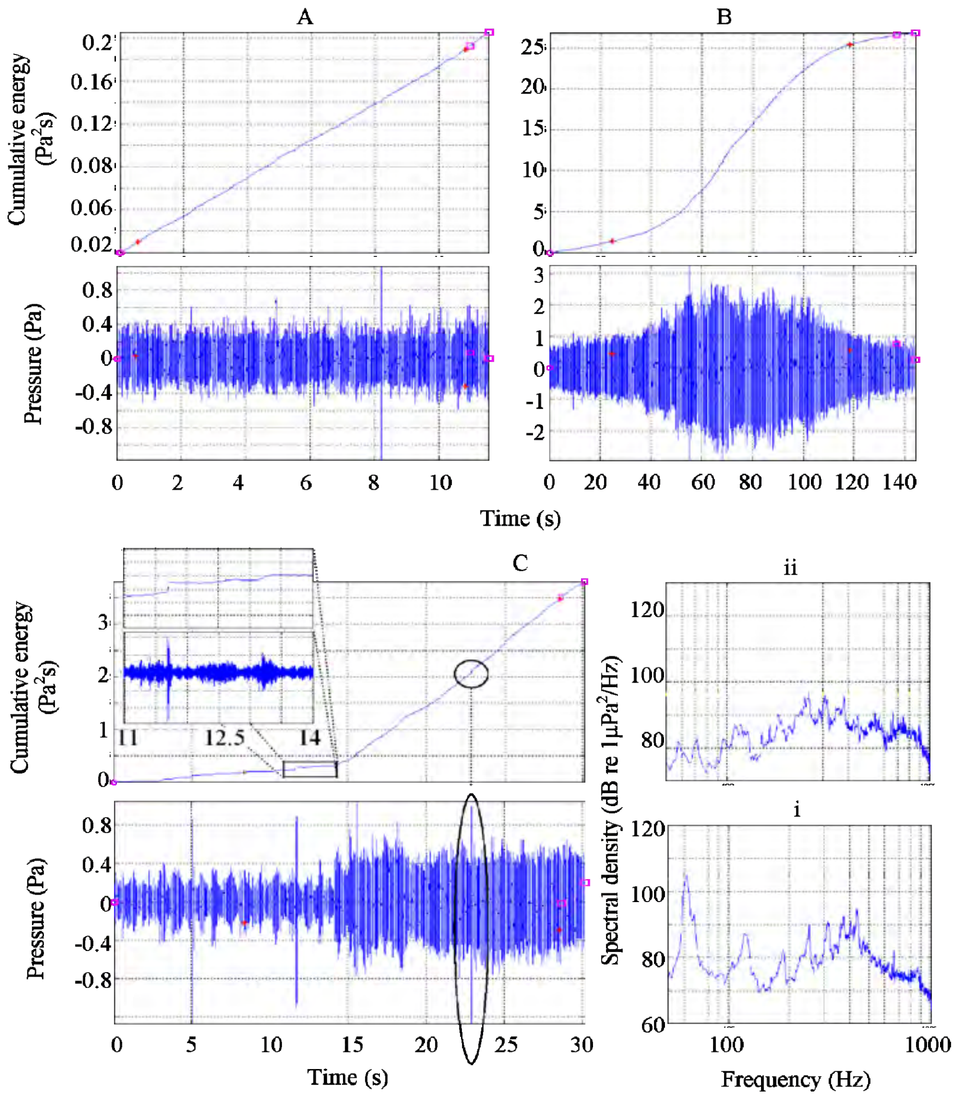

Figure 7. Cumulative energy (upper) and waveforms (lower) for noise samples taken at approximately (a) 17:30 (little biological noise and a distant vessel at constant range), (b) 18:00 (vessel passing the hydrophone at a range of approximately 100 m) and (c) 18:30 (distant vessel and distant callers during the first 15 seconds, followed by the engine running of a nearer vessel for the following 15 seconds masking the distant callers). Spectral content between 50 and 1000 Hz are shown for the first (i) and second (ii) 15 seconds of c. Pink dots represent the boundaries of noise samples used in analysis and red crosses mark the 5 and 95% energy boundaries.

To model fish call SPLs a calling fish was simulated by modelling a call of known SL in Matlab. A duty cycle was created from the determined call repetition rate. This calling period is shown by Figure 8 where a 16 pulse, 0.29 s (call time t_c), Category 2 call, was repeated every 3.2 s (duty cycle T_{dc}).

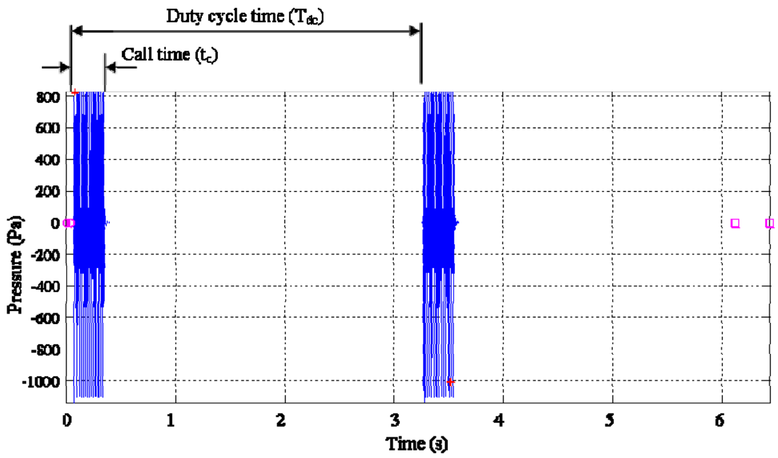

Figure 8. Pressure waveform of a simulated mulloway call, highlighting the call duration and duty cycle time for a repetitive caller.

The call was repeated for the duration of the two minute segment and SPLs were calculated for this hypothetical caller at ranges of 25, 50, 100 and 200 m from the hydrophone. Combinations of a number of callers were investigated to see how the caller number varied with overall received SPLs.

6.2.4 Ex situ studies

Captive studies of the target species were conducted at the aquaculture units of the Fremantle Challenger Institute of Technology and Curtin University of Technology. The Aquaculture Development Unit (ADU) at Challenger Institute of Technology possessed tanks holding wild-caught and captive-bred mulloway, as well as captive-bred black bream and snapper. The CARL has held an adult dhufish in their display, 60,000 L tank for the past two months. Recordings have currently been taken of the captive and wild-caught mulloway at Challenger ADU and of the dhufish at the CARL. In each case a HTI-90min hydrophone was positioned in the water, at the side of the tank and attached to either a Sony DAT recorder or an HR-5 Jammin Pro solid state recorder.

6.3 Fishers' Views

While the timing and location of some aggregations can be predicted, many are ephemeral and often remote. This makes targeting individual aggregations problematic. As such, the knowledge and 'time at sea' of commercial and recreational fishers provides an informative source of data (Hamilton *et al.*, 2005). Fishers' experiences were also considered an important source of information during the current study. Informal discussions took place on a one-to-one basis, beginning with a description of the project and its objectives. Numerous recreational fishers, commercial fishers and researchers have been consulted regarding spawning times and locations of the four target species. These types of informal discussions have previously provided a successful source of data in a stock assessment of Spanish mackerel (Mackie *et al.*, 2003).

The discussions provided information on the location and timing of aggregations; the type of habitat associated with particular fish; the density of the aggregations that form and; whether the fish have been heard (or felt) producing a sound upon capture. These consultations were important for planning deployments and supporting the logistics of deployments. They led to the spatial and temporal targeting of the Frankland River black bream, Geographe Bay and Abrolhos Island dhufish, and the Augusta dhufish and mulloway deployments.

6.4 Ground-truth and complementary data

A simple resolution to ground truth fish calls would be concurrent, calibrated audio and visual recording, similar to that reported by Sprague and Luczkovich (2004). However, behaviourally unbiased, *in situ*, ground truthed recording of fish calls, in dark or turbid waters, is improbable at such short ranges. *Ex situ* methods often provide the best method of confirming vocal behaviour in a species, however, some species have been shown to exhibit restricted vocal behaviour in captivity (Midling et al., 2002) and other species, such as WA dhufish, may alter spawning behaviour and/or resist spawning altogether (Jenkins, G., Challenger Institute, pers. com.). Therefore, numerous techniques have been applied, where available, in order to add credence to confirmation of vocal behaviour and/or numbers of fish present in the spawning aggregation.

At each study site, concurrent data is collected with the acoustic recordings to aid ground truthing sound source (species), the associated behaviour and the number of individuals in the vicinity when a sound is produced. Where possible, information was collected to confirm that the recordings were taken near a spawning aggregation of the target species. Additional environmental data has also been collected to help understand the environmental drivers behind spawning.

6.4.1 Biological sampling

Acoustic surveys of snapper in Shark Bay and Cockburn Sound have been conducted in conjunction with the DoFWA and run concurrently with biological sampling. Sampling comprised either capture of spawning fish or plankton tows for eggs and larvae by the DoFWA. Although these data would not necessarily confirm actual spawning within the duration of recording, the presence of 'running ripe' females or eggs/larvae in plankton samples provides evidence that spawning was about to or had very recently occurred. Where possible, deployments targeting dhufish have been conducted as near as possible to sampling conducted by the DoFWA, in particular a research project investigating the occurrence of juvenile dhufish. Black bream have been donated by recreational fishers and purchased from markets to investigate any possible mechanism of sound production.

6.4.2 Active acoustic techniques

During FRDC Project 2004/051 a single-beam Simrad EQ60 echosounder was mounted aboard the *RV Snipe* to identify mulloway in the Swan River. However, it was found that the mulloway were too sparsely populated and too close to the riverbed to be observed. The DoFWA often use sidescan sonar to locate snapper in the Cockburn Sound (Fairclough *pers. comm.*). A similar Humminbird sidescan sonar system (recently purchased by the CMST) was employed to observe mulloway at other study sites. However, in order to estimate volumes of schools a multi-beam system is required to accurately represent the fish in three dimensions, whilst concurrently recording with sea-noise loggers. During multibeam surveys of snapper in project 2004/051 it was observed that traditional mounting positions (nadir beams directed vertically downwards) of multibeam sonar were not conducive to surveying schools of this species, which aggregates to spawn in shallow water (Parsons, 2010, Mackie *et al.*, 2009; Wakefield *et al*., 2011). The traditional mounting required the vessel to be directly above the school, resulting in avoidance behaviour by the mobile snapper. Therefore, the plan was to sideways mount a system similar to that of Gerlotto *et al.* (1998; Figure 9) which allows the vessel to pass up to hundreds of metres from the school.

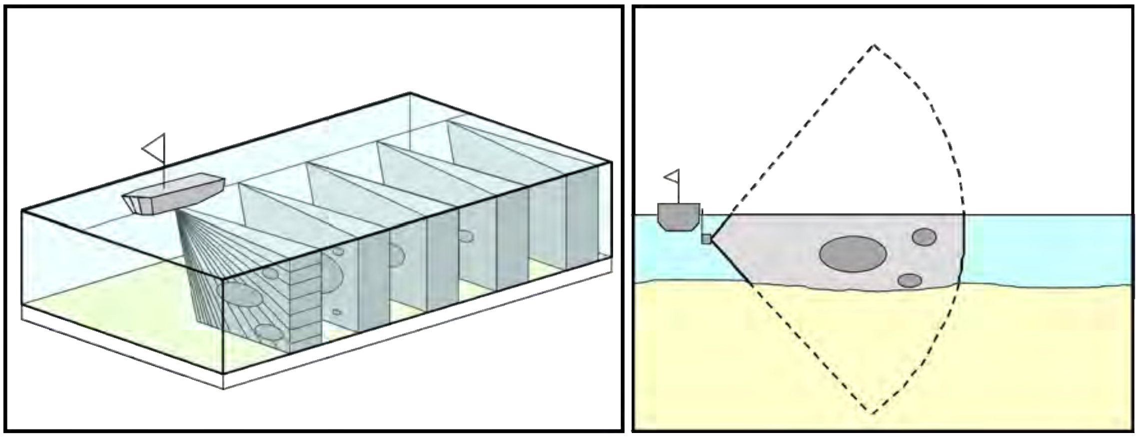

Figure 9. Side mounting of a multi-beam sonar in shallow water. Figure adapted from Gerlotto et al. (1998).

6.4.3 Video

Where possible, still and video cameras were deployed with sea-noise loggers to obtain video footage of vocalising fish. During the deployments at Canal Rocks (off Cowaramup) targeting dhufish the DoFWA conducted video transects from the RV Naturaliste to investigate the presence juvenile dhufish in the area. As vocalisations often occur at times of low light and/or visibility, visual confirmation at the time of sound production is rare (Parsons, 2010). However, video evidence of the predominant species present in the surrounding area provides evidence of the species as the source of recorded biological sounds.

6.4.4 Environmental variables

Previous studies have shown that the timing and SPLs of mulloway choruses correlate significantly with environmental variables such as sunset, high tide, temperature and salinity (Ueng and Huang, 1998). These trends are comparable with current knowledge about biological requirements for mulloway spawning (Jenkins, G. pers. com.). Similar types of correlation with environmental drivers have been found with other species (Barrios, 2004). Long-term datasets on solar, lunar (Geoscience Australia), tidal (Department of Planning and Infrastructure - DPI), water temperature, salinity, dissolved oxygen and pH level (Swan River Trust) patterns were provided for correlation against chorus levels and times in the Swan River.

7.0 RESULTS

Acoustic deployments have currently acquired a total of 2.48 Tbytes of data. All deployments successfully recorded ambient noise of the surrounding waters, with one exception. Biological examination and theoretical modelling of the likely call characteristics have been conducted for each species.

7.1 Mulloway

Previous studies have highlighted some of the characteristics and mechanism behind mulloway sound production (Parsons, 2010, Ueng and Huang, 1998, Ueng *et al.*, 1999, Parsons *et al.*, 2006, 2009). However, further steps have been taken to improve understanding the biological method behind the sounds and possible reasons for some of the call characteristics.

7.1.1 Anatomy

Dissection of mulloway at CMST, as part of FRDC projects 2004/051 and 2010/004, revealed bilateral, dark-red, sonic muscles comprising dorsoventral fibres, lining the posterior two thirds of the swimbladder. An example 836 mm (total length) mulloway displays muscles in Figure 10 (dotted lines), comparable with sonic muscles reported in *A. regius* (Lagadere and Mariani, 2006). The muscle block in Figure 10 was located 5 cm from the posterior of the 33 cm body cavity and extended forward 19 cm, finishing 9 cm from the body cavity anterior. This muscle block surrounded a smaller portion of the swimbladder than that of *A. regius* and did not taper towards the posterior, as was reported by Lagadere and Mariani (2006). The block was positioned at the same cavity height as the lipid deposits which surrounded the swimbladder. White muscle fibres (orientated in an anterior-posterior direction, Figure 10 mark i) surrounded the body cavity aponeurotic lining (Figure 10, marks ii and iv). The sonic muscle fibres (Figure 10a, mark iii) appear to have developed under the body cavity lining around Figure 10a mark v, splitting the lining in two, as with *A. regius* (Lagardere and Mariana, 2006). Similar to other Sciaenidae (Ona and Poss, 1982), it is thought that the sonic muscle fibres extended ventrally, such that the sonic muscles were partially bounded by the body cavity lining (Figure 10a inset, and b). Figure 10b inset shows the orientation of the sonic muscle fibres in relation to the body cavity. These muscles were not observed in any previously dissected specimens, ranging up to 56 cm total length and are thought to develop fully in association with maturation.

The 32 cm long and 6.2 cm wide swimbladder (recorded from a flattened swimbladder) shown in Figure 10c highlighted the enlargement of the anterior appendages (Figure 10c, thin black line). The swimbladder material was 1.71, 2.54 and 2.32 mm thick at the top, middle and bottom of the anterior section, thinning to 1.09, 1.59 and 1.37 mm for the same locations, at the posterior. Internally, an enclosed 0.39 mm thick membrane was connected to the inside wall of the swimbladder, from posterior to approximately 5 cm from the anterior, where it separated from the wall. The swimbladder was connected to the vertebral column at the anterior: the posterior was loosely attached at the anus, and two lines of fine tendons loosely attached the top of the swimbladder to the aponeurotic lining at the top of the body cavity. Thus when the body cavity volume is greatest the swimbladder is effectively suspended from its roof.

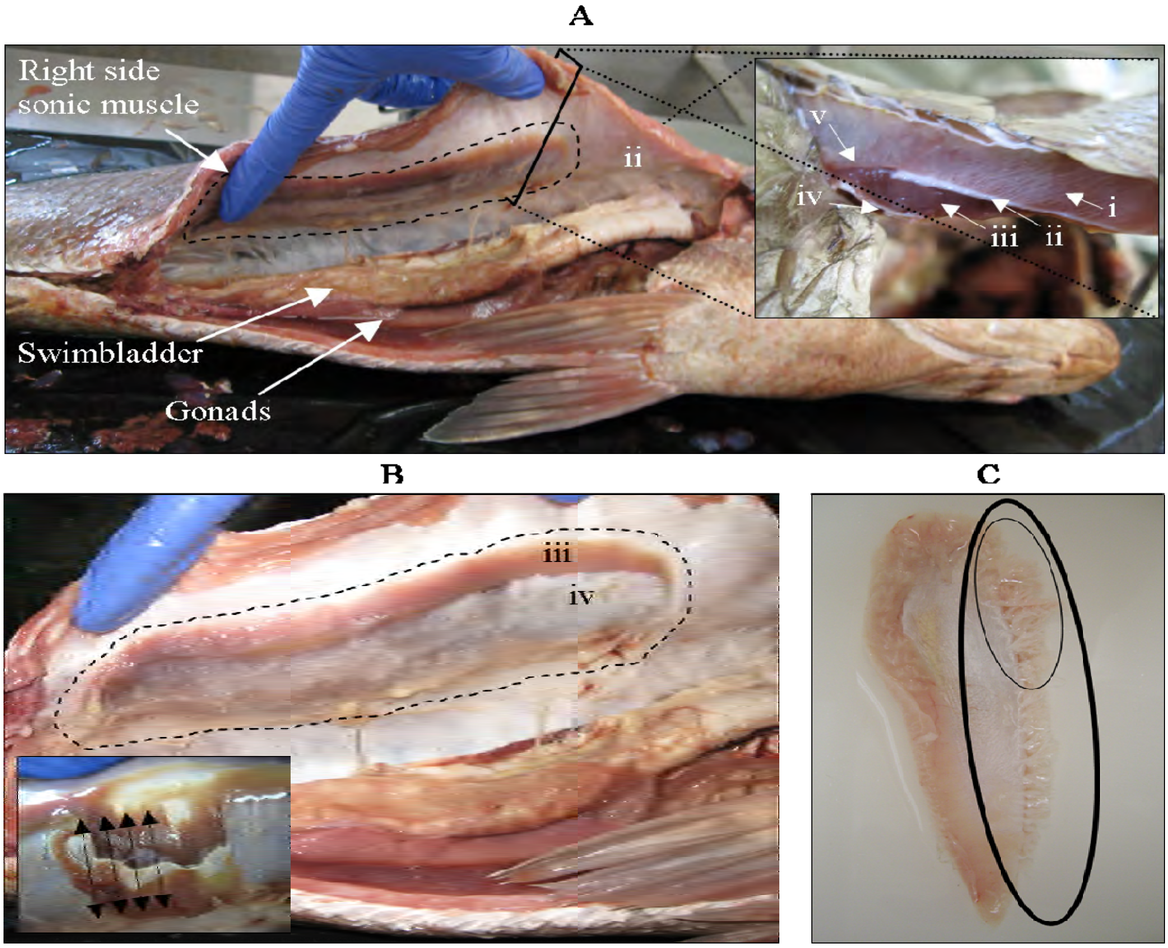

Figure 10. Photos of dissected 83.6 cm mulloway. (a) Body cavity, highlighting positions of swimbladder, gonads and right side sonic muscles. Inset shows cross section of sonic muscle area with: white body muscle fibres (i); aponeurotic lining (ii); dark red sonic muscle (iii); aponeurotic lining outside sonic muscle (iv). (b) Expansion of sonic muscle area with inset showing muscle fibre direction. (c) Separate swimbladder plan view image with all aborescent appendages on one side (thick black line) and enlarged anterior appendages (thin black line) highlighted. Images taken from Parsons, 2010.

7.1.2 Categorisation of calls

Parsons et al. (2014) characterised three categories of mulloway calls in the Swan River by spectral features, amplitude variation and waveform structure. *In situ* mulloway calls exhibited call spectral peak frequencies varying between 175 and 350 Hz and mean pulse repetition frequencies of approximately 59 Hz. It was suggested that mulloway exhibit a considerable range of spawning-related vocalisations, generalised into three categories; short grunts of 1-6 pulses ('Bup') which are more predominant as the aggregation forms and separates; long grunts comprising 11-32 pulses ('Baarp') as a broadcast call of attraction between spawning males and females; and a series of short calls of 1-5 swimbladder pulses ('Thup') observed only once or twice each evening (Figure 11). The second category is divided into several types of call where a single audible tone can also be broken into two or more parts, often preceded by one or more short 'Bups' (for example, 'Bup-bup-baarp').

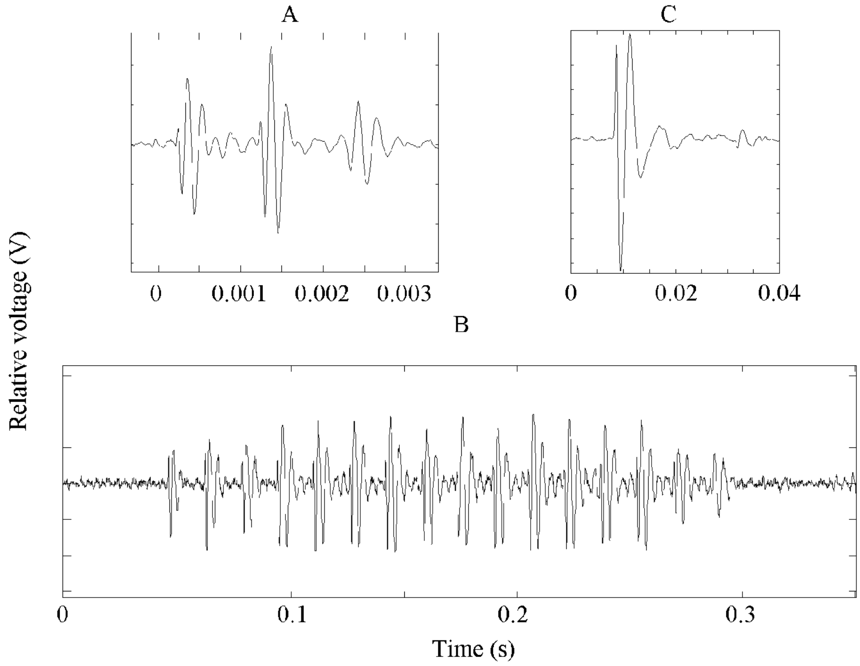

Figure 11. Example wave forms of mulloway Category 1 short calls (a), Category 2 long calls (b) and single pulse Category 3 calls (c) as recorded by a hydrophone positioned on the riverbed (Parsons et al., 2014).

An example 17 seconds of mulloway calling recorded in the Swan River in 2007 is shown in Figure 12. This shows the spectral content and waveforms of two categories of call, a short call (bounded by white box) and long calls (three examples marked by dashed lines).

7.1.3 Short-term changes in call characteristics

In several recorded Mosman Bay mulloway calls distinct variations within individuals' calls were observed in pulse durations, pulse resonant frequencies and pulse repetition frequencies (PRF) (Table 6). All three characteristics were observed not only remaining constant, but increasing and decreasing throughout an individual call. These changing features resulted in several spectral variations (Figure 12a, Marks i, ii and iii, representing Calls 1, 2 and 3, respectively). Where pulse duration and repetition rate remained constant, so too did the respective spectral peak and repetition frequencies (Figure 12a, iii). However, varying pulse durations and amplitudes altered the spectral peak frequencies as the call progressed (Figure 12a, i and ii). Expansions of Calls 1, 2 and 3 are shown in Figure 13, showing a call which increase in PRF (Call 1), increase and then decreases in PRF (Call 2) and remains constant (Call 3). In Figure 13 the top panels display the waveform (a) and spectral content (b) of the whole call. In the next panels (c) the expanded waveform of each pulse within the call overlaid over each other for comparison (the start of each pulse has been synchronised to the initial amplitude peak). Distinct variations in PRF (d) and resonant frequency of each pulse (e) were observed throughout the calls. Similarly, the amplitude of each waveform peak (illustrated by the differences in the detected pressure amplitude between successive waveform peaks within each pulse) displayed significant variations, as seen in (f).

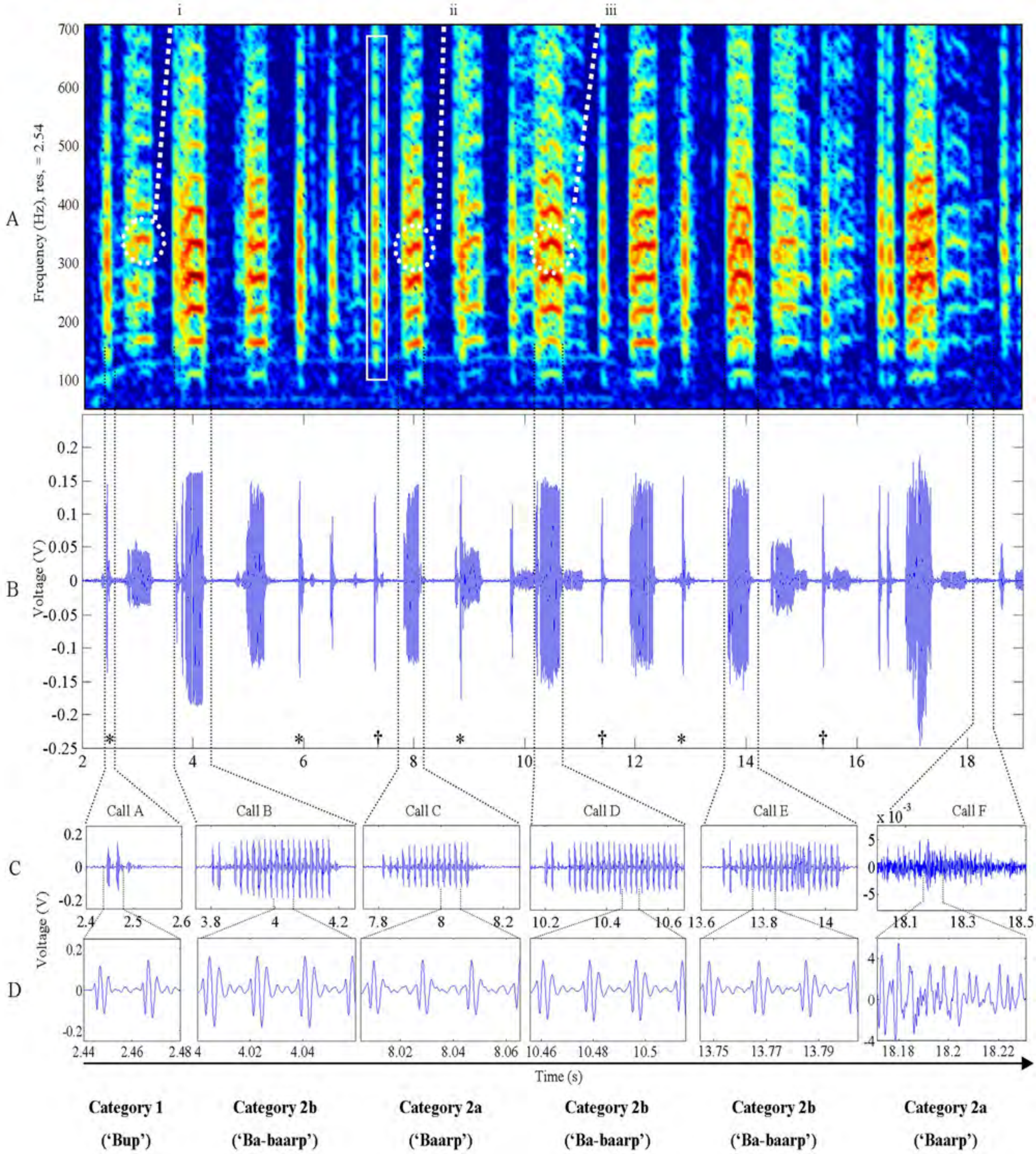

*Figure 12. Spectrogram (a) and waveforms (b) from 17 seconds of Mosman Bay mulloway calling, recorded at 4 m depth in 19 m of flat water at 19:35, 17th January, 2007 highlighting two categories of mulloway calls. Spectrogram frequency bandwidth and waveform sampling frequency were 2.54 Hz and 10,416 Hz, respectively. Expansions of six selected call waveforms highlighting the entire calls (c) and sets of swimbladder pulses (d) are shown. Call F highlights an audible call of low signal-to-noise where waveform structure is distorted by noise. Symbols * and † denote examples of suspected repetitive Category 1 calls from individual fish. Marks i, ii, and iii note long calls while the white box marks the spectral content of short calls. Image adapted from Parsons (2010).*

Table 6. Characteristics of the changing pulse repetition frequencies in mulloway Category 2 calls.

Type of Frequency Change within call	Number of calls analysed	Fundamental Frequency (max, min) Mean frequency of call (Hz)	Mean frequency change within a call (Hz)
Constant	53	56.3 ±2.9 (60.5, 48.6)	1.5 ± 0.7 (2.6, 0.6)
Rise	71	60.2 ±2.7 (63.3, 56.7)	6.4 ± 1.5 (8.7, 4.6)
Rise and fall	109	58.5 ±2.9 (59.1, 57.3)	5.7 ± 0.9 (7.2, 4.3)
Fall	41	54.9 ±1.7 (56.4, 51.8)	4.2 ± 1.1 (5.9, 2.8)

Figure 13d panels illustrate how the amplitudes of initial pulses and PRF were often lower than those of succeeding ones. Although the y-axis in the graph of Call 2 has been truncated to illustrate the trend of the PRFs throughout the main body of the calls in Figure 13a (PRF between pulses 2 and 3 was 18 Hz), this call highlights how there was often an extended gap between initial pulses and those following them. In Call 1 the duration and amplitude of the first two waveform cycles increased significantly after the first three pulses and then continued to increase throughout the call (Figure 13a). The spectral peak frequencies (b) and amplitude peaks (f) increased significantly after the first three pulses (Figure 13b, approximately 7.85 seconds) and continued to throughout the call (Figure 13b), while the resonant frequency of each pulse decreased (e). By comparison, in Call 2 as the call continued the waveform amplitudes increase and then decrease (c and f) and the peak frequencies rise and fall (b). At the same time the PRF increases and decreases (d) while the resonant frequency decreases and then increases (e).

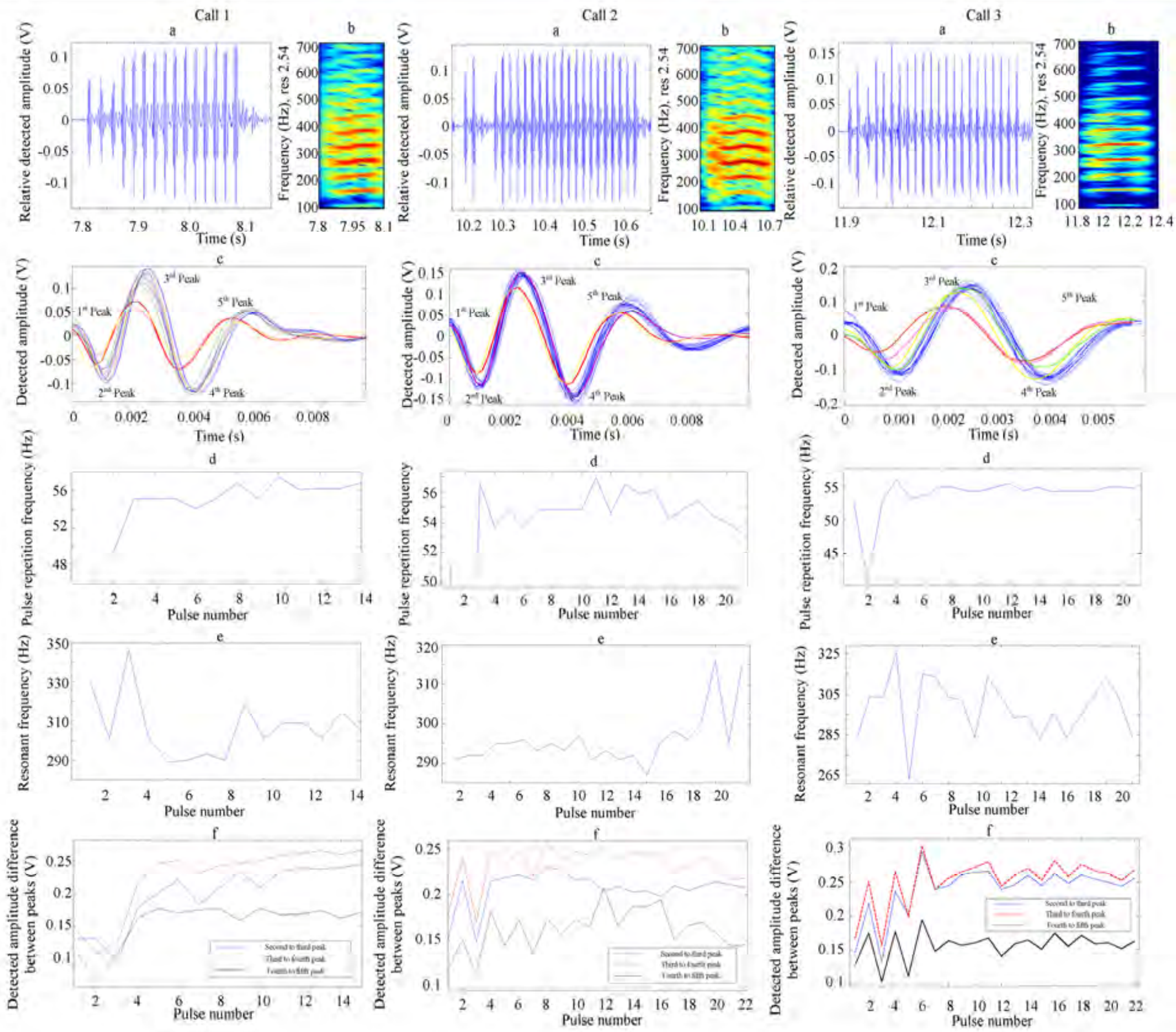

Figure 13. Waveforms (a) and, spectrograms (b) of Calls 1, 2 and 3 from Figure 11 with each pulse waveform synchronised to the first pressure peak of the pulse (c). In each waveform the initial pulses are shown in red, yellow, magenta and green and peaks of each half cycle have been numbered. Pulse repetition frequency (d), resonant frequency (e) and the progressive amplitude differences between three sets of peaks throughout the call (f, blue, red and black lines) are shown

Each of the calls reflect the general trend of all calls analysed in that an increase in PRF correlated with a decrease in resonant frequency and also an increase in waveform amplitude (see Table 6 for PRF characteristics of all calls). The maximum change in PRF and therefore fundamental frequency of the sound during a call was 8.7 Hz (from 53.6 to 62.3 Hz), over 0.27 s. At these frequencies, this ~15% difference equates to approximately almost a minor third in musical terms. The greatest change in resonant frequency was between 310 and 374 Hz over 0.31 s.

To confirm that the changes above were not a result of relative movement of the fish compared to the hydrophone it was necessary to examine the characteristics of a single call, as observed by each of the hydrophones in the array deployed into the river. Figure 14 shows the spectral content of an individual call, together with the location of the call relative to each hydrophone position. Each spectrogram displays one second of the recording. The apparent difference in call duration between spectrograms is due to the signal-to-noise ratio in each recording. The horizontal spectral lines at the same frequencies in Figure 14b and c (approximately 250 Hz), were due to a passing water-ski vessel. However, these spectral lines are at a different frequency in Figure 14d (approximately 238 Hz). The difference between these two frequencies is due to the relative motion of the vessel and the resultant Doppler shift. The spectral content of the call as recorded by each hydrophone, however, does not show such discernible differences.

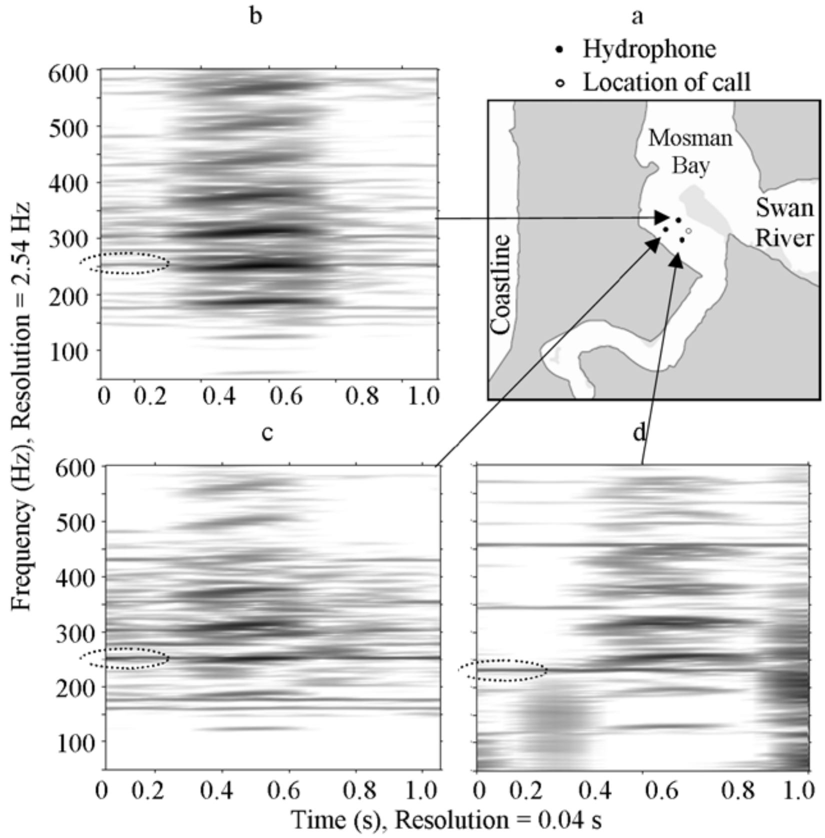

Figure 14. Map of the hydrophone array in the Swan River (A). Spectrograms display the same call as received by three hydrophones within the array (B, C and D). Colour scale on each spectrogram differ due to range from the respective hydrophone, however, the relative colour scale remains the same. Dotted ovals mark the frequency of spectral peaks due to a passing water ski vessel (approximately 250 Hz in B and C, approximately 235 Hz in D).

7.1.4 Spatial mapping of mulloway in the Swan River

Spawning mulloway and their calls and choruses have been observed at various locations around the Swan River. However, the Swan and Canning River systems covered tens of kilometres of possible spawning locations. Simultaneously sampling such a large area would require numerous hydrophones to map the presence and relative abundance of mulloway. This project has had a maximum of three noise loggers and two portable recording units which could be used to target the mulloway during their spawning period. As such, spot recordings have been taken around the river systems (Figure 2) throughout the duration of the project. These recordings have been taken within two hours after sunset to be related to the long-term recordings acquired between Mosman Bay and Garden Island (see Section 4.1.1.5). SPLs associated with mulloway were observed, particularly between Mosman Bay and downstream of Blackwall Reach as well as around Rocky Bay, and the Narrows Bridge (Figure 15. Lower levels of calling were also detected around Canning Bridge with occasional sounds from mulloway further up the Canning River. However, it is often suggested that the mulloway appear at the upstream sites at times late into the night and anecdotal evidence of mulloway catches have been reported to the author as far upstream as the Causeway Bridge in the Swan River and Kent St Weir in the Canning River. It should be noted that no evidence of mulloway calls were detected near the Causeway. It is possible that the fish are around this area later in the evening than the spawning sites around Mosman Bay.

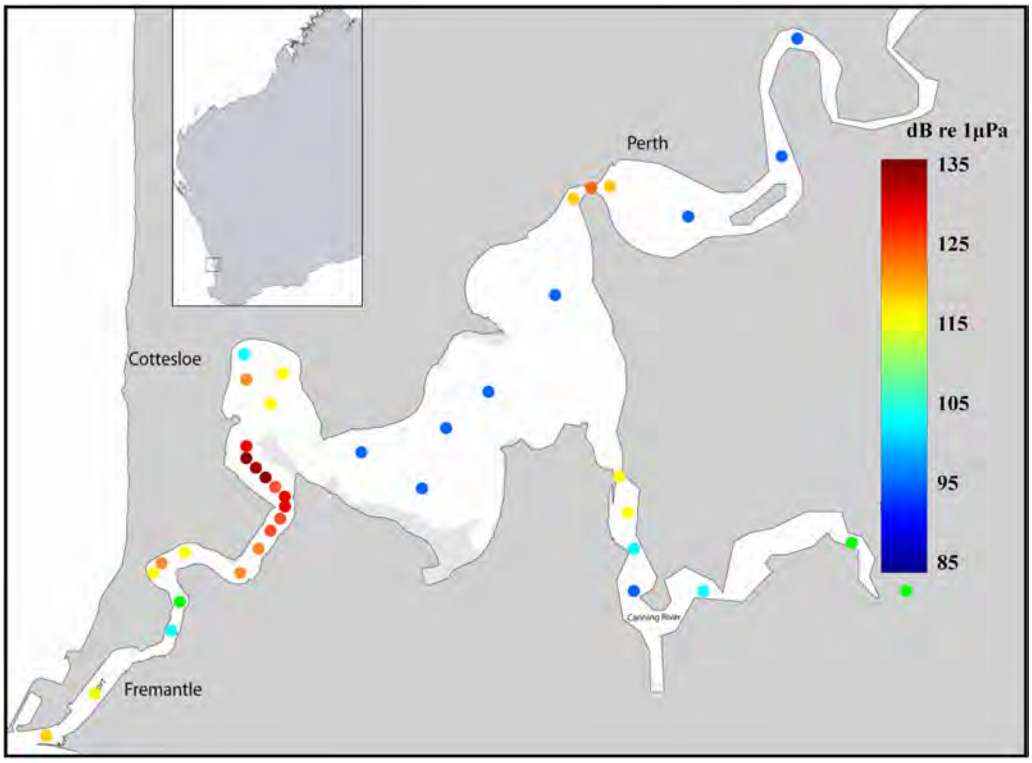

Figure 15. Maximum SPLs attributed to mulloway calls recorded at various sites around the Swan and Canning River systems. Levels are as per the colour bar and represent the maximum level from a two minute segment of a recording.

7.1.5 Variations in chorus levels along the Swan River

Parsons *et al.* (2006) hypothesised that in the Swan River male mulloway form individual display areas, into which they attempt to entice females to spawn similar to lekking cod (Engan and Folstad, 2000). An array of hydrophones was deployed on 8th March, 2007 to localise individual mulloway (Parsons *et al.*, 2009). The recordings showed that the localised fish appeared to move down stream at ~0.25 ms^{-1} and during the early evening at least, maintained a minimum distance between calling fish, however, overall SPLs from multiple mulloway calls increased earlier in the evening at the downstream hydrophone. The localisation of individual mulloway, spatial mapping of mulloway choruses in the Swan River and long-term monitoring of the aggregation chorus at a single location have shown that the presence of the mulloway chorus is not a binary system and that both individuals and the aggregation move around the river. Long-term recordings, taken at three locations (Mosman Bay, Coombe Reserve and Blackwall Reach), together with recordings at four other sites (Fremantle Port, two sites within Cockburn Sound and one near Garden Island), from concomitant studies around the Swan River were designed to examine how the aggregation moved along the river (Figure 16, Table 7). The datasets from Fremantle Port and Garden Island were supplied by the Fremantle Port Authority and Carnegie Wave Energy Limited (data collected as part of its environmental monitoring program for the CETO3 wave energy convertor deployment), respectively.

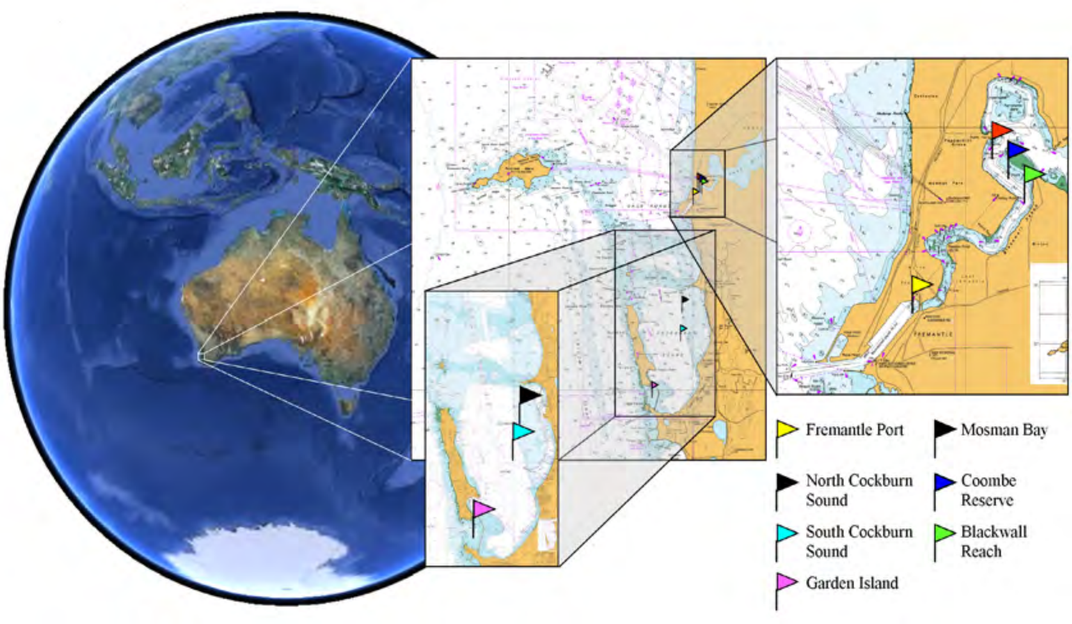

Figure 16. Approximate locations where recordings were taken represented by the red (Mosman Bay), blue (Coombe Reserve), green (Blackwall Reach), yellow (Fremantle Port), black (North Cockburn Sound), cyan (South Cockburn Sound) and magenta (Garden Island) flags.

Table 7. Sampling schedules and settings for each recording, along with deployment periods.

Site	Recording Period	Sample rate	Low and high frequency roll-offs	Sampling schedule
Mosman Bay	30/09/09-15/05/10	8 kHz	8 Hz and 5 kHz	300 s each 900 s
Blackwall Reach	04/03/10-16/04/10	22 kHz	8 Hz and 8 kHz	300 s each 900 s
Fremantle Port	31/03/10-03/06/10	22 kHz	8 Hz and 8 kHz	300 s each 900 s
Cockburn Sound North	08/10/10-06/10/10	8 kHz	8 Hz and 5 kHz	780 s each 900 s
Cockburn Sound South	08/10/10-06/10/10	8 kHz	8 Hz and 5 kHz	780 s each 900 s
Mosman Bay	19/10/10-23/05/11	8 kHz	8 Hz and 5 kHz	300 s each 900 s
The Coombe Reserve	01/04/11-23/05/11	22 kHz	8 Hz and 5 kHz	300 s each 900 s
Blackwall Reach	01/04/11-23/05/11	22kHz	8 Hz and 5 kHz	300 s each 900 s
Garden Island	01/05/11-17/05/11	8 kHz	8 Hz and 5 kHz	600 s each 1800 s

Each chorus was examined for start, peak and end times and the peak power spectral levels over the 150-500 Hz band for each chorus were noted. A chorus was deemed to have started when more than two fish were detected calling within a one-minute period. Power spectral levels were calculated for every 30 s of each recording, from which the time and level of peak calling was determined. A chorus was deemed to have ended when less than three fish could be detected calling on the recording. Tidal pattern data were supplied by the Bureau of Meteorology and the time of high tide was compared with the peak calling at each location. As the times of Mosman Bay choruses are related to the changing time of sunset and high tide (Parsons, 2010) the times of start, peak and cessation of calling were compared between each location for individual days to see how they compared.

All recordings displayed evidence of mulloway choruses, with the exception of the Cockburn Sound sites where only a maximum of two mulloway were detected at any one time. Chorus durations were typically 4 to 7 hours, at Mosman Bay (349 ±80 mins, maximum = 483, minimum = 227), the Coombe Reserve (277 ±78 mins, 402, 124), Blackwall Reach (239 ±85 mins, 372, 56) and Garden Island (280 ±126 mins, 512, 44) in 2011 and Mosman Bay (223 ±81 mins, 407, 77) and Blackwall Reach (286 ±72 mins, 409, 151) in 2010. In 2010 the Blackwall Reach chorus on average started earlier and lasted longer than at Mosman Bay. However, in the following year this reversed (Table 8). These differences in timing and the intensity between chorus locations each year were apparent in the stacked spectrograms (Figure 17 and Figure 18). There was, therefore, considerable overlap in the chorus timings (Figure 19), showing that different fish were present, calling at various locations. However, while mulloway calls at the Fremantle Port site did form a chorus (under the definition used for the purposes of this study), durations of calling were difficult to determine due to masking by passing vessels and machinery (Figure 18). It was therefore difficult to compare the chorus levels at this site with the other choruses.

Table 8. Differences in chorus start, peak, end times, duration and peak levels between recording sites where mulloway choruses were detected (maximum and minimum values shown in parentheses).

	2011				2010
	Mosman Bay-Coombe	Coombe-Blackwall Reach	Mosman Bay-Blackwall Reach	Mosman Bay - Garden Island	Mosman Bay-Blackwall Reach
Difference in chorus start time (mins)	33 ±30 (97, -18)	16 ± 59 (85, -170)	48 ±54 (113, -80)	100 ±63 (196, -73)	-45 ±47 (160, -24)
Difference in chorus peak time (mins)	63 ±41 (146,-12)	13 ±48 (105, -111)	77 ±45 (150, -52)	43 ±79 (175, -165)	24 ±44 (126, -48)
Difference in chorus end time (mins)	104 ±51 (198, -42)	23 ±39 (129, -31)	128 ±70 (312, -12)	22 ±120 (228, -226)	18 ±31 (44, -95)
Difference in chorus duration (mins)	72 ±49 (160, -73)	37 ±74 (185, -92)	109 ±94 (270, -67)	121 ±137 (376, -122)	-63 ±48 (22, -197)
Peak Spectral Level dB re 1μPa^2/Hz	5 ±6 (11, -16)	7 ±10 (15, -29)	2 ±11 (25, -16)	1 ±8 (17, -12)	2 ±4 (4,-10)

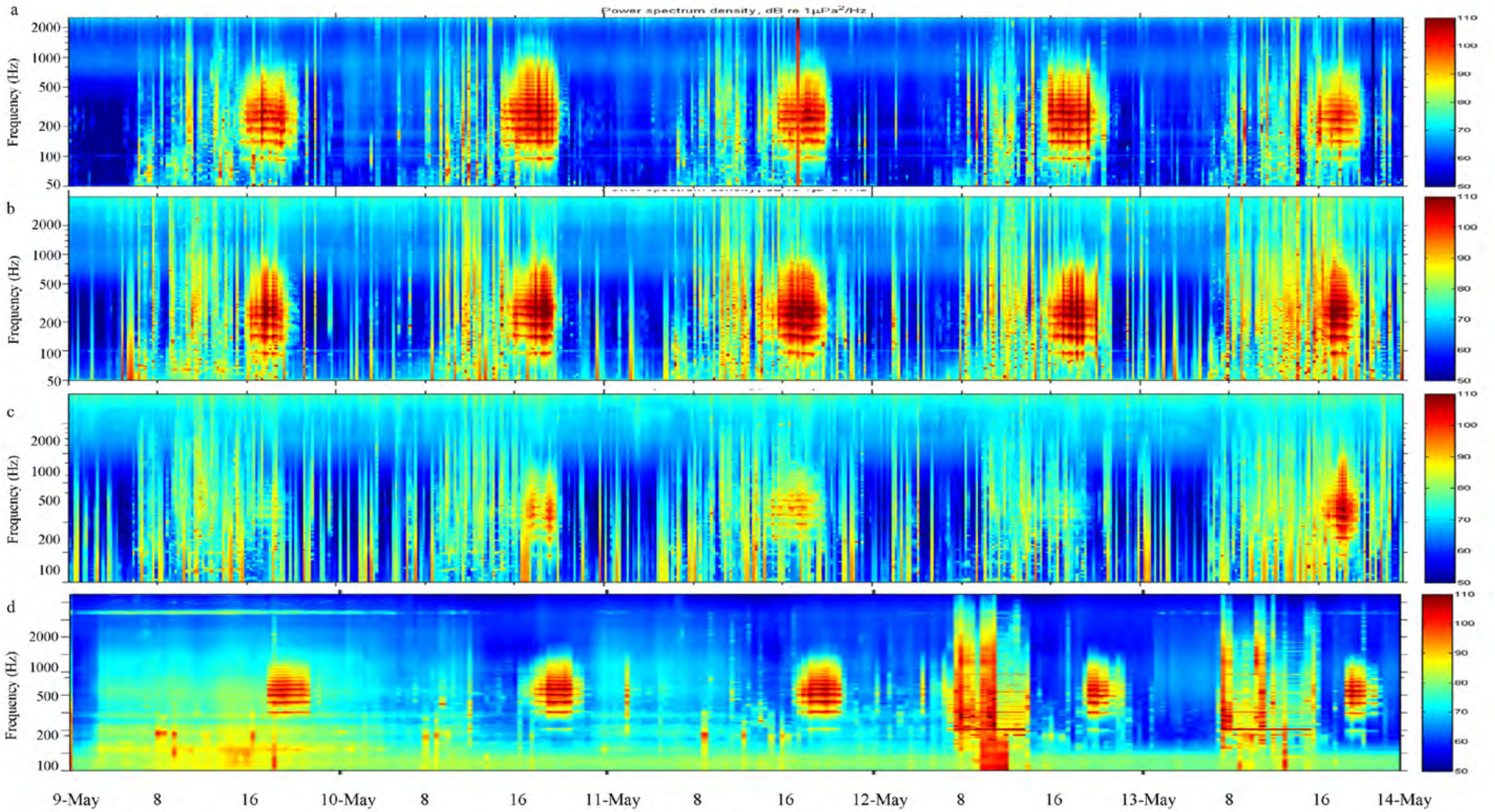

Figure 17. An example spectrogram of five nights of mulloway spawning, as recorded by four of the CMST sea-noise loggers at Mosman Bay (a), Coombe Reserve (b), Blackwall Reach (c) and Garden Island (d) in May 2011.

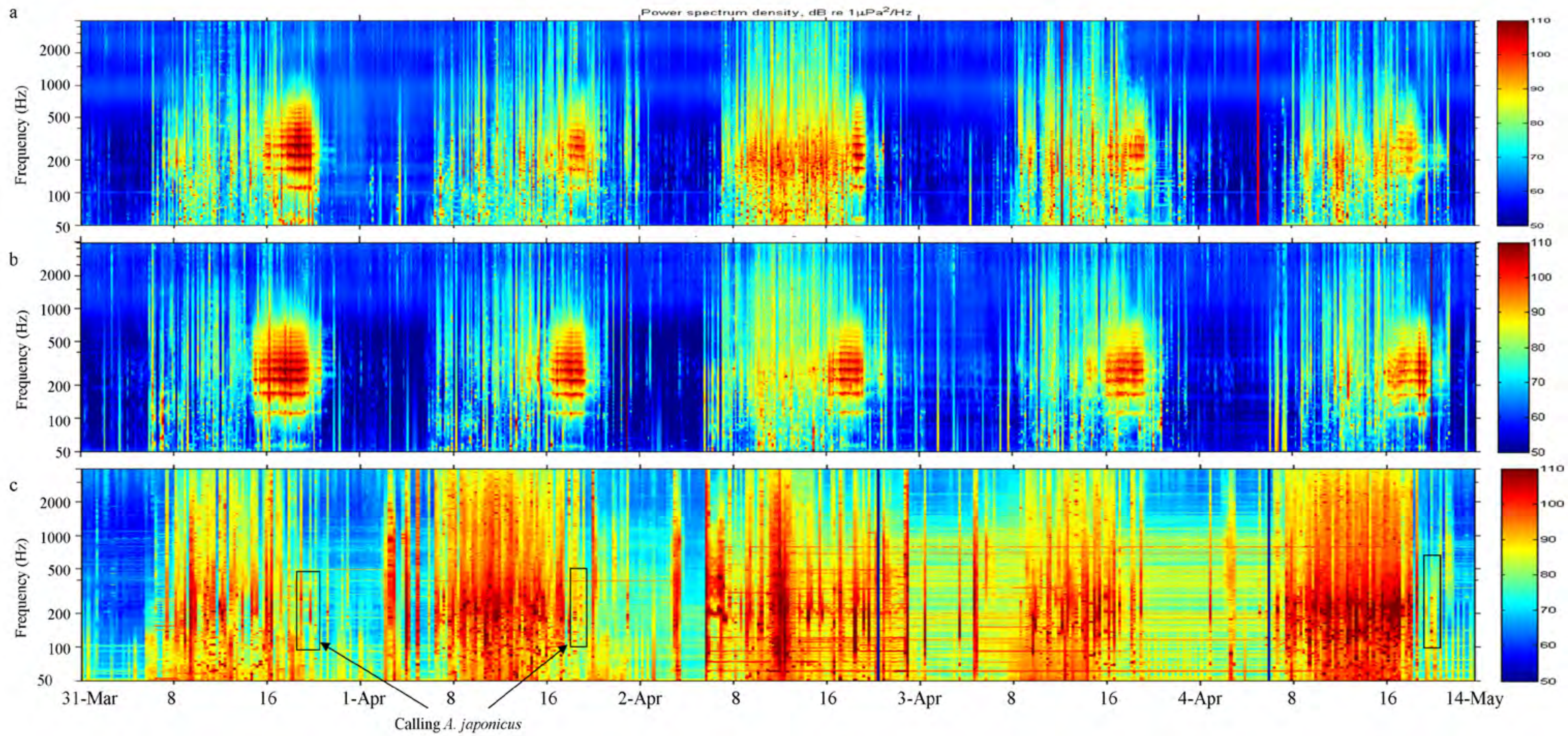

Figure 18. An example spectrogram of five nights of mulloway spawning, as recorded by three of the CMST sea-noise loggers at Mosman Bay (a), Blackwall Reach (b) and near Fremantle Port (c) in April 2010.

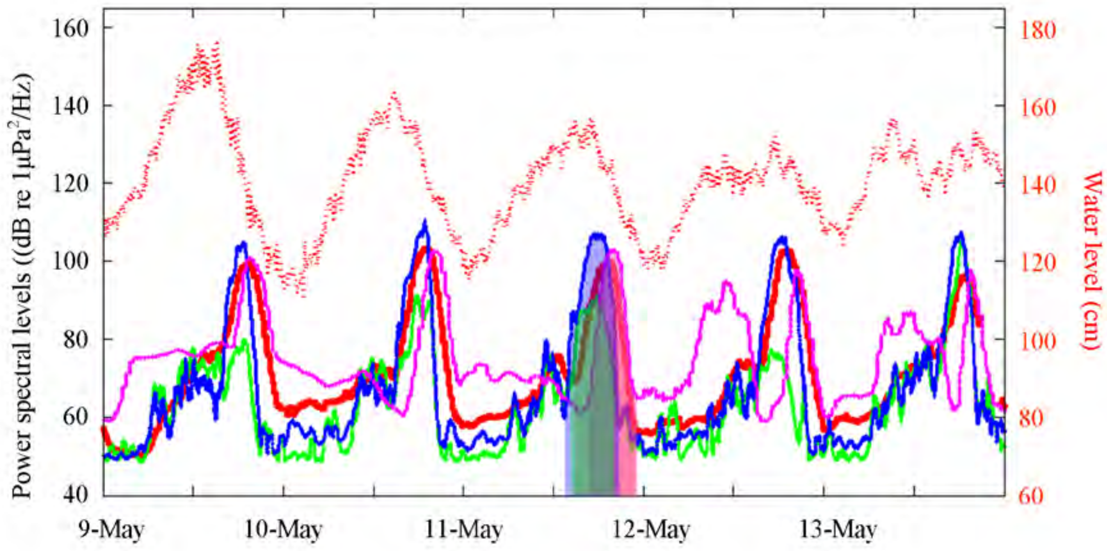

Figure 19. Power spectral levels due to mulloway calling, over the 150-500 Hz bandwidth, each evening. Locations are shown by the red (Mosman Bay), blue (Coombe Reserve), green (Blackwall Reach), and magenta (Garden Island) continuous lines. Tide levels at Mosman Bay shown by the dashed red line. Shaded regions on the 11th May, 2011 highlight the times of the chorus at each location.

On average peak spectral levels were higher in Blackwall Reach than Mosman Bay in 2010 and higher in Mosman Bay in 2011 suggesting that not only were fish calling for longer, but also that more fish were at the respective sites during this time. Additionally, the peaks at each site occurred after high tide and while there were relatively few data points (roughly two months in each year), a relationship between the timing of peak calling and time of high tide was apparent (Figure 20). The Garden Island chorus, however, while of similar spectral levels to those of the Swan River choruses, occurred later in almost all cases (Figure 20).

These findings show that while the region between Blackwall Reach and Mosman Bay houses the highest numbers of calling mulloway there can be significant movement of the centre of the aggregation around this area. This has significant implications for sampling and that to provide a full estimate of calling fish within the river requires more than one sampling point.

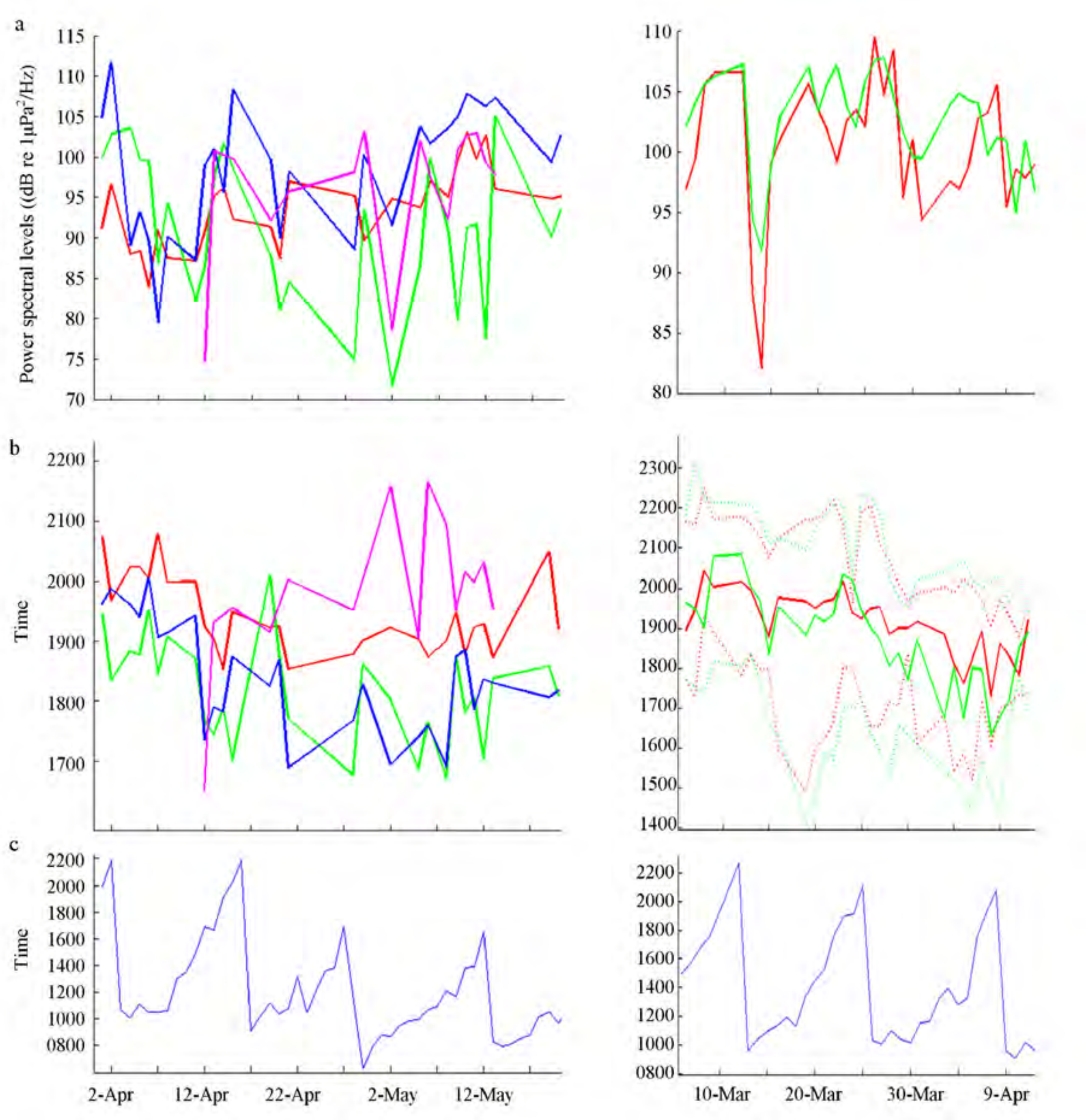

Figure 20. Power spectral levels over the 150-500 Hz bandwidth (a), time of peak calling (b) and time of high tide (c) for each of the defined choruses during the deployments in 2011 (left) and 2010 (right). Locations are shown in red (Mosman Bay), blue (Coombe Reserve), green (Blackwall Reach) and magenta (Garden Island).

7.1.6 Long-term trends in sound production

Sound production by fish has been shown to be indicative of circadian rhythms for a species and some environmental-related trends in mulloway vocal behaviour *in aquaria* have previously been reported (Ueng and Huang., 1998). However, captivity has been shown to affect calling behaviour from that exhibited in the wild (Midling et al., 2002).

Each acoustic dataset from Mosman Bay showed evidence of mulloway choruses over the summer and can be seen in stacked spectrograms, during periods of high spectral levels (Figure 21). The mulloway choruses are highlighted in Figure 21 by the intense red areas, including horizontal lines of “sidebands of amplitude modulation” at frequencies typical of mulloway calls between 100 and 1000 Hz. Varying sources of anthropogenic noise were distinguishable over a similar frequency band. Vessel noise typically occurred prior to, and overlapping with, fish vocalisation, such that mulloway calls were often masked. Acoustic characteristics of vessel noise features on spectrographic figures have been well documented. Vessel propeller cavitation and engine noise leave a signature horizontal line of noise on high temporal resolution spectrograms at the characteristic frequency of the engine (Parsons *et al.*, 2006a). If time averaged, over a longer period (for example 5 minutes), the additional SPLs of the passing vessel leave tonals across the associated frequencies (Figure 5, local pre-chorus peaks and Figure 21, thin vertical light blue/yellow/red lines). Noise was observed between 15 and 25 Hz (Figure 21), similar to that of peak hour traffic on a nearby highway and the local train timetable. This energy was speculated to arrive in the river via coupling through the local limestone bed (R. McCauley, Curtin University, *pers. comm.*). Vessel noise was significantly more prevalent over the weekend.

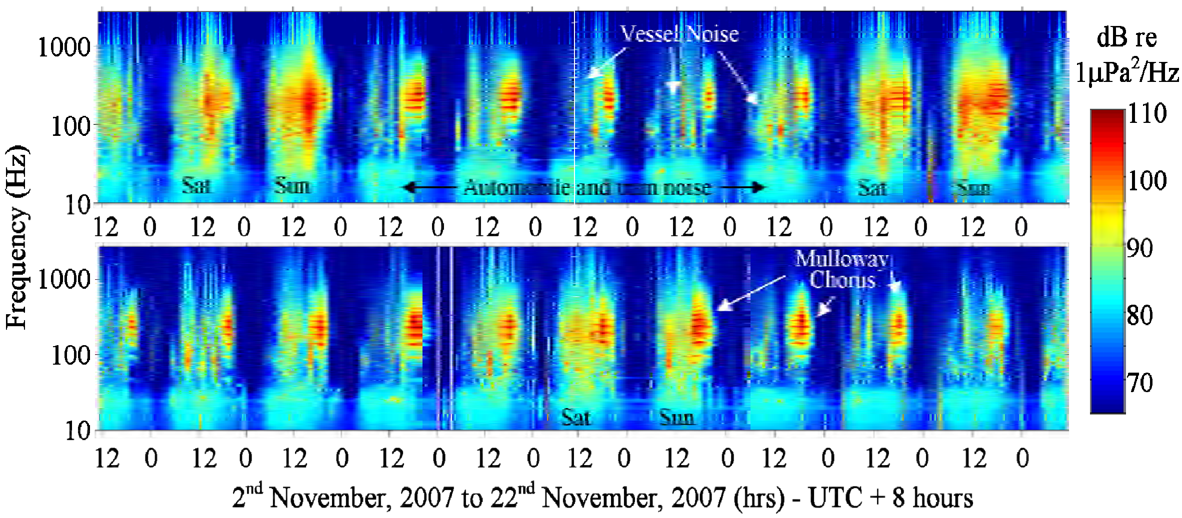

Figure 21. Stacked spectrograms of five minute samples on logarithmic frequency scale from 2nd – 22nd November, 2007 with spectral levels as per the colour bar. Typical evidence of mulloway calls, vessel, automobile and train sounds are highlighted. Saturdays and Sundays exhibiting extensive vessel noise are marked.

Daily peak spectral levels at Mosman Bay occurred predominantly approximately one hour after sunset, as shown by Figure 22a, which also shows effect of weekend vessel noise at chorus time by its difference with Figure 22b. Weekend noise (Figure 22b dotted lines) can significantly increase spectral levels in the hours before sunset, when compared to spectral levels on weekdays (continuous lines). While examination confirmed masking of early evening calls during periods of vessel noise there was little effect on overall fish spectral levels recorded later in the day, as measured by the 250 Hz centred, one third octave (Figure 22b). These responses highlighted the necessity to limit the tested period to one hour prior to sunset for vessel presence, while confirming that the four hour period (one hour prior to three hours post sunset) encompassed greater than 95% of the total sound production.

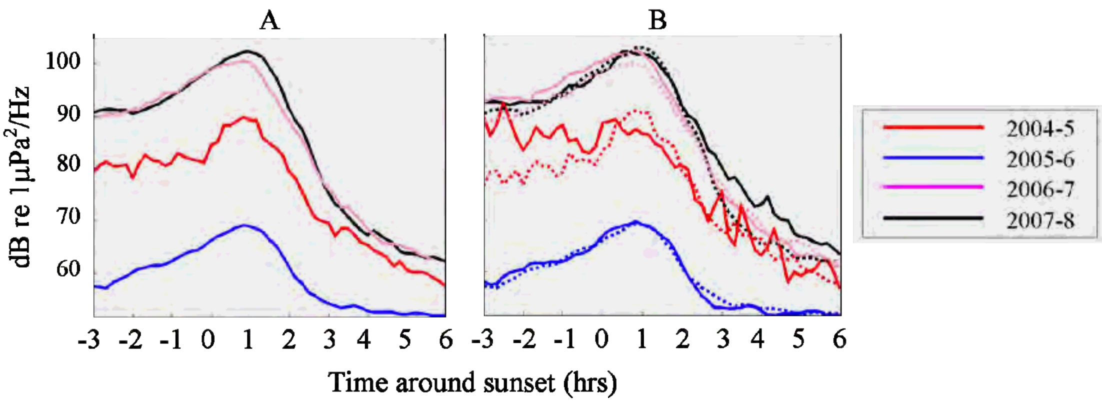

*Figure 22. Average spectral levels from seasonal acoustic recordings, zeroed around sunset. All sound production (a). Monday-Friday (dotted line) and weekend (solid line) sound production (b). Spawning seasons are identified by colour. *A failure in the hydrophone connector produced an offset in the overall levels of the data collected in the 2005-6 season.*

Figure 23 displays the time-averaged spectral levels in Mosman Bay over evening spawning cycles from one hour prior to three hours post sunset over the eight spawning seasons. The datasets were synchronised to the October full moon for inter-season comparison, rather than the Gregorian calendar. Where the datasets have been acquired early enough in the season the arrival of the choruses can be detected and, by proxy, the spawning season (Figure 23, magenta, black and beige lines). Single-evening recordings taken in late September and early October of the 2006-7 and 2007-8 seasons displayed little or no aural/spectral evidence of fish vocalisations illustrating that the low levels recorded in the evening are due to a lack of chorus (and not a lack of vessel noise). After the full moon in October, and once water temperature had exceeded 18.5° C, choruse related spectral levels increased rapidly (30 to 40 dB re 1µPa^2/Hz) in October/November, (Figure 24). While the choruses develop quite quickly, the cessation at the end of the season appears to occur over a more prolonged period, and a defined drop in chorus levels is more difficult to discern (Figure 23, right hand side of all lines). Overall, the highest chorus levels occurred between late November and early January, typically followed by a drop-off in January or February. It is inferred that this is because less fish are present in Mosman Bay, rather than because less fish are calling. In 2005-6, 2006-7, 2008-9, 2009-10 and

2011-12 there is another increase between February and April. These changes indicate that either the fish are not around Mosman Bay during the period of low sound levels or they cease calling for some reason. Due to the underwater connector failure, spectral levels of the 2005-6 season are currently not comparable to recorded levels of other seasons, though the trends are in sound production within the season are likely to be reflective of the variation in calling fish.

Comparing the spectral levels with individual drivers, it can be seen that significant variations variables such as temperature, salinity, dissolved O_2 and pH (Figure 24) occur at the same time as similar variations in the spectral levels. It is also possible to see a weak semi-lunar pattern in many of the recordings (Figure 24, blue line 2005-6 season). While individually these correlates may describe short-term trends in the chorus levels they do not explain all the variation.

Peak spectral levels of 113 dB re 1 μPa^2/Hz in December of the 2009-10 and 2010-11 seasons were comparable with 111 dB re 1 μPa^2/Hz for the same period in the 2006-7 season and 110 dB re 1 μPa^2/Hz in 2007-8 (Figure 23C, pink and black lines, respectively). By comparison, the 2011-12 season peaked at 112 dB re 1 μPa^2/Hz in February (Figure 23). This indicates that the greatest number of fish were present for the longest period in the 2009-10 and 2010-11 seasons.

High correlations between mean chorus levels around sunset and the peak chorus levels (R^2 = 0.93, 0.87, 0.77, 0.81, 0.79, 0.62, 0.83 and 0.89 for the consecutive spawning seasons), confirm that the observed peak choruses were due to fish vocalisations, rather than vessel noise. SPL spikes due to vessel noise would skew the sound production curve towards the time of vessel noise, with unrealistically high values and therefore lead to a lower correlation.

The correlation and explained deviance displayed by the final chosen Generalised Additive Models (GAMs) for each spawning season can be seen in Table 9. In each case a significant proportion of deviance was accounted for (all adjusted D^2 values were greater than 0.58 and 0.52 for mean chorus levels and peak chorus time respectively).

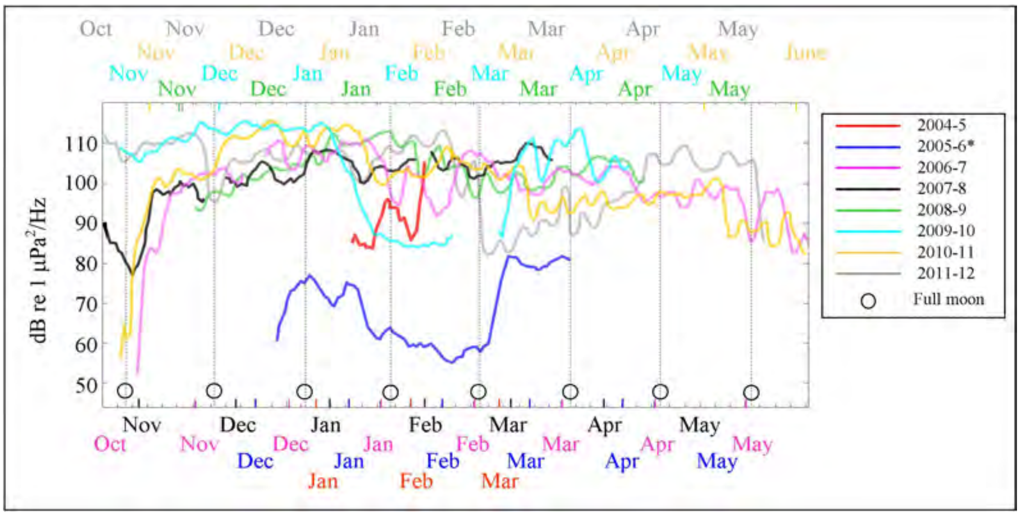

Figure 23. *Two-day averaged power spectral levels for the 250 Hz centred one-third octave across one hour prior and three hours post sunset across the eight spawning seasons (2004-5, 2005-6, 2006-7, 2007-8, 2008-9, 2009-10, 2010-11 and 2011-12 years shown by red, blue, magenta, black, green, cyan, brown and grey lines, respectively). All datasets have been synchronised to the October full moon with the Gregorian calendar shown in the colour of each respective spawning season. *A fault in the 2005-6 deployment means that only trends (rather than values) may be compared.*

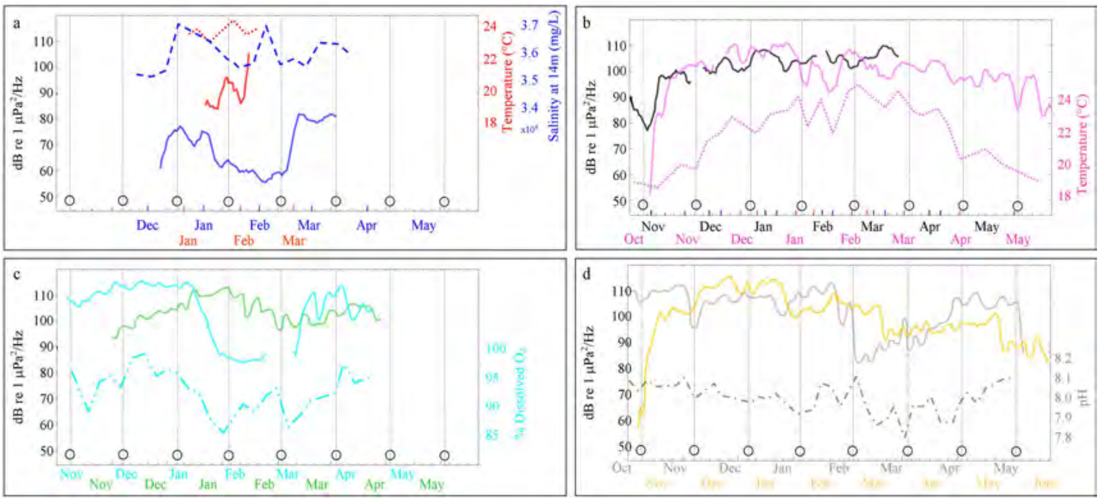

Figure 24. *Average spectral levels of the Mosman Bay mulloway chorus for the four hours around sunset for the 2004-5 (red) and 2005-6 (blue) seasons (a), 2006-7(magenta) and 2007-8 (black) seasons (b), 2008-9 (green) and 2009-10 (cyan) seasons (c), 2010-11 (beige) and 2011-12 (grey) seasons (d). Example trends of environmental variables that displayed trends similar to those of the spectral levels (temperature - dotted lines, salinity – dashed lines, pH – dot dashed line and dissolved oxygen – dot dot dashed lines) have been shown in several years.*

Table 9. Overall deviance explained (D^2), adjusted D^2 (adj D^2) and correlation values (cor) for each of the three tested mulloway spawning season GAMs run with mean chorus spectral levels around sunset, peak chorus levels and the time of peak chorus.

		Mean chorus spectral level around sunset (dB re 1µPa^2/Hz)	Time of peak chorus	Maximum Chorus SPL (dB re 1µPa)
2005-6 (n=98)	D^2	0.79	0.56	0.79
	adj D^2	0.77	0.52	0.77
	cor	0.80	0.64	0.75
2006-7 (n=149)	D^2	0.64	0.75	0.77
	adj D^2	0.63	0.74	0.76
	cor	0.80	0.86	0.84
2007-8 (n=222)	D^2	0.85	0.75	0.77
	adj D^2	0.64	0.73	0.76
	cor	0.88	0.87	0.75
2008-9 (n=197)	D^2	0.87	0.74	0.84
	adj D^2	0.73	0.71	0.60
	cor	0.88	0.72	0.79
2009-10 (n=234)	D^2	0.79	0.64	0.64
	adj D^2	0.65	0.52	0.61
	cor	0.63	0.64	0.78
20010-11 (n=165)	D^2	0.71	0.65	0.68
	adj D^2	0.62	0.63	0.67
	cor	0.71	0.68	0.70

The most parsimonious GAMs determined five descriptors that contributed most significantly to explained deviance in chorus levels. Figure 25 shows the selected GAMs with the explained deviance by each descriptor alone and their respective contributions to the models overall explained deviance. Temperature, salinity and sunset explained the most deviance in the spectral levels, but tidal range and levels, dissolved O_2 and pH also contributed significantly in some years. Individually, temperature and salinity explained similar levels of deviance (Figure 25, potential contributions). However, the fact that both contributed significantly to the selected model suggest that the descriptors were, to an extent, correlated with different aspects of the chorus variation.

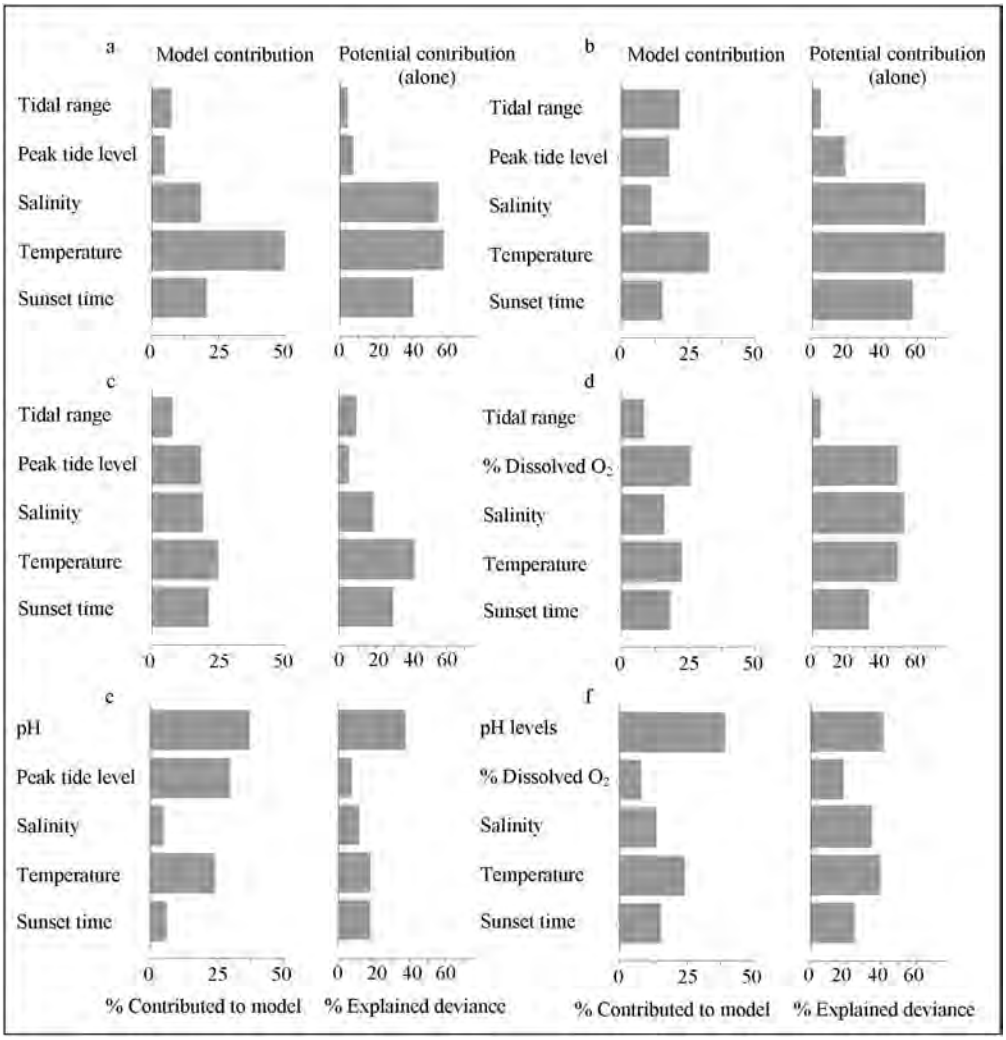

Figure 25. Correlations of AIC selected descriptor variables to recorded mean received levels during the four hours around sunset as a percentage of their relative contributions to the model and the explained deviance if the variable were considered alone in the most parsimonious Generalised Additive Model for the 2006-7 (a), 2007-8 (b), 2008-9 (c), 2009-10 (d), 2010-11 (e) and 2011-12 (f) spawning seasons.

As an example, the response curves for each selected variable in the 2006-7 model for mean spectral levels around sunset are shown in Figure 26. These show that the model displayed best responses to temperatures above 20 °C, salinity between 34,500 and 36,800 mg/L, sunset earlier than 18:45, and high peak tides of low tidal range. The sunset time response curve appears counter intuitive, in that later sunset (associated with summer) were expected to be positively correlated with sound production. In fact, it has been inferred that, during the summer (later time of sunset), variations in temperature and salinity provide a better explanation of the deviance, while the sunset time explained a higher proportion of the deviance during early and later months.

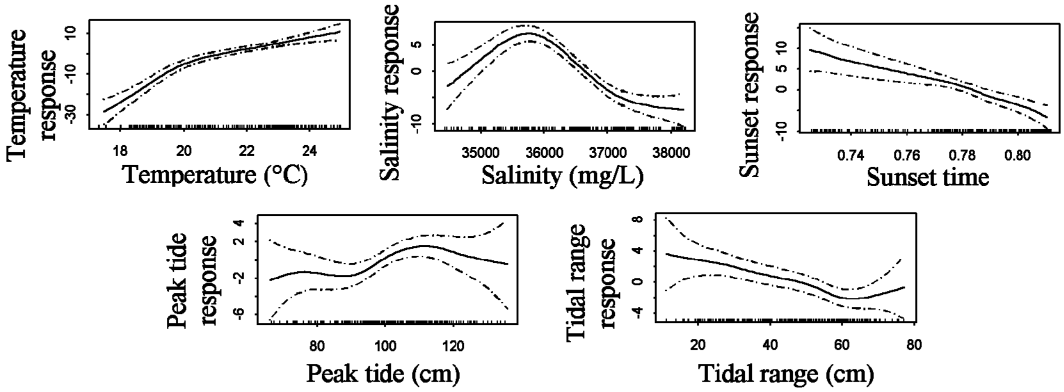

Figure 26. Response curves (continuous lines) and 95% confidence limits for the AIC selected descriptor variables for the 2006-7 season for the Generalised Additive Model shown in Figure 25.

Notably, the GAM for the 2005-6 season, was covering a significantly shorter period than other years, also selected the lunar phase as a contributor to the explained deviance. The model illustrated semi-lunar spawning behaviour, explaining deviance well at the new and full moons. A similar, but simpler, model was generated for the daily peak time of the chorus. During the 2006-7 spawning season, for example the final model determined that only the time of sunset, temperature and salinity, in descending order of contribution, explained the deviance in the peak calling times, as shown in Figure 27a and b. Maximum chorus times related most to later sunset, temperatures below 19 °C and above 21 °C, and low levels of salinity, explaining nearly 75% of the deviance in time of maximum spectral levels (Figure 27c).

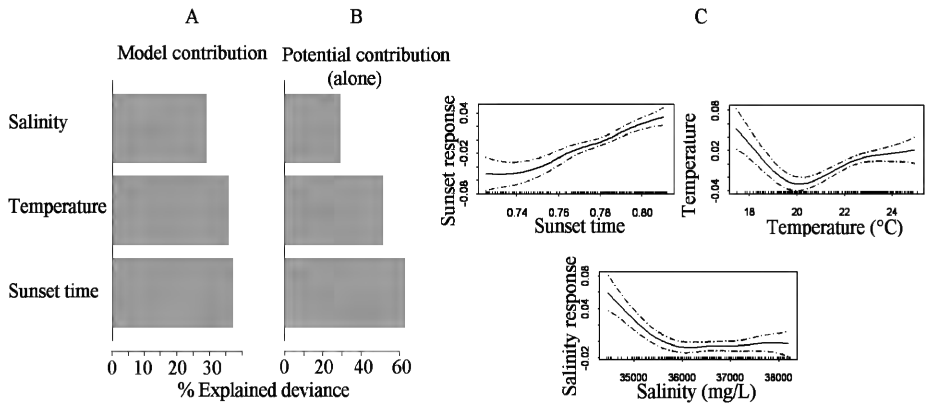

Figure 27. Correlations of AIC selected descriptor variables with the time of peak chorus as individual correlates (a) and their relative contributions to explained deviance in the best Generalised Additive Model (b) together with the response curves for the 2006-7 spawning season (c).

Similar to the GAM describing mean sound production (Figure 26), not all of the deviance in peak chorus time was explained (Table 9). The models appeared to better explain broad-scale temporal trends. Shorter trends were also observed in the data, similar to the trend within the declining spectral levels of the 2005-6 season, peaking at the full and new moon (Figure 23c, blue line). The GAM model trend was removed from month long sections of data in each season. Standardised residuals were positively correlated with the new and full moons in seasons between 2006-7 and 2009-10 (R^2 = 0.65, 0.69, 0.62 and 0.64), but less so in the last two seasons (R^2 = 0.55, 0.52). Evidence of these semi-lunar cycles can be seen in the spectral levels zeroed around sunset, in Figure 28, when compared with the difference between high tide time and sunset (white line). This displays how, in an approximately two week cycle, the peak of the chorus occured later, longer after sunset, where each successive cycle occurred later in the day than the previous one as summer approached and earlier (closer to the time of sunset) as autumn approached (Figure 28).

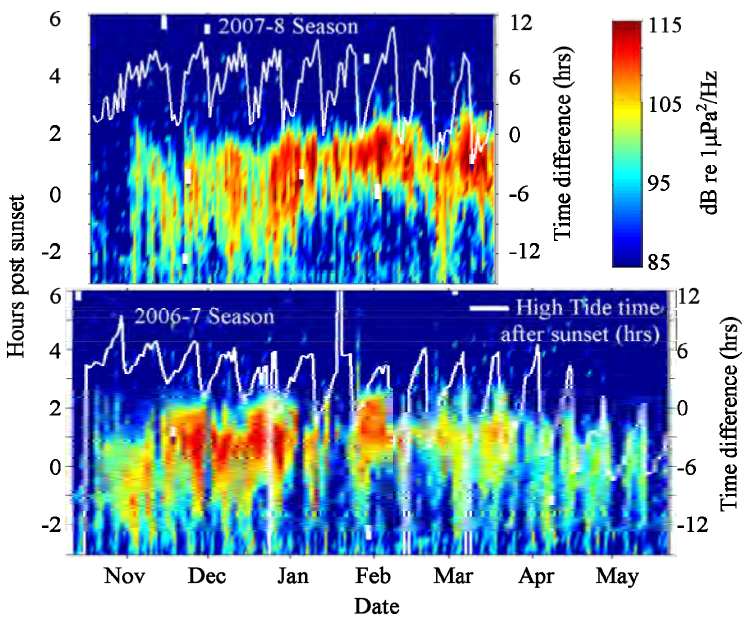

Figure 28. Spectral levels zeroed around sunset times for the 2006-7 and 2007-8 mulloway datasets. Time difference between sunset and high tide in hours is displayed by continuous white line.

The greatest variation in SPLs over consecutive days was 24 dB re 1μPa with the maximum variation in peak chorus time being 2.2 hours (s.d. = 28 mins), but these didn't necessarily correspond to a similar variation in the environmental predictor variables. Local spectral levels maxima occurred every 3.89 days (s.d. = 1.93, max = 10, min = 2) across all seasons, similar to the variation in days between maximum egg counts observed from mulloway broodstock *in aquaria* (author pers.obs.)

It was not only the chorus levels and timing that varied throughout the season, but also the spectral peak frequency of the calls (Figure 29). Correlations were comparatively low, likely due to the significant variation in call frequency (R^2 = 0.516 and 0.415 for 2006-7 and 2007-8 seasons, respectively), however, an increase in water temperature in both seasons occurred with an increase in average call spectral peak frequency over the evening's calling (Figure 30).

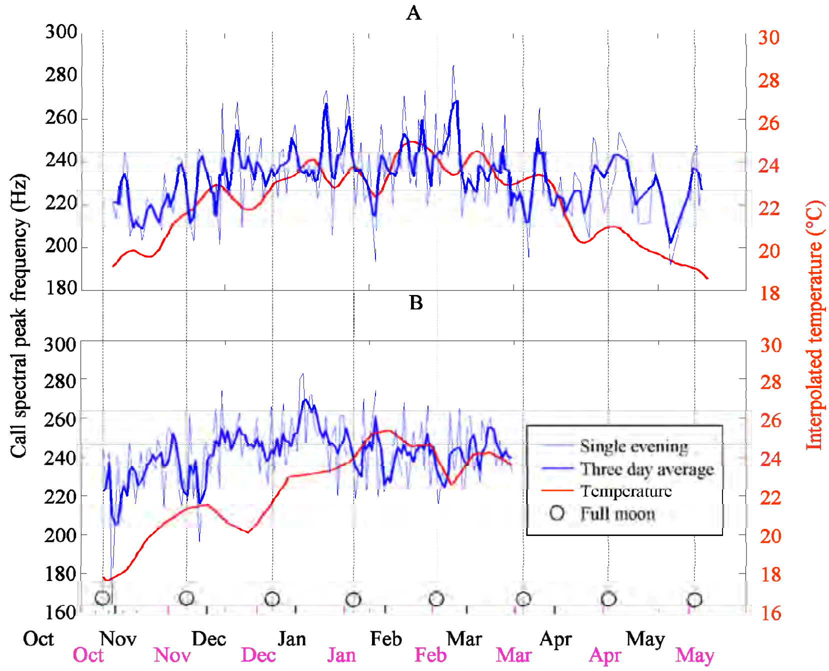

Figure 29. Variation of spectral peak frequency throughout the 2006-7 (a, pink dates)) and 2007-8 (b, black dates) spawning seasons with the associated temperature trends.

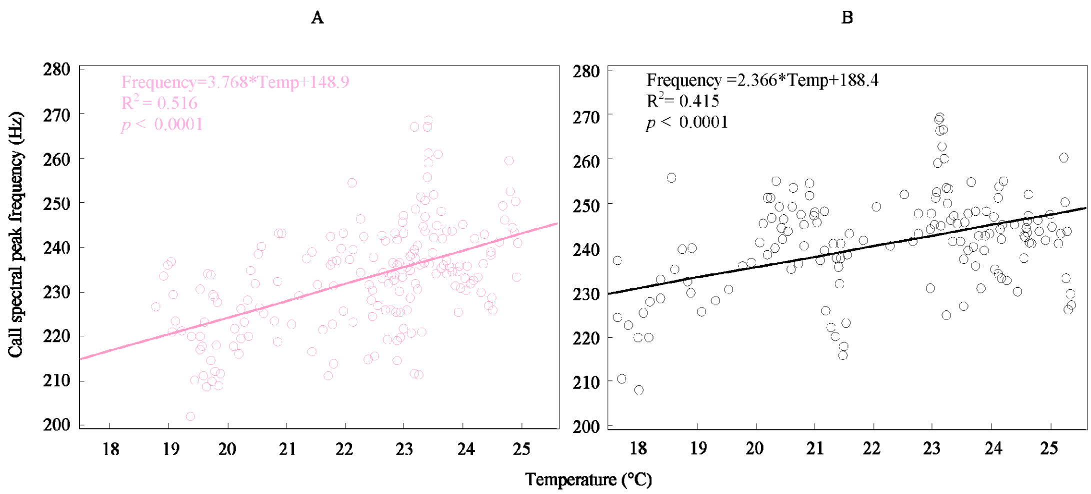

Figure 30. Relationships between call spectral peak frequency and temperature during the 2006-7 (a) and 2007-8 (b) spawning seasons.

7.1.7 Mulloway call source levels

In 2009, Parsons *et al.* localised 213 mulloway calls (65 and 148 Category 1 and 2 calls, respectively) using a hydrophone array. Of these calls, 53 Category 1 and 112 Category 2 calls, at ranges of approximately 20 to 100 m, contained sufficient noise sample points and offered signals of sufficient clarity to determine RLs due to the call. One tracked fish produced 65 Category 2 calls during a 4-minute period for SPL analysis. Table 10 (Parsons et al. 2012c) displays the regression-determined transmission losses and SLs of each call category.

Table 10. Extrapolated call sources levels for each category of mulloway call from least squares linear regression. Values display SPL source levels and equivalent spreading losses together with 95% confidence limits and the curve correlation with data points. (Parsons et al. 2012c)

Call Category		Orientation	Number Calls	Source Level (dB re 1 µPa) (± 95% confidence limits)	Transmission Loss (log(r)) (± 95% confidence limits)	R^2
Category 1	All	N/A	53	163 (148, 179)	-25.39 (-35, -16)	0.42
Category 2	Individual	N/A	65	172 (163, 180)	-23.94 (-30, -17)	0.61
	All	N/A	112	172 (168, 176)	-23.74 (-26, -22)	0.82
Category 3	All	N/A	28	157 (152, 162)	-23.04 (-27, -19)	0.88
	One pulse	Towards	7	156 (151, 162)	-18.67 (-26, -11)	0.89
		Away	4	152 (144, 159)	-19.17 (-27, -11)	0.98
	Two pulse	Towards	3	163 (98, 227)	-27.53 (-102, 47)	0.96
		Away	10	154 (150, 158)	-18.81 (-24, -14)	0.93

Transmission loss with range for the analysed Category 1 calls can be seen by the modelled regression lines in Figure 31. These calls often varied, not only in the number of pulses, but in the amplitude of those pulses. The maximum amplitude of the first pulse in Category 1 calls was frequently less than 80% of that of the second pulse. The linear regression of RLs from all the 53 Category 1 calls produced a SL of 163 ±16 dB re 1µPa at 1 m and estimated spreading losses of 25.4 $\log_{(10)}(r)$ (Figure 31 and Table 10) more closely resembling that of spherical spreading than cylindrical spreading (Parsons *et al*., 2012c).

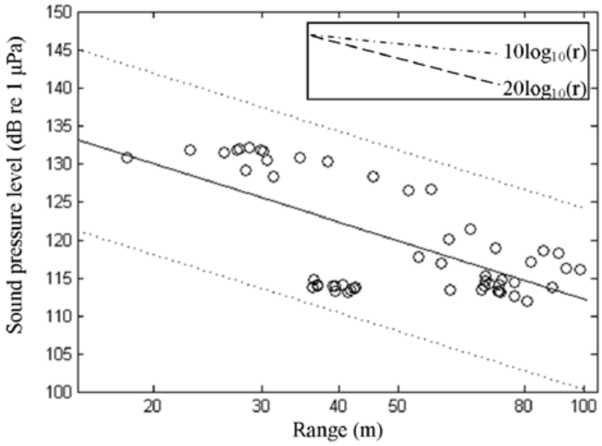

Figure 31. Detected sound pressure levels (dB re 1µPa) with range (log scale) for 53 Category 1 calls. Continuous line illustrates linear regression model of transmission losses with 95% confidence limits of source level shown (dotted lines). Example cylindrical ($10log_{10}r$) and spherical ($20log_{10}r$) spreading losses are shown in the inset. (Figure taken from Parsons et al., 2012c)

Least squares linear regression determined that the Category 2 call SL was 172 ± 3.6 dB re 1µPa (Table 10). There was less variation in the regression-calculated SL of the Category 2 calls, compared with the Category 1 calls (Figure 32, R^2 = 0.82). However, similar to Category 1 calls, the Category 2 call transmission losses more closely resembled spherical than cylindrical spreading losses (Figure 32, continuous, dash and dot-dashed lines, respectively).

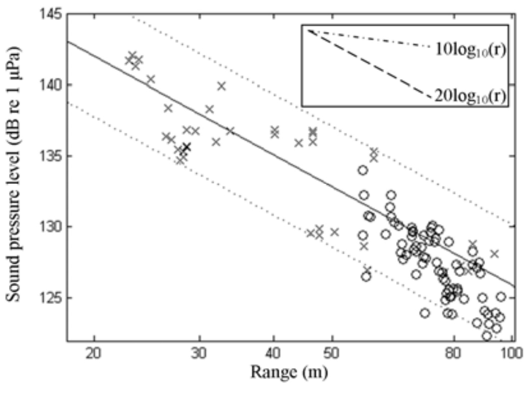

Figure 32. Detected sound pressure levels (dB re 1µPa) with range (log scale) for Category 2 calls. Calls of a tracked individual fish (○) and those of all remaining fish (x) are shown. Continuous line marks the linear regression determined transmission losses with 95% confidence limits (dotted lines). Example cylindrical ($10log_{10}r$) and spherical ($20log_{10}r$) spreading losses are shown in the inset. (Figure taken from Parsons et al., 2012c)

In one recording an individual fish approached the hydrophone emitting Category 3 calls. Its range was determined by geometry from the difference in arrival-time of the direct and surface reflected call waveforms (Parsons *et al*., 2012c). As one call was located less than 1.6 m of the hydrophone the fish was deemed to have been swimming close to the riverbed and then assumed to remain at that depth for the preceding and following seconds. Localization of Category 2 calls has shown that they were generally emitted from positions on, or near, the riverbed (Parsons *et al.,* 2009). The individual fish provided both single (n = 11) and double (n = 17) pulse calls for SL analysis, at a variety of ranges up to 16 m (Parsons *et al*., 2012c).

Parsons *et al*. (2012c) assumed that the fish remained in the same orientation throughout its calls, as it swam past the hydrophone, providing a comparison of SL between orientations of towards and away. The steady call rate with range suggested a direct route at approximately 0.5 ms^{-1} was taken and the fish assumed to be directed towards the hydrophone (Parsons *et al*., 2012c). Figure 33 displays the RLs with range for the fish swimming towards and past the hydrophone. The 'o' and 'x' markers indicate calls comprising 1 and 2 pulses respectively, emitted as the fish approached and departed. Least-squares regression curves and 95% confidence limits for Category 3 calls are shown in Figure 33 by continuous and dotted lines respectively.

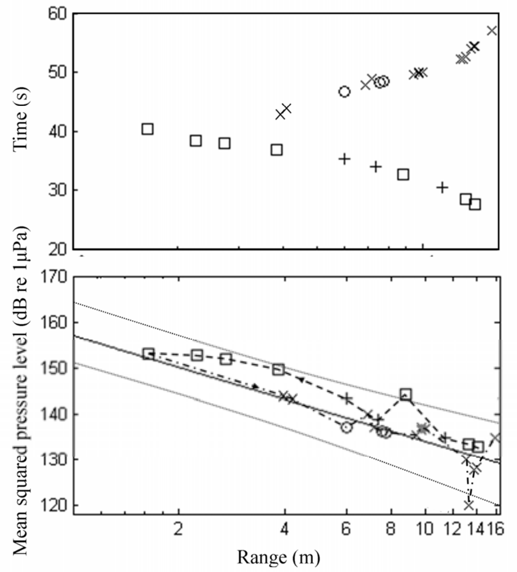

Figure 33. Time of fish calls with range ($log_{10}(r)$) (top) highlighting the order of one-pulse (o and □) and two-pulse (x and +) Category 3 calls. Sound pressure levels (dB re 1μPa) against range (log scale) (bottom) as the fish approached (□ and +, dashed line) and passed (o and x, dot-dashed line) the hydrophone. Positions of the o, □, x and + illustrate whether the fish was orientated towards or away from the hydrophone and whether the call was a single or double pulse call. Least squares regression curve and 95% confidence limits are shown by the continuous and dotted lines respectively. The order of calls is indicated by arrows. Calls not suitable for range analysis have been omitted. (Figure taken from Parsons et al., 2012c)

The regression model for all Category 3 calls estimated a SL of 157 ± 5.2 dB re 1µPa at 1 m, lower than both Category 1 and 2 calls and greater when comprising two pulses than one pulse (Parsons *et al*., 2012c). In both types of call the SLs were greater with fish facing towards the hydrophone, however, given the small sample size this is not statistically significant. Figure 34 shows the distribution of SLs for each category based on the determined transmission losses to the receiver for each category, which were back-calculated from the recorded SPLs and range.

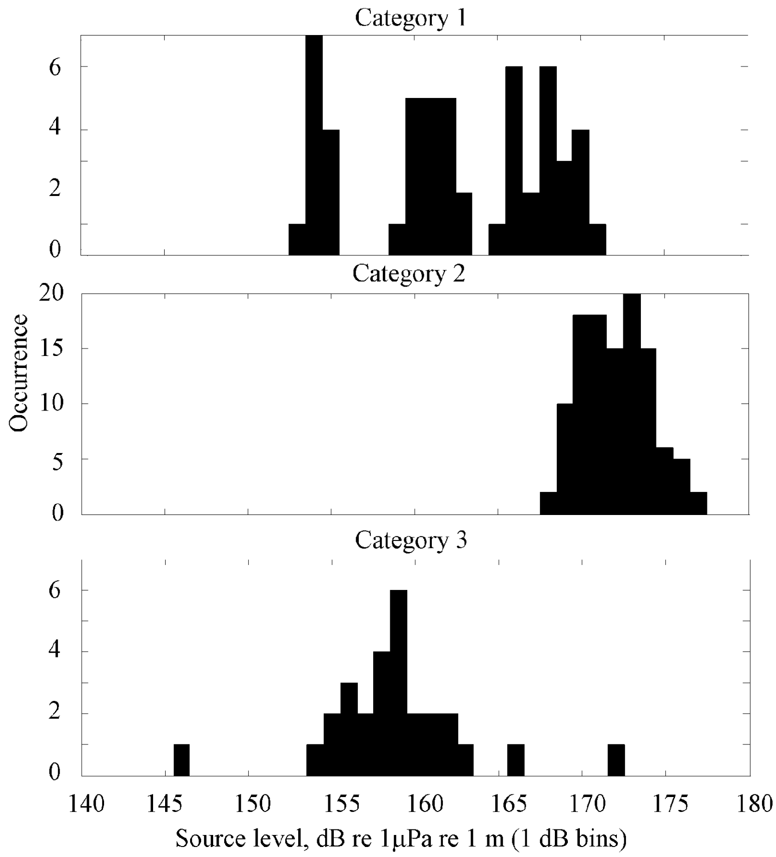

Figure 34. Distribution of source levels (dB re 1µPa at 1 m) for each mulloway call category from recorded SPLs based on the estimated transmission losses only. (Figure taken from Parsons et al., 2012c)

Regression models were also determined for the SEL and peak-to-peak pressure SLs for each category (Table 11). Root-mean-square SPL (dB re 1 µPa) is equivalent to the SEL (dB re 1 µPa^2.s) minus 10log$_{(10)}$(call length) and therefore the difference between SPL and SEL of a single call is determined by the call lengths (Parsons *et al*., 2012c).

Table 11. Values of source levels with standard deviation, based on recorded values. Source levels (dB re 1µPa at 1 m) using 20log$_{(10)}$(r) losses are shown. Data is also for three types of source level as they are often reported (SPL, SEL equivalent energy and peak-to-peak pressures). For each method and call category the calculated source level, transmission loss curve constant and correlation coefficient are shown. Mean call lengths for each category are also shown. Table taken from Parsons et al. (2012c)

		Call Category 1	Call Category 2	Call Category 3
Source level (dB re 1µPa) 20log(r) transmission loss (s.d.)		153 (6)	165 (2)	156 (4)
Sound pressure level (dB re 1µPa at 1 m)	Source level (95% c.l.)	163 (148, 179)	172 (168, 176)	157 (152, 162)
	Transmission loss (log$_{(10)}$(r)) (95% c.l.)	-25.4 (-34.6, -16.2)	-23.7 (-25.9, -21.6)	-23.0 (-26.6, -19.5)
	R^2	(0.42)	(0.82)	(0.88)
SEL (dB re 1µPa^2.s at 1 m)	Source level (95% c.l.)	152 (138, 166)	165 (156, 173)	136 (132, 139)
	Transmission loss (log$_{(10)}$ (r)) (95% c.l.)	-22.9 (-31.1, -14.6)	-21.8 (-27.2, -16.5)	-17.4 (-21.2, -13.5)
	R^2	(0.64)	(0.64)	(0.74)
Peak-peak pressure (dB re 1µPa at 1 m)	Source level (95% c.l.)	183 (173, 195)	194 (189, 201)	167 (165, 170)
	Transmission loss (log$_{(10)}$ (r)) (95% c.l.)	-25.2 (-31.7, -18.6)	-27.2 (-30.8, -23.6)	-16.1 (-18.8, -13.5)
	R^2	(0.77)	(0.86)	(0.83)
Mean call length (s) (s.d.)		0.054 (0.021)	0.346 (0.063)	0.018 (0.015)

The lowest ambient noise levels during the course of these recordings were at 108 dB re 1µPa. However, the maximum noise levels detected during recordings in this study included vessel traffic or calling mulloway and reached 148 dB re 1µPa. Background noise is one of the defining factors that determine call detection range for both intended recipient and observer (Urick, 1983, Sprague and Luczkovich, 2004). As a simple comparison, the range at which the signal would attenuate to background noise levels (based on the regression estimated loss and also using spherical spreading as the loss) was estimated for each call category and the two example ambient noise levels (Table 12). This does not use statistical analysis of the probability of signal detection or account for fish hearing critical ratios and so should not be used as an estimation of the ranges over which fish may detect calls. It does show, however, that a call that may be detected at several hundred metres in low ambient noise may only be detected at less than 10 m if a powered vessel is passing close by.

Table 12. Coarse estimates of detection range (r) for all call categories (using basic signal processing) during two levels of background noise (110 and 150 dB re 1µPa), calculated by assuming the regression calculated TL determined from the data and losses due only to spherical spreading. Call/vessel noise energy was computed over broadband spectra. As this calculation does not account for critical hearing ratios, frequency bandwidths used by mulloway to detect calls and no probability of signal detection has been applied, this is a simple calculation of the range at which the signal attenuates to background noise levels. (Table taken from Parsons et al., 2012c)

		Detection Range (m)			
		Regression calculated transmission loss and noise levels (dB re 1µPa)		Spherical transmission loss and noise levels (dB re 1µPa)	
Call Category	Source level (dB re 1µPa at 1 m)	110	150	110	150
1	163	123	3	231	2
2	172	396	8	660	7
3	157	112	2	117	1

7.1.8 Estimating call numbers from a single hydrophone

To estimate the mulloway chorus SPLs it is necessary to remove the background noise levels. Periods of ambient noise without mulloway calls or passing vessel were found to differ very little in SPLs throughout the evening, However predominant noise variations were due to the presence of distant vessels. It was only in the late evening, once nearly all vessel noise ceased, that evidence of shrimp clicks became commonplace and background noise reduced to a minimum of 87 dB re 1µPa, in comparison with nearly 112 dB re 1µPa, early in the evening. The presence of vessel noise was accounted for in chorus level analysis by either elimination of the period including vessel noise from the segment, or rejection of the segment altogether. When calling density was such that all calls merged, the contribution of vessel noise to overall SPLs was complex to determine precisely, thus an estimate of vessel noise was made from aural scrutiny.

During segments where calls could be discriminated from each other, comparing direct counts of audible calls with counts from visual scrutiny of waveform and spectrograms, produced similar estimates of total call numbers, with a mean difference of -1.6 (s.d. = 0.07, max. = 13, n = 31). Figure 35 shows 30 s samples from four segments recorded throughout the evening. The cumulative energy from six distant calls (a), seven calling fish; including one at approximately 30 m range (b), many calling fish at varying ranges upwards of 50 m (c), and multiple shrimps clicks with distant mulloway Category 1 short calls (d) show the difference in SPLs generated by different combinations of calling fish.

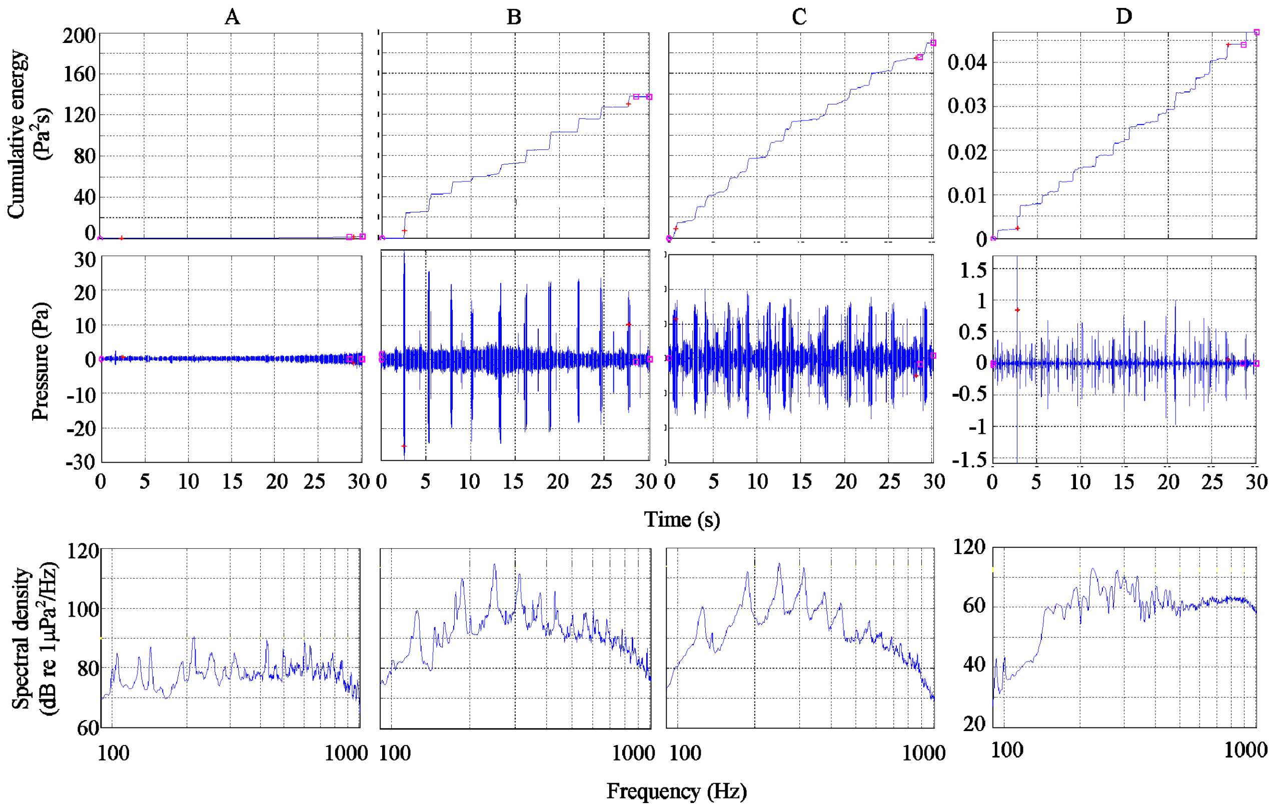

Figure 35. Cumulative energy (top), waveform (middle) and power spectral density (bottom) from thirty second periods of: A) few vocalising fish at 17:00; B) vessel noise interrupting vocalising fish (one fish at 25-35 m range) at 19:00; C) high density of calling fish at > 35 m range where calls overlap and background noise is dominated by distant fish calls at 22:30; D) no vessel noise, many distant Category 1 calls at similar maximum amplitudes to several shrimp clicks.

The SPLs, total number of calls and estimated number of individual fish calling (where determined) in each segment are shown in Figure 36 (Parsons, 2010). Between 18:30 and 19:00 the number of calling individuals and total calls observed was only 7 to 10 callers emitting 135 to 245 calls. However, between 19:00 and 20:00 SPLs increased as the calling fish came within 50 m of the hydrophone (Figure 36). At 19:00 a single fish, calling at approximately 30 m range appeared and SPLs rose sharply to 127 dB re 1μPa. While other fish maintained relatively consistent ranges the nearer fish moved from approximately 30 to 60 m range and the SPLs dropped to 118 dB re 1μPa, illustrating the siginificant effect that range of a single caller with such a high SL as mulloway has on the overall SPLs. Such range effects are further highlighted by The green line in Figure 36 highlights this effect, showing the SPLs of the simulated caller in Figure 6, at 25, 50, 100 and 200 m ranges, as if it were calling consistently through a two minute segment at each range.

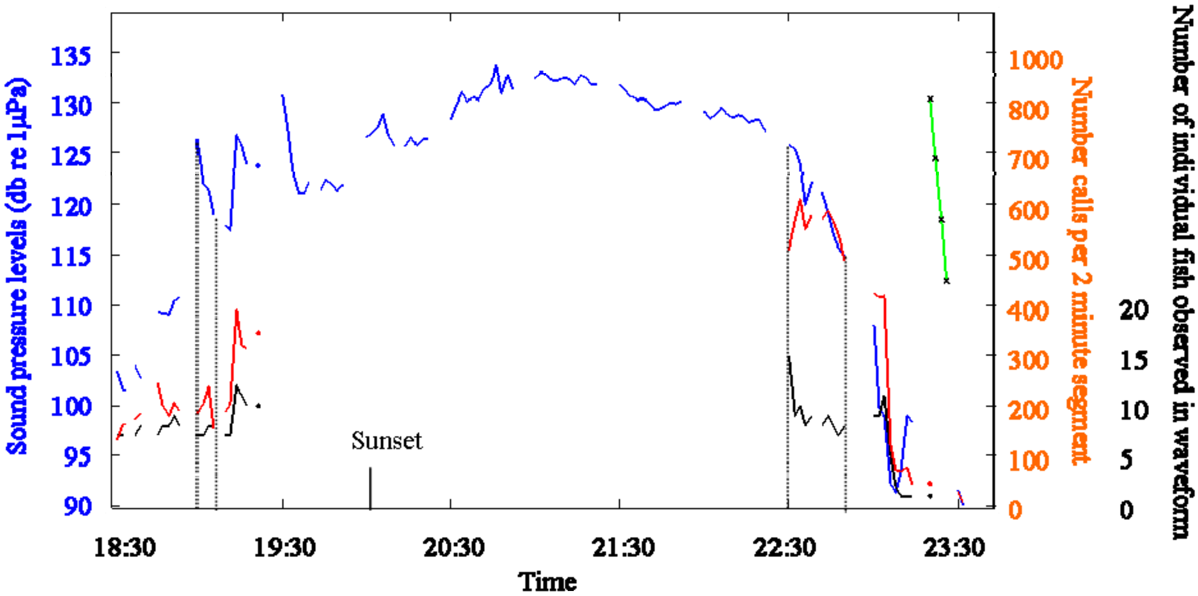

Figure 36. Sound pressure levels (blue), total number of recorded calls (red), and number of individual repetitively calling fish observed in the pressure waveforms (black) for each segment between 18:30 and 23:35. Times of interest are highlighted by dotted lines. The green line illustrates the variation in SPLs from a simulated Category 2, mulloway call repeated every 3.7 seconds throughout the two-minute segment at 25, 50, 100 and 200 m range (as the line moves from left to right).

SPLs remained consistently above 130 dB re 1μPa between 20:40 and 21:30, peaking approximately one hour after sunset. This period of peak calling was dominated by multiple calling fish rather than a single, close-range caller. However, during this period, calls overlapped and could not be counted individually, thus SPLs could not be related to the exact number of fish. At 22:18 Category 1 short calls appeared (or were no longer masked by the greater number of Category 2 calls) and by 22:30 dominated the waveforms. With no vessel noise at this time, and short call duration being less than 0.1 s, calls could be counted. Between 22:32 and 22:48 the number of callers and calls remained similar, while the SPLs dropped from 125 to 115 dB re 1μPa, as the fish range increased.

By 23:12 only one caller remained, emitting a short call every 2.15 s (s.d. = 1.3 s) over the two minutes, slowing to 2.93 s (s.d. = 1.6 s) between calls at 23:22. Despite the comparatively large abundance of calls, due to the higher call rates, the Category

1 short calls were estimated to be at ranges in excess of 400 m, generating lower SPLs than early evening Category 2 calls. At this time, biological noises from shrimp clicks were also prevalent, contributing to the cumulative energy Figure 7.

As in Section 6.2.3.4 callers were assumed to be stationary, of similar size (and therefore of similar SL), randomly distributed and calling at a constant rate. The total mean-squared pressure transmitted over the duty cycle of the call (T_{dc}), period from the start of one call to the start of the callers next call) will be equal to the total transmitted mean squared pressure multiplied by the ratio of call time to duty cycle time, given by:

$$\left\langle p^2 \right\rangle_{Total\,dc} = \left\langle p^2 \right\rangle_{Total\ transmit} . \frac{t_c}{T_{dc}} \qquad (13)$$

For an individual fish this can then be expanded to the whole two-minute segment to be analysed. From Parseval's theorem the overall received pressure from all callers is equal to the sum of the partial pressure (p_i) from each caller over the two-minute segment.

$$\left\langle p^2 \right\rangle_{\mathrm{Re}ceived} = \sum_{i=1}^{N} \left\langle p_i{}^2 \right\rangle_{Total\ i\ received} \qquad (14)$$

where N is the number of transmitters.

If the range is equal or less than the water depth then spherical spreading is used as a minimum estimate for transmission losses, which provide a reasonable estimate for these purposes, thus:

$$\left\langle p^2 \right\rangle_{Total\ i\ received} = \frac{1}{r^2} . \left\langle p^2 \right\rangle_{Total\ transmit} \qquad (15)$$

where r is the caller range. If the fish are randomly distributed then these last two equations become:

$$\left\langle p^2 \right\rangle_{\mathrm{Re}ceived} = \left\langle p^2 \right\rangle_{Total\,dc} . \sum_{i=1}^{N} \frac{1}{r_i^{\,2}} \qquad (16)$$

Due to transmission losses the number of callers required to create the same SPLs as a single caller at 1 m increases with range by a ratio of 4N for every doubling of the range, where N is the previous number of callers. This would mean, for example, that, assuming the calls are not in phase, the time-averaged, mean-squared received levels from one caller at 25 m range are the same as four callers at 50 m, or 16 and 64 callers at 100 and 200 m ranges respectively.

Figure 37 illustrates the received SPLs for segments where the number of calls and callers had been counted. There was also significant overlap between the SPLs received from a small number of callers and SPLs during peak calling. For example, within 95 % confidence limits a time averaged segment SPL of 130 dB re 1µPa could be explained by anything more than nine callers, as shown in Figure 37. The SPLs were therefore more dependent on the range of the callers than the number of them.

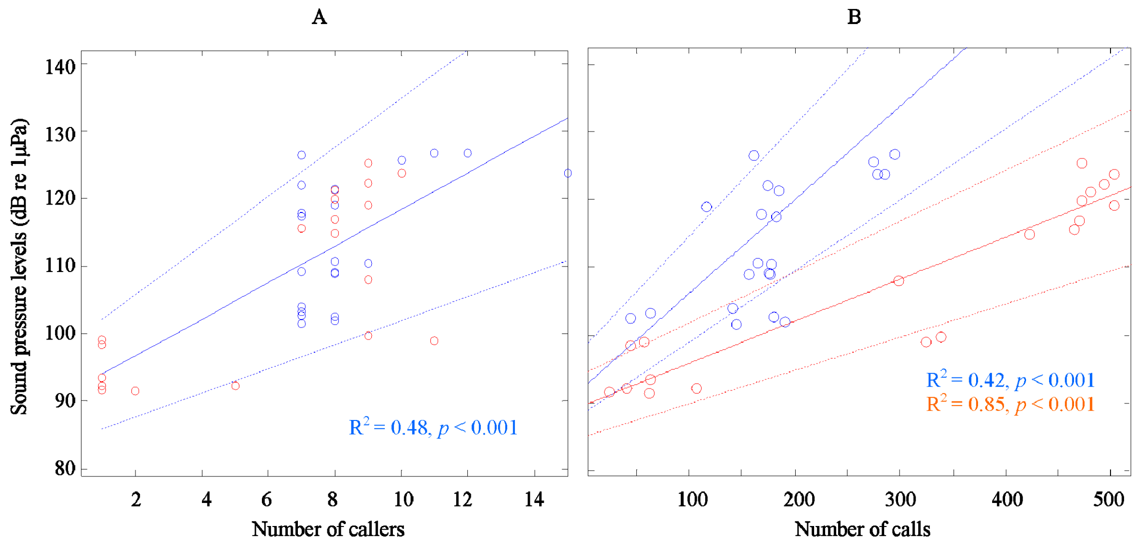

Figure 37. Sound pressure levels against the determined number of callers (A) and total number of calls (B) per segment during periods of low density Category 2 calling prior- (blue) and post- peak (red) chorus time. The mean trends (continuous line) with 95 % confidence limits (dotted line) are shown.

The two curves shown in Figure 37 represent the relationship between the number of callers (left) and the total number of calls (right) counted within each two-minute segment. The difference between the gradients of the pre- (blue) and post-spawning (red) values highlight the difference in contribution of individual calls to overall SPLs due to the differing call lengths of Category 1 calls (generating the greater number of calls post spawning, red) and Category 2 calls (the longer calls which dominated the period immediately prior to peak chorus, blue).

For ease of calculation the following analysis assumes that all received call related SPLs are produced by Category 2 long calls. As a higher number of Category 1 calls (and therefore a higher number of fish) originating at the same source distance would be needed to produce the same SPL the assumption of Category 2 calls only would lead to an underestimate of fish numbers.

The required number of callers at range *r* to produce the recorded SPL is restricted by the available calling area (the centre of the river channel is a finite area), compared to the spatial separation exhibited between mulloway callers. Therefore a range limit may be determined, above which calls are not considered to contribute to the SPLs, because an improbable calling density would be required to create the required SPL.

A minimum number of callers within the range-restricted area can then be determined for the recorded SPLs. So for *N* callers at ranges < *r*:

$$\sum \frac{1}{r_i^{\,2}} > \frac{N}{r^2} \qquad (17)$$

Localisation data estimated a minimum separation distance between calling fish of approximately 25 m. If such separation was consistent throughout the later, high-density calling, it may be possible to predict fish distribution throughout the area surrounding the hydrophone. For example, the 20:42 to 20:44 segment of recording produced a mean squared pressure of 131 dB re 1μPa (Figure 36). This SPL could be matched by two example scenarios shown in Figure 38. The first scenario being one caller at 30 m, three at 60 m and four at 120 m range and the second scenario, 36 callers at 100 m.

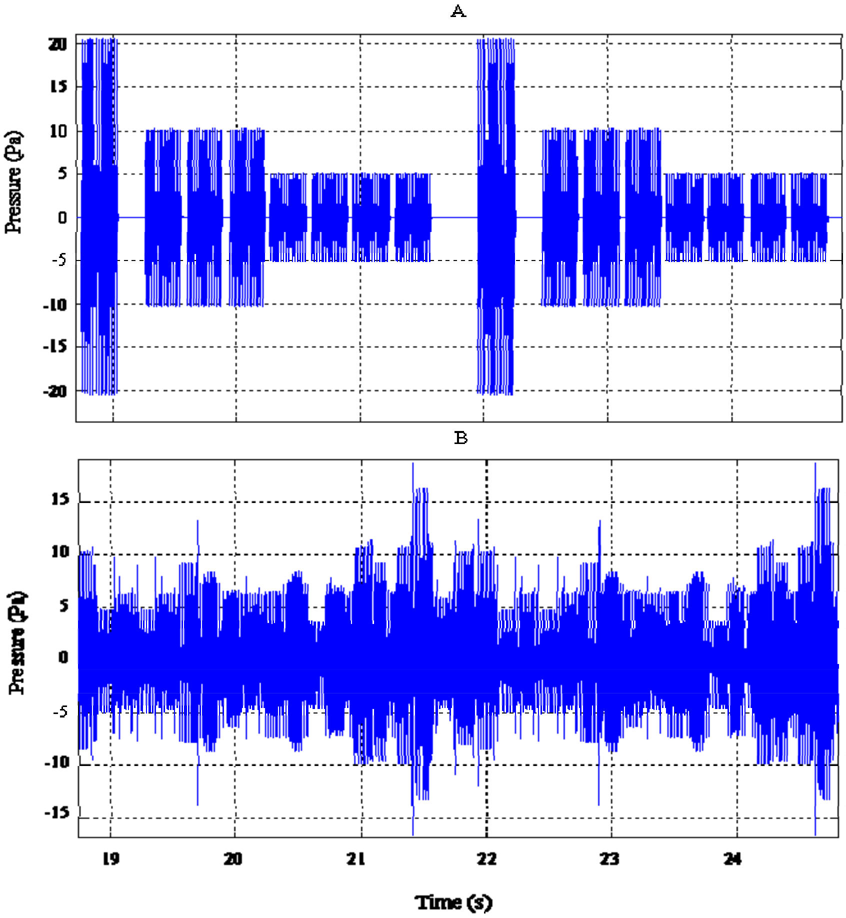

Figure 38. Example pressure waveforms for two simulated scenarios of mulloway callers creating two minute time averaged mean squared pressure levels of 131.3 dB re 1μPa. Sound pressure levels created by one caller at 30 m range, three at 60 m and four at 120 m (a), and thirty six callers at 100 m range (b). Parsons (2010).

For a given SL of all fish in the area a minimum number of callers for each minimum range can be determined For example, the minimum number of callers, greater than 100 m from the receiver,to produce mean-squared SPLs of 131 dB re 1μPa over the two minute segment, is 36. However, the pressure waveform may clearly demonstrate a caller at considerably closer range than other fish, similar to that of the waveform in Figure 8b, where one caller was modelled at 16 m range. If the signal-to-noise ratio of a close caller can be considered great enough to assume that interference from the pressure amplitudes produced by background calls has little effect on the pressure amplitude of the close caller then a minimum range can be estimated for the close caller. Alternatively, no single call in Figure 8c exhibits pressure amplitude greater than 20 Pa. If little destructive interference is assumed for the closer calls, then this would suggest that conservatively, no fish called within 50 m range of the receiver. Using this method of removing callers that are estimated to be within a specific range and than analysing the remaining partial pressure contributions from the remaining fish is shown in Figure 39. This involves an iterative process of sequentially removing the contribution from the nearest fish to the total chorus level. One fish in Figure 39b is calling at significantly lower range than the others.

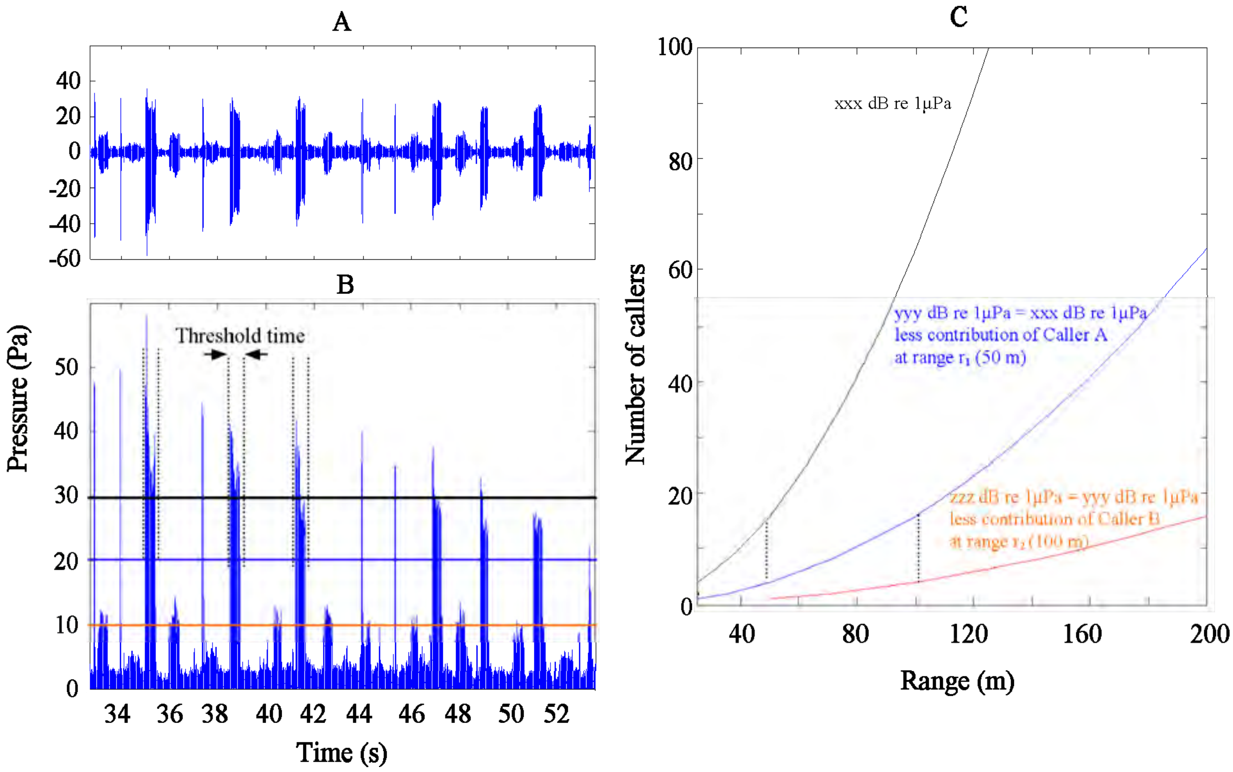

Figure 39. Pressure waveform (A) and absolute pressure (B) for 20 seconds of chorus calling in Mosman Bay, as recorded by a bottomed hydrophone in 18.5 m of water. Threshold time marks the length of a call over which automated programs would search for pressure amplitudes greater than the determined pressure threshold (black, blue and red lines in B). Minimum number of callers at minimum range r to produce a given sound pressure level (C). Black, blue and red lines denote the theoretical number of callers at various ranges to produce arbitrarily chosen sound pressure levels and display the removal of call contributions from callers A and B above a threshold level. Parsons (2010)

Setting a threshold for pressure levels could be used to detect and remove calls from a fish at a given range, similar to that of Caller A in Figure 39b which exceeds the 30 Pa black line threshold of a fish at 30 m range. Signals meeting similar criteria of pressure thresholds for a fish at a given range *r* could be attributed to a single fish. An example case is shown Figure 39c where the recorded SPL of xxx dB re 1μPa (xxx, yyy, zzz are specific to each species and recording dataset and are to be defined by the user, but in this case have been estimated based on mulloway call SL) could be explained by approximately 15 fish at 50 m or 100 fish at 120 m. However, the removal of call contributions from a fish at <50 m leads to a remaining SPL of yyy dB re 1μPa and a subsequently lower number of fish at given ranges greater than 50 m (Figure 39c). If another fish (Caller B) could be determined at a second threshold the process could be repeated (there was no such fish above the blue threshold in Figure 39b). The removal of Caller B pressure contributions would further reduce the

SPLs to zzz dB re 1μPa. The process would be repeated until the distribution of the remaining amplitudes in the pressure waveform could not be reasonably split into separated callers.

It could therefore be possible to estimate the ranges at which specific contributors are positioned to give boundaries of the numbers of calling fish to produce the received mean- squared SPLs. As discrimination between the nearer fish and the background calling improves, the more accurate the abundance range estimate will be.

Ground truth data

It had been anticipated that a multi-beam sonar system would be used to help ground truth the number of callers in the vicinity of the hydrophones during this survey. Unfortunately none were available at that time. As a result a survey was conducted with a Humminbird LL Sidescan system. With the sea-noise loggers set to record for five of every 15-minutes, acoustic transects were conducted during the 10-minutes of non-recording. A 4 m vessel travelling at between 3.5 and 4 knots towed the Humminbird system housed in a towfish submerged 1 m below the surface. Operated at 400 kHz the system range was approximately 75 m. Parallel, 500 m long transects were conducted approximately 100 m apart to ensure overlap between the acquired backscatter (Figure 40). While not an optimum system to use it was hoped that the sidescan sonar would be able to detect the swimbladders of mulloway on the riverbed. By comparing the start of the evening, when few mulloway are observed to call, with the height of calling, it was hoped that a number of acoustic targets would appear between transects. As mulloway have been shown to move slowly (anticipated to be around 200 m over the 15 minutes between transects over the same area) acoustic targets which either move or appear between transects were deemed likely to be fish. The typical torchlight of divers was not observed on the evening of this survey and so any moving targets were thought not to be divers.

The system was able to detect multiple high backscatter acoustic targets on the riverbed in each transect (Figure 40). However, almost all of them remained stationary throughout all sidescan transects indicating they were river bed features such as moorings, wrecks or general debris. Very few targets appeared or disappeared during the evening survey, while some groups of small targets moved between transects (Figure 40, blue ellipses). Although it is possible that some mulloway were being detected it was decided that there was not sufficient confidence in the data to use this as a method of ground truthing the number of fish within the area. The moving targets (Figure 40, blue and beige ellipses) may well be mulloway, but this requires further investigation. It is anticipated that a more powerful, higher resolution system, preferably an MBS system (to give greater coverage of the water column) would serve this purpose significantly better.

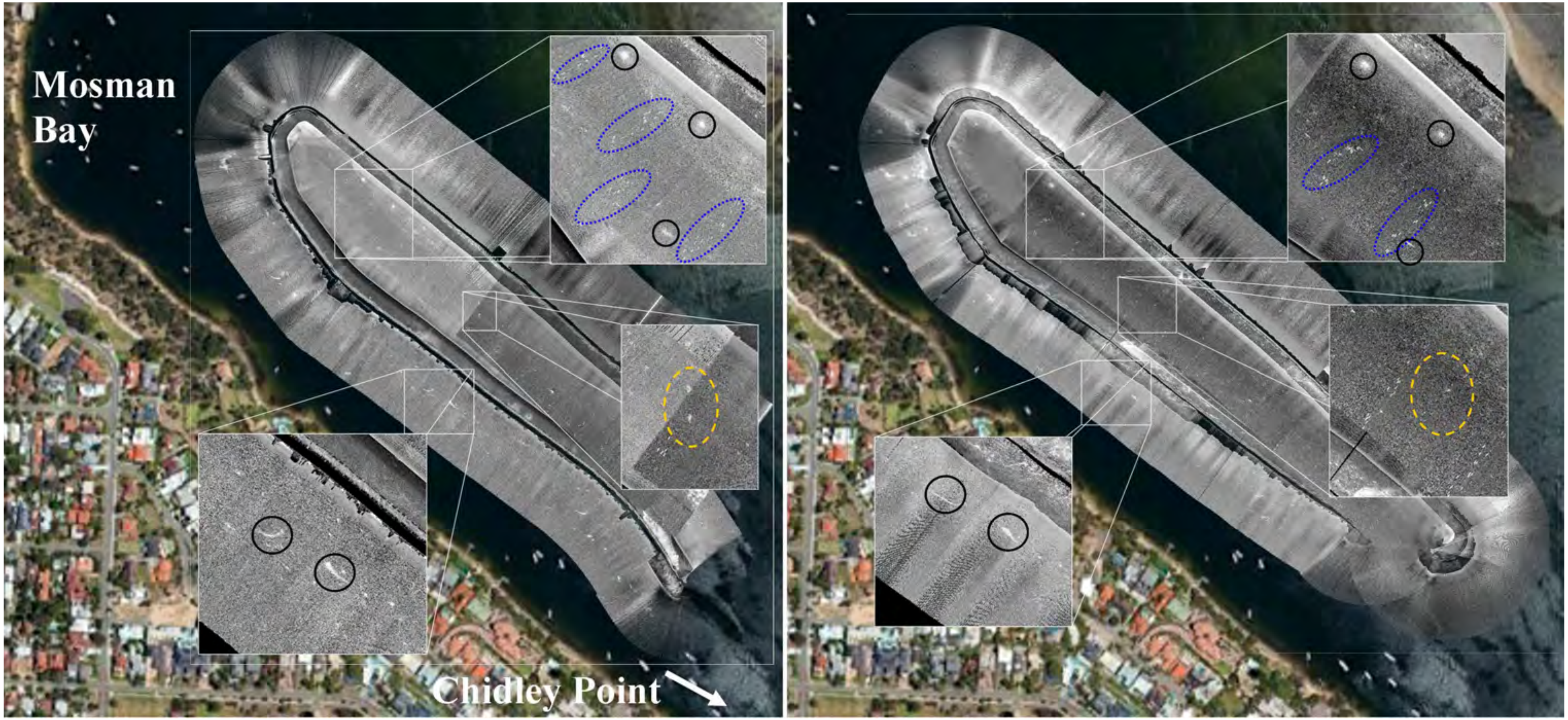

Figure 40. Sidescan imagery of the 17:15 (left) and 19:45 (right) transects of the area between Mosman Bay and Chidley Point in the Swan River. Black circles highlight example acoustic targets which do not move throughout the evening period, dotted blue ellipses represent example marks which moved location in the two and a half hours between transects and the dashed beige ellipse highlight example marks which disappear

7.2 West Australian Dhufish

Previous studies have not been able to confirm vocal behaviour in any species of the Glaucosomatidae family. Although FRDC project 2004/051 illustrated the likelihood that WA dhufish could produce sound by feeling vibrations from WA dhufish held in fishers and researchers hands, no evidence of sound production underwater was observed. During a juvenile WA dhufish survey conducted aboard the *RV Naturaliste* in February, 2011 a DoFWA researcher felt and possibly heard a juvenile WA dhufish grunting whilst being held on deck (P. Lewis, pers. comm.). As the fish produced a number of sounds it was unlikely that this was gas being expelled on rising to the surface.

7.2.1 Anatomy

Observation of two juvenile WA dhufish dissected by the DoFWA and dissection of six purchased adult WA dhufish at Curtin University revealed evidence of muscles likely used for twitching the swimbladder. Figure 41 highlights the position of the swimbladder within the fish and body cavity (Figure 41a and b) for juvenile (left images) and adult (right images) WA dhufish. Intrinsic, bi-lateral sonic muscles are attached to the anterior of the swimbladder and extend forward, attached at points near the brain and otoliths (Figure 41c). An area of thick walled tissue protruding forwards at the anterior of the swimbladder just below the sonic muscles, was observed in the adults. In one individual of standard length 333 mm the swimbladder and total sonic muscle lengths were 180 and 46 mm, respectively. With the exception of the thick walled tissue on the anterior the rest of the swimbladder appeared to be of one material.

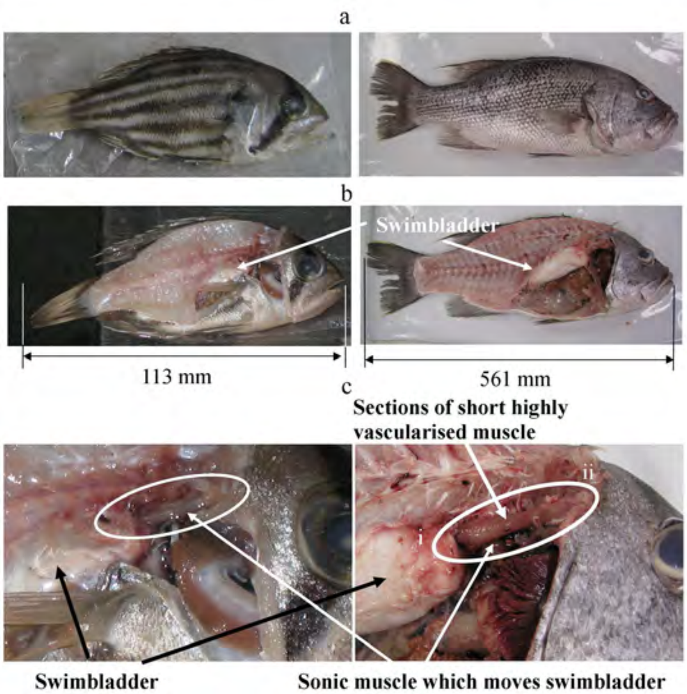

Figure 41. Juvenile (left) and adult (right) West Australian dhufish (a) and longitudinal-section (b) with total lengths and swimbladder highlighted. Swimbladder location and bi-lateral, muscle attaching the anterior of the swimbladder closely with the posterior of the brain casing are shown (c). Figure adapted from Parsons et al., 2013b.

7.2.2 Theoretical modelling of call characteristics

Given the highly vascularised nature of the dhufish sonic muscle, a contraction rate between 50 and 100 Hz, with muscular displacement maximum velocity of 12 muscle lengths per second would be a reasonable assumption (Rome, 2005). However, recordings have only shown calls of a single pulse or a few pulses. If a WA dhufish is able to compensate pressure within the swimbladder with increasing depth, calculations based on Vu (2007) provide a resonant frequency at 10 m depth of approximately 150 Hz. When used in CMST's Matlab program 'SynthCall' the waveform and spectral content given in Figure 42 and Figure 43 is produced, providing an estimate of what a dhufish call may sound like.

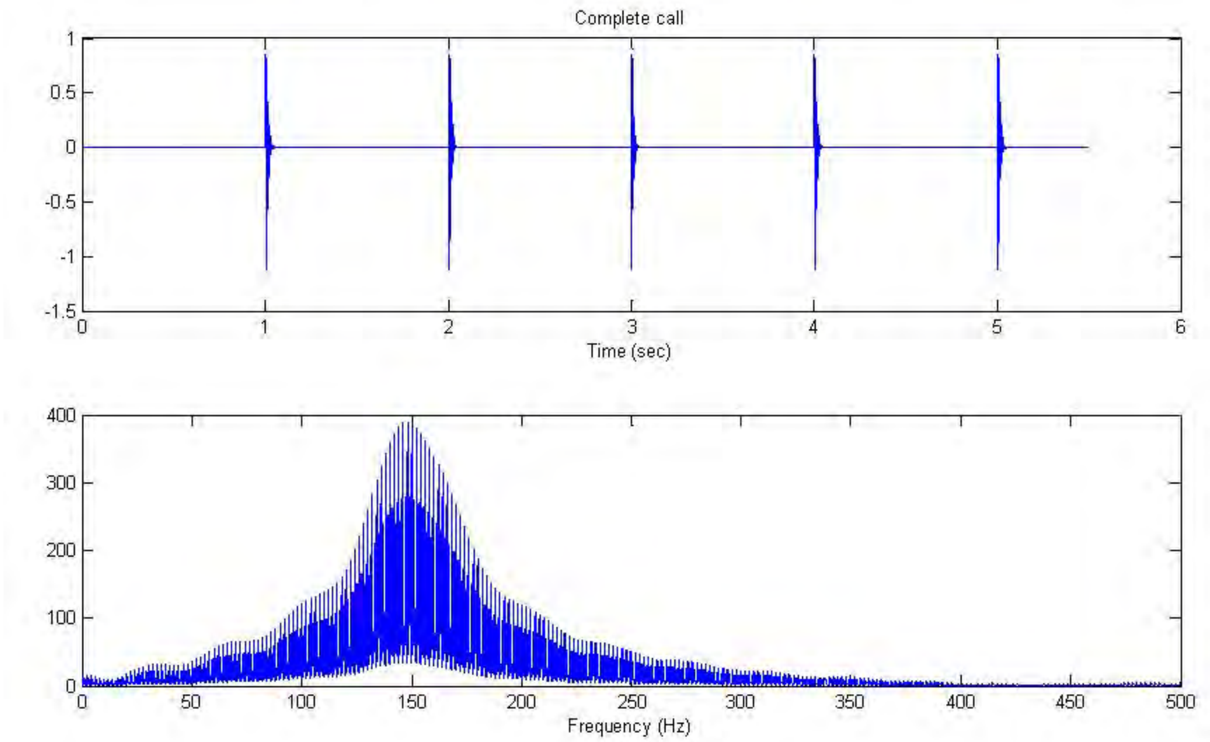

Figure 42. Example of modelled waveform (top) and spectral content (bottom) of a possible 333 mm dhufish call with 1 Hz pulse rate using CMST Matlab program 'SynthCall' assuming a resonant frequency of 150 Hz and a sonic muscle contraction frequency of 1 Hz.

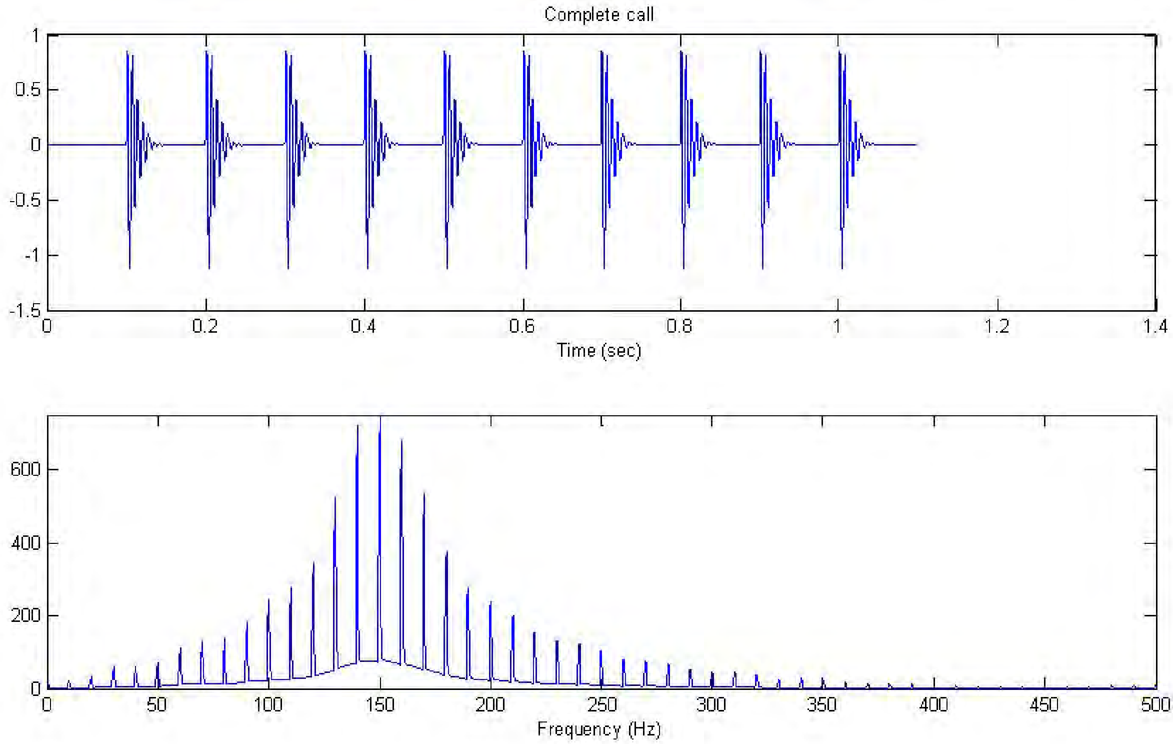

Figure 43. Example of modelled waveform (top) and spectral content (bottom) of a possible 333 mm dhufish call with 10 Hz pulse rate using CMST Matlab program 'SynthCall' assuming a resonant frequency of 150 Hz and a sonic muscle contraction frequency of 1 Hz.

7.2.3 WA dhufish disturbance sounds

On 13th December, 2011, two male WA dhufish were captured using rod and line in 14 m of water near Rottnest Island during a DoFWA monitoring program. Upon capture, the fish were raised to the surface over a of ten minute period in order to minimise the amount of swimbladder expansion, due to the pressure change. During this time a hydrophone (HTI 96-min) was located approximately 1 m from the fish. The sex of each fish was determined from the presence of the dorsal fin filament which is only extended in males, and the total length of each fish was measured to the nearest 1 cm. Each fish was then returned to the seabed using a release weight. During the release the CMST sea-noise logger was also deployed to the seabed and kept as near as possible to1 m from the fish.

The two fish were measured at 32 and 45 cm long and thus considered to be sexually mature based on the L_{50} at maturity of males (Hesp *et al.*, 2002). Both produced sounds while being brought to the surface (see Table 13 for acoustic characteristics) and, when close to the surface, vibrations of the body were visibly detectable simultaneously with sound production. The mean of the maximum SLs over all calls from the two fish were 126 ±6 dB re 1µPa at 1 m (n= 67, max = 137, min = 107), with spectral peak frequency at 154 ±44 Hz (max = 251, min = 82) and mean 3 dB bandwidth of 110 Hz (Figure 44 and Figure 45). Although calls contained between 1 and 14 pulses, two pulses per call were most common (Table 13). The distribution of SLs revealed a number of calls of maximum SL > 125 dB re 1µPa at 1 m and the maximum SL recorded in any one call reached 137 dB re 1µPa at 1 m (Figure 44). The maximum SL decreased in calls with an increasing number of pulses (Figure 46) and, in calls of multiple pulses, the pulse repetition frequency (the rate of individual swimbladder pulses within a single call) decreased as more pulses were used in a call (Table 14).

Table 13. Characteristics of calls of differing numbers of pulses, produced by two male WA dhufish, including source levels in sound pressure level (dB re 1µPa at 1 m), maximum sound exposure level (dB re 1µPa^2.s at 1 m) and peak-to-peak pressure (Pa). Numbers in parentheses for call type are the sample number. Elsewhere numbers in parentheses represent the standard deviation, maximum and minimum values. Table taken from Parsons et al. (2013b)

Call Type (n)	Peak-peak pressure (Pa)	Maximum SL (dB re 1µPa)	Maximum SEL (dB re 1µPa^2.s)	Duration (s)	Spectral peak frequency (Hz)	Bandwidth (Hz; 3dB down)
All calls (67)	10.8 (7.4, 35.2, 2.3)	124 (6, 137, 113)	116 (6, 126, 97)	0.38 (0.37, 2.6, 0.01)	154 (44, 251, 82)	110 (50, 242, 20)
1 Pulse (10)	15.1 (9.3, 28.3, 5.5)	126 (7, 133, 117)	119 (5, 125, 113)	0.11 (0.11, 0.39, 0.01)	148 (45, 220, 98)	140 (55, 193, 83)
2 Pulse (19)	10.6 (8.7, 35.2, 2.3)	124 (6, 137, 116)	116 (6, 126, 97)	0.19 (0.08, 0.38, 0.05)	149 (43, 221, 95)	97.1 (51, 201, 20)
3 Pulse (14)	9.7 (5.6, 20.0, 3.6)	125 (7, 133, 117)	116 (5, 123, 108)	0.31 (0.15, 0.75, 0.17)	163 (33, 217, 103)	81 (24, 112, 48)
4 Pulse (6)	14.7 (6.8, 21.2, 4.5)	126 (6, 132, 119)	118 (6, 123, 110)	0.43 (0.08, 0.55, 0.35)	198 (52, 251, 117)	175.2 (64, 242, 78)
5 Pulse (9)	6.7 (9.0, 5.3, 14.6, 3.1)	122 (5, 127, 113)	112 (3, 116, 107)	0.57 (0.23, 0.93, 0.14)	138 (31, 199, 103)	107 (26, 166, 69)
6 Pulse (5)	8.9 (5.3, 14.6, 3.1)	123 (5, 130, 116)	116 (5, 123, 109)	0.59 (0.17, 0.81, 0.38)	143 (46, 205, 95)	117 (50, 191, 79)
7 Pulse (1)	2.5	121.9	108.3	0.8	141	59
8 Pulse (1)	20.6	126.6	122.5	0.7	237	117
9 Pulse (1)	10.0	119.9	117.7	1.3	82	100
14 Pulse (1)	11.2	116.5	110.6	2.6	102	196

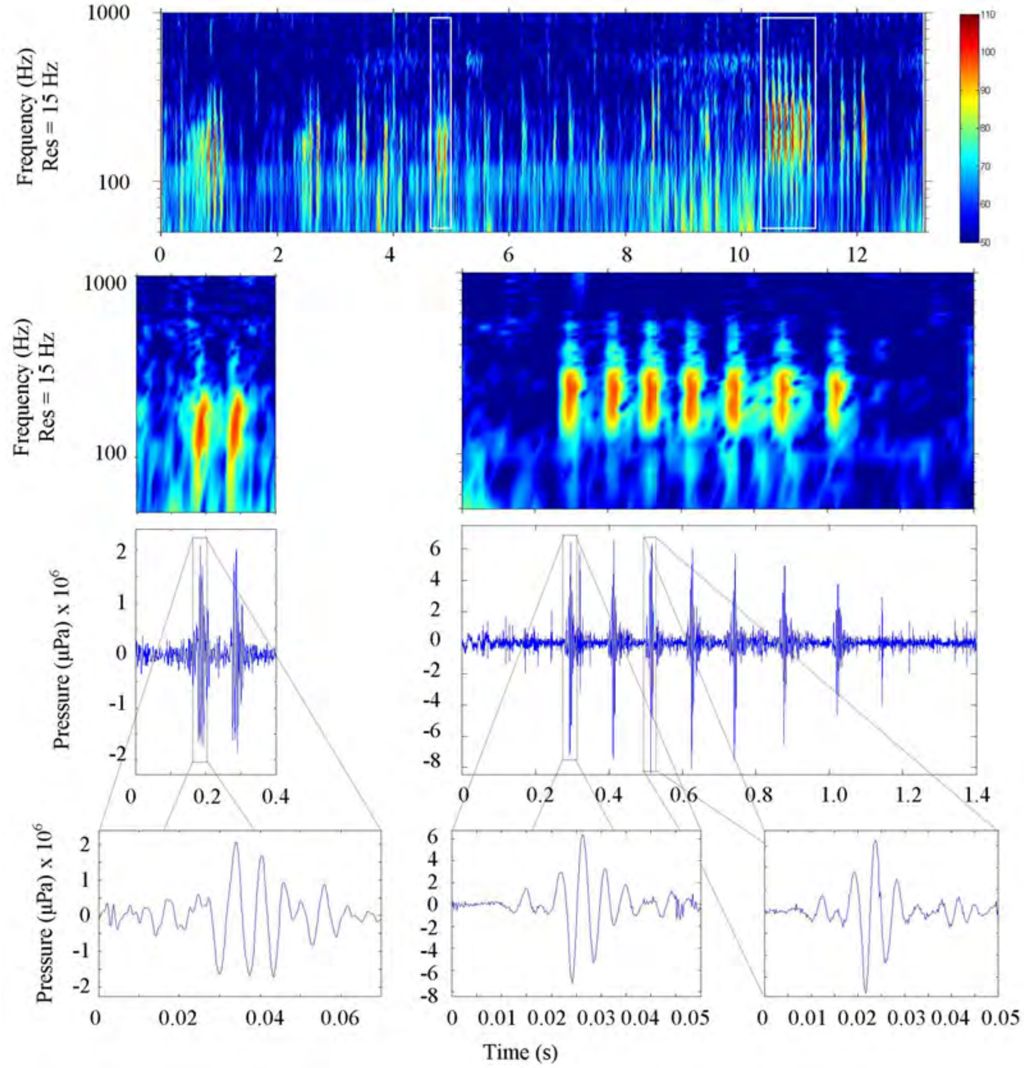

Figure 44. Spectrogram and waveforms of two example dhufish calls recorded off Rottnest Island comprising two (left) and seven (right) pulses of the swimbladder. The magnified waveform of a single pulse from each call is shown. Figure taken from Parsons et al. (2013b).

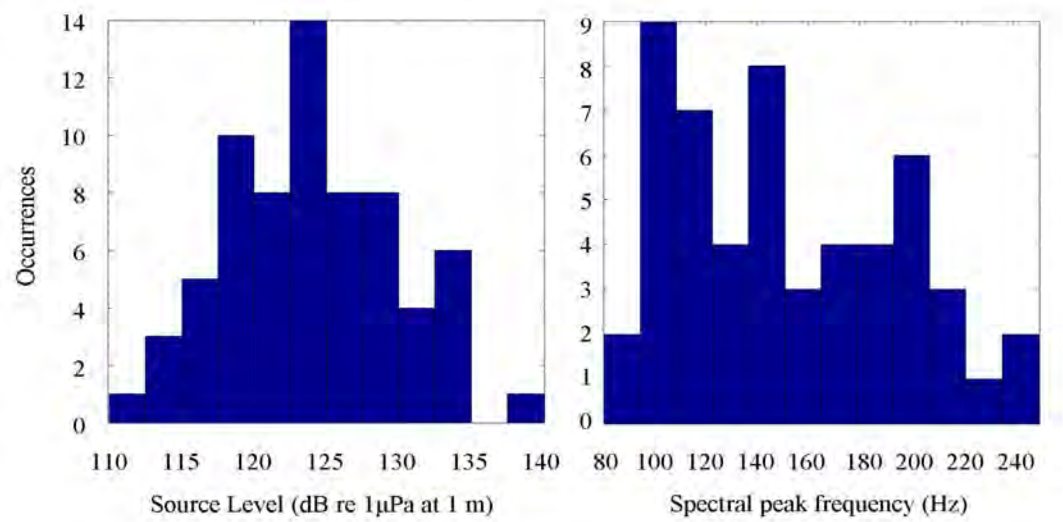

Figure 45. Distribution of maximum source levels (left) and spectral peak frequencies (right) of all calls.

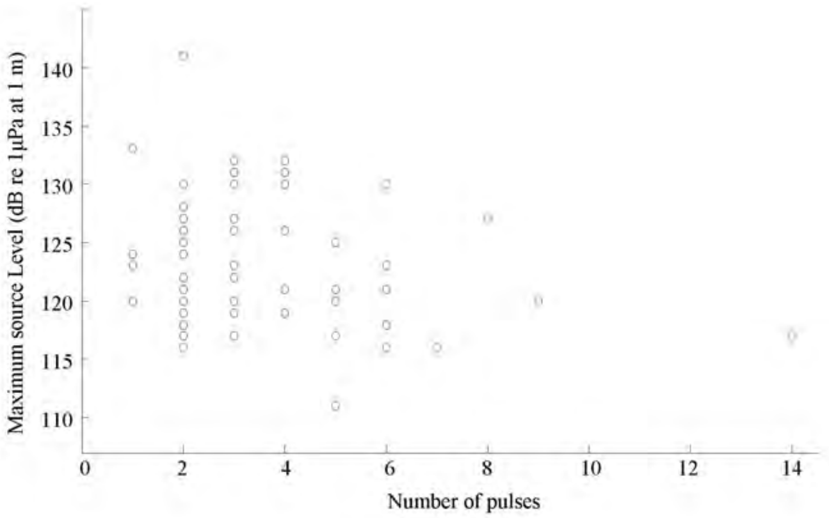

Figure 46. Distribution of maximum source levels against the number of pulses within the call.

Table 14. Pulse repetition frequencies for multiple pulse calls. Table taken from Parsons <u>et al</u>. (2013b)

Number of pulses within call (n)	Pulse repetition frequency between pulses (Hz) (max, min, s.d.)											
	Pulse set 1-2	Pulse set 2-3	Pulse set 3-4	Pulse set 4-5	Pulse set 5-6	Pulse set 6-7	Pulse set 7-8	Pulse set 8-9	Pulse set 9-10	Pulse set 10-11	Pulse set 11-12	Pulse set 12-13
2 (19)	10.08											
3 (14)	9.46	9.18										
4 (6)	8.69	8.69	7.20									
5 (9)	9.83	8.59	8.44	7.71								
6 (5)	10.96	10.93	9.47	9.22	7.95							
7 (1)	8.50	9.78	8.94	8.62	7.45	6.88						
8 (1)	8.65	8.45	8.19	7.57	7.17	7.55	7.22					
9 (1)	8.68	5.68	5.65	4.96	5.39	7.21	6.35	6.28				
14 (1)	7.75	8.40	8.25	6.79	6.93	6.81	6.31	7.32	7.29	5.27	1.53	7.89

7.2.4 Sounds of <u>in situ</u> WA dhufish

While the recordings of captive WA dhufish have shown that the species possesses the ability to produce sound, it was necessary to acquire recordings in the wild to confirm that these sounds are produced with a natural associated function and whether these sounds could be useful for monitoring purposes. The *in situ* sounds were targeted on two fronts, the first in an area where dhufish (predominantly juvenile) are present throughout the year and the second at locations where dhufish reportedly aggregate to spawn.

Sounds produced by WA dhufish in the wild

In waters off Augusta, artificial reefs where multiple juvenile WA dhufish are frequently observed by researchers, have been the subject of study by the DoFWA and CARL for the past two years. A sea-noise logger was deployed to a patch of sand, 10 m from artificial reefs designed to attract juvenile WA dhufish (Figure 47). The logger recorded throughout December, 2012 and January, 2013.

Figure 47. Still shots from video of a sea-noise logger deployed near artificial reefs near Augusta showing a single juvenile WA dhufish next to the sea-noise logger (top) and multiple juveniles by a nearby patch of artificial reef (bottom). (Parsons et al., 2014)

During the recording period researchers from CARL, conducting concomitant research, noted three cohorts of WA dhufish, estimated at approximately 100, 200 and 300 mm in total length, each of which are often seen within 10 m of the noise logger (Figure 47). The site has been visited numerous times throughout the year by both DoFWA and CARL researchers and the habitat consistently supports many juvenile dhufish and, on occasion, mature WA dhufish. The only other species observed by the researchers were snapper, weeping toadfish (*Torquigener pleurogramma*), and Western king wrasse (*Coris auricularis*)), plus a single juvenile Rankin's cod (*Epinephelus multinotatus*) which was also noted by the CARL researchers on the 15th January, 2013.

The recordings displayed significant wave and mooring noise throughout the deployment. However, a large number of fish calls were detected during periods of low ambient noise. Many of these calls closely resembled the acoustic characteristics of calls recorded from the captive WA dhufish at Rottnest Island. Calls comprising individual pulses or pulses separated by up to 1 s were detected (Figure 48), as well as calls comprising several pulses in quick succession (Figure 49), and in each case displayed spectral peak frequencies between 100 and 300 Hz (Table 15). The maximum RL and SEL of the recorded calls were 129 dB re 1 μPa and 120 dB re 1 $\mu Pa^2.s$, respectively, with the mean respective values at 122 dB re 1 μPa and 118 dB re 1 $\mu Pa^2.s$. These levels are well within the range of the SLs recorded for the WA dhufish at Rottnest and imply that the callers in this case were within 10 m of the logger when calling.

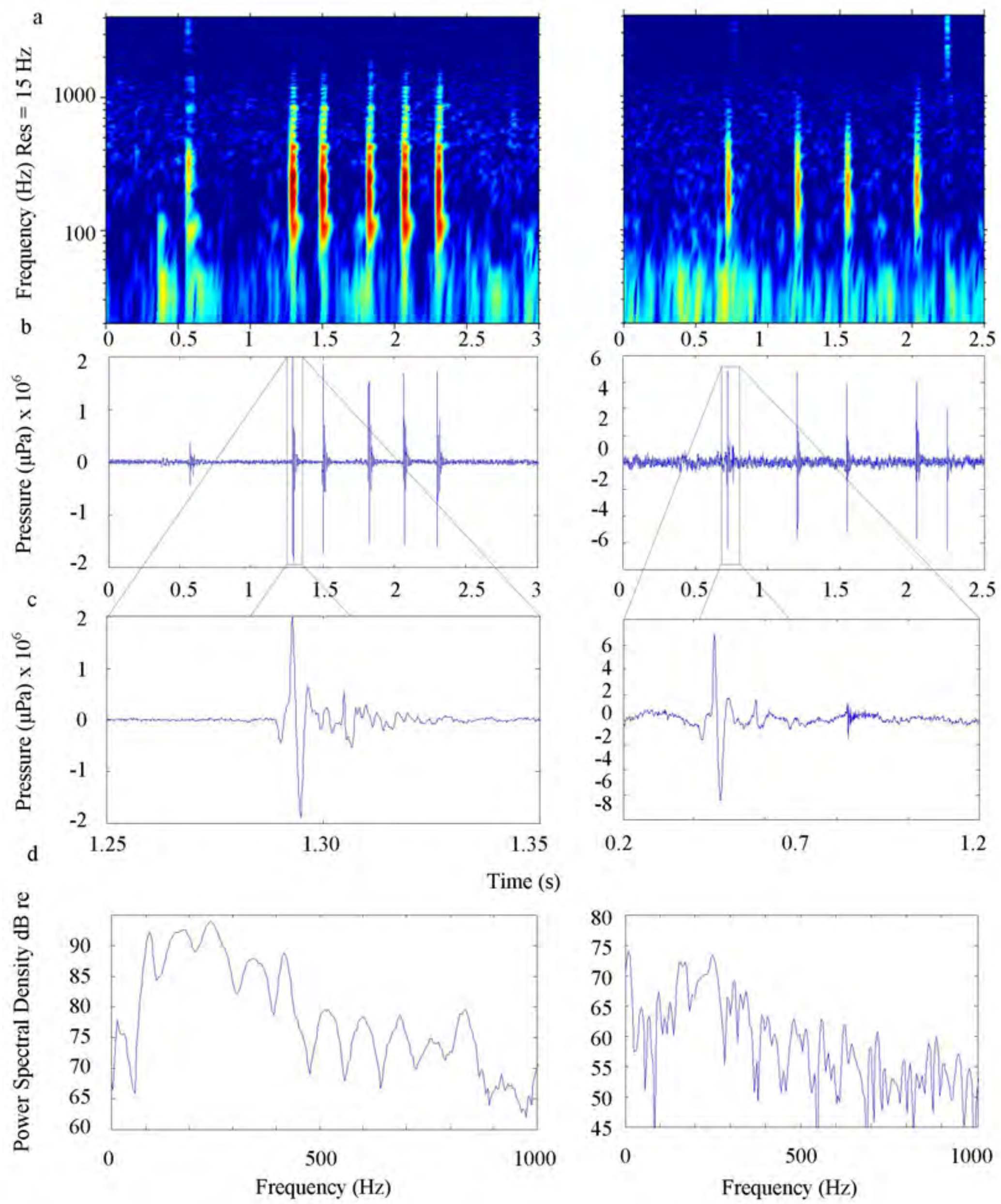

Figure 48 Spectrogram (a) and waveform (b) of likely WA dhufish calls recorded in December, 2012, Augusta. Expanded waveforms of individual pulses (c) and power spectral density of the overall calls (d) are also shown. (Parsons et al., 2014)

The similarities between the spectral peak frequencies and waveforms suggest that both the single pulse and multiple pulse calls came from the same fish, or at least via the same mechanism. While ground truth data was not available at the exact time of these calls, few other species have been observed in the area by researchers and none as often as the juvenile WA dhufish present here. The acoustic characteristics of the calls recorded at this location were very similar to those of mature WA dhufish recorded off Rottnest Island.

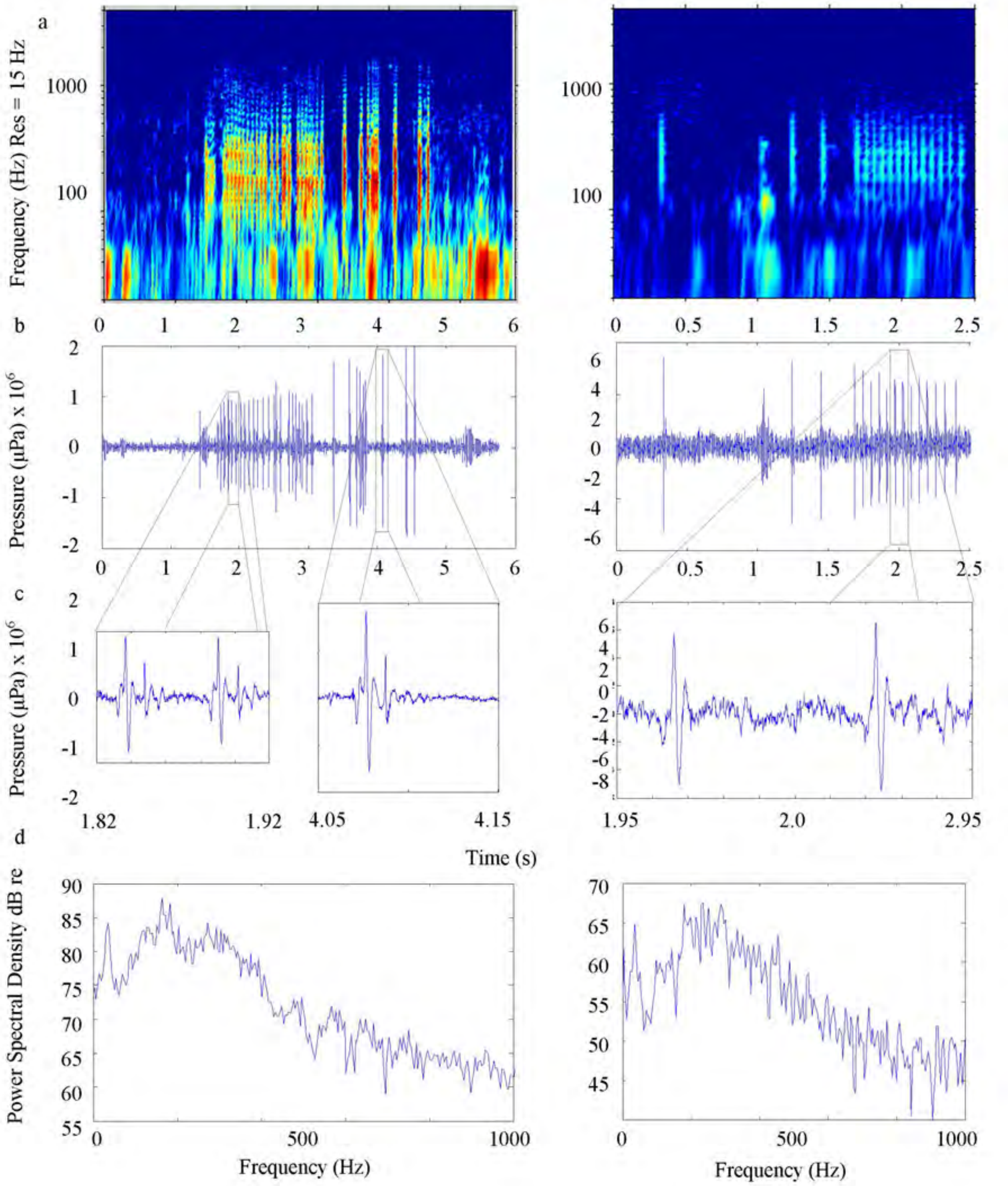

Figure 49. Spectrogram (a) and waveform (b) of multiple pulse dhufish calls recorded in December, 2012, Augusta. Expanded waveforms of individual pulses (c) and power spectral density of the overall calls (d) are also shown. (Parsons et al., 2014)

Table 15. Acoustic characteristics of calls recorded in an area where multiple WA dhufish are often reported.

Call Type (n)	Peak-peak pressure (Pa)	Maximum RL (dB re 1µPa)	Maximum received SEL (dB re 1µPa^2.s)	Duration (s)	Spectral peak frequency (Hz)	Bandwidth (Hz; 3dB down)
All calls (31)	19.8 (5.2, 31.7, 5.3)	126 (6, 129, 113)	116 (3, 120, 95)	2.7 (0.61, 4.1, 0.01)	221 (62, 298, 103)	139 (59, 305, 71)
Pulses in quick succession (7)	15.1 (9.3, 28.3, 5.5)	126 (7, 127, 117)	116 (3, 119, 111)	3.13 (0.41, 4.1, 1.01)	148 (58, 298, 91)	110 (61, 193, 71)
Separated pulses (19)	20.6 (5.3, 31.7, 5.3)	124 (6, 129, 113)	118 (4, 120, 95)	0.11 (0.08, 0.16, 0.05)	149 (66, 251, 99)	157 (57, 305, 89)

Sounds possibly produced by adult WA dhufish

Recordings taken in Geographe Bay (2011) and waters off Cape Naturaliste (2011-12 and 2012-13), as well as datasets from recordings near the HMAS Swan wreck in Geographe Bay (2009 and 2010), all detected a number of calls which could feasibly have been produced by WA dhufish. Those with similar acoustic characteristics to the restrained dhufish calls are presented in this section.

The offshore logger, located approximately 6 n.m. west of Cape Naturaliste (Figure 3), recorded many fish calls between December, 2011 and February, 2012 examples of which are shown in Figure 50. From an example 75 calls, the mean spectral peak frequency was determined as 239 ± 37 Hz (min = 86, max = 297) and pulse repetition frequency at 8.3 ± 3.2 Hz (min = 4.2, max = 14.7). An increase in SPLs over the 50-200 Hz band was also observed for prolonged periods (Figure 50), particularly between the 29th December, 2011 and the 4th January, 2012, when anecdotal evidence from recreational fishers suggested significant numbers of WA dhufish were present in the surrounding area.

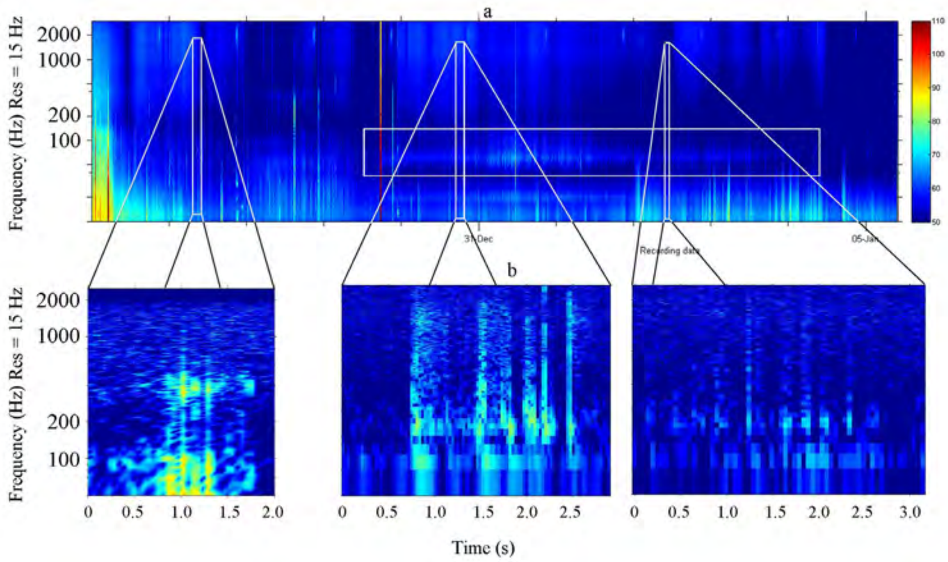

Figure 50. Spectrogram from 10 days of recording in waters west of Cape Naturaliste (a). Spectrograms of a example sound with similar characteristics to WA dhufish calls (b) and increased SPLs during a period when significant numbers of WA dhufish were captured in the area; this period is within the known spawning season of WA dhufish (highlighted by horizontal rectangular white box; Hesp et al., 2002). Taken from Parsons et al. (2013a)

On 20th December, 2012 an array of three sea-noise loggers were deployed into the same area as the offshore loggers during the 2011-12 season (Table 3), separated by approximately 100 m. These sea-noise loggers recorded for seven of every nine minutes until their retrieval on the 7th February, 2013. During this time recreational fishers reported low numbers of WA dhufish catch, compared with that of late December, 2011 and early January, 2013. Significant mooring noise was observed on all three datasets, compared with the 2011-12 recordings, suggesting a higher level of current or surge (Figure 51a and d). In between periods of noise, a few speculated dhufish calls were observed (Figure 51b and c); however, no prolonged increase in SPLs were observed over the frequency band of WA dhufish calls, possibly due to masking by the mooring noise. This was observed to varying extents on all three loggers.

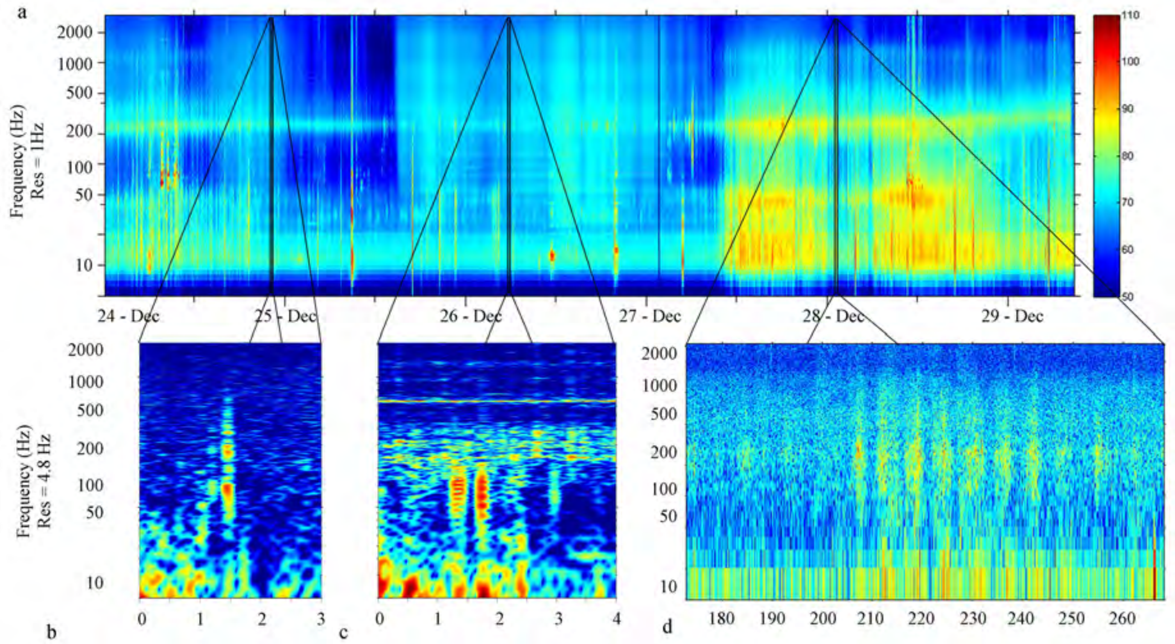

Figure 51. Spectrogram of five days recording from waters off Cape Naturaliste in January, 2013 (a). Expansion of spectrogram comprising 3 s of recording on the 25th December, 2013 (b) and 4 s recording on the 26th December (c). Spectrogram of wave noise in a regular pattern, consistent with that of surge or swell (d).

7.2.5 Propagation and likely detection ranges of WA dhufish calls

Background noise levels in Geographe Bay between the 29th December, 2011 and 4th January, 2012 ranged between 87 and 119 dB re 1µPa over the 50-500 Hz bandwidth (outside periods of mooring related noise). Similar to mulloway call propagation, the background noise has significant impact on the detection range of a call to both intended recipient and observer (Urick, 1983, Sprague and Luczkovich, 2004, Parsons *et al.*, 2012b). For simple comparative purposes a coarse minimum detection range of the SL was calculated. This is the range at which the signal would have attenuated to background noise level using signal processing, based on spherical spreading as the transmission loss. It does not use statistical analysis of the probability of signal detection or account for fish hearing critical ratios and so should not be used as an estimation of the ranges over which fish may detect calls. However, the difference between background noise and SL suggest a coarse estimate of a detection range of up to 250 m or greater at the lower ambient noise levels and 10-20 m at the higher level. It should be noted that high levels of mooring noise would mask the calls altogether.

The RLs of calls detected at the Cape Naturaliste Offshore Logger A site were 93 dB re 1µPa. Applying spherical spreading as a coarse estimate of transmission losses and WA dhufish maximum SL of 137 dB re 1µPa, this would imply that if the source was a WA dhufish (or even a fish producing calls of similar SL) they were located approximately 160 m from the hydrophone. This means, that for this level of ambient noise, there is a minimal effective sample area of 80,000-100,000 m^2 around the hydrophone.

7.3 Snapper

7.3.1 Anatomy

Samples dissected in this study were either bodies or frames donated from the DoFWA subsequent to their examination in one of two current DoFWA research projects. Figure 52 illustrates the swimbladder, gonads and related musculature of a 75.8 cm, spawning male snapper taken from Cockburn Sound in November 2010. Similar results were found in samples taken from the Western Gulf of Shark Bay in July 2010. Figure 52b and c illustrate the volume of the body cavity taken up by the gonads of a mature male snapper and the comparative size of a 74.1 cm^3 swimbladder (individual was raised slowly from <10 m depth). Only white muscle fibres were observed surrounding the swimbladder (Figure 52c), although two red muscles were found to attach close to the anterior of the swimbladder (Figure 52d). No evidence of pharyngeal teeth capable of noise production was observed (Figure 52e). The interior of the swimbladder displayed a complex structure, whereby ribs and tendons were woven through the top section of the swimbladder (Figure 52f and g). The effect this structure might have on the vibration of the swimbladder and therefore any produced sound is unknown.

7.3.2 Theoretical modelling of call characteristics

Biological examination of the male snapper revealed a swimbladder of approximately 74 cm^3. This volume produces resonant frequencies at 10 m depth of approximately 50 Hz when modelling the swimbladderas a simple gas-filled bubble. As no evidence of sonic muscle was found and there was little area in the body cavity to vibrate (in particular due to the volume of the swimbladder and gonads) it is unlikely that this species produces calls of frequency greater than a few hundred Hz. The presence of the ribs and tendons throughout the top half of the swimbladder leaves only the bottom wall to vibrate freely. The impact this will have on the acoustic characteristics of any call is unknown. Therefore for modelling purposes a contraction repetition frequency of 20 Hz has been assumed and the swimbladder has thus far been modelled as a prolate spheroid allowed to vibrate freely. The characteristics of a possible call, as generated by SynthCall can be seen in Figure 53.

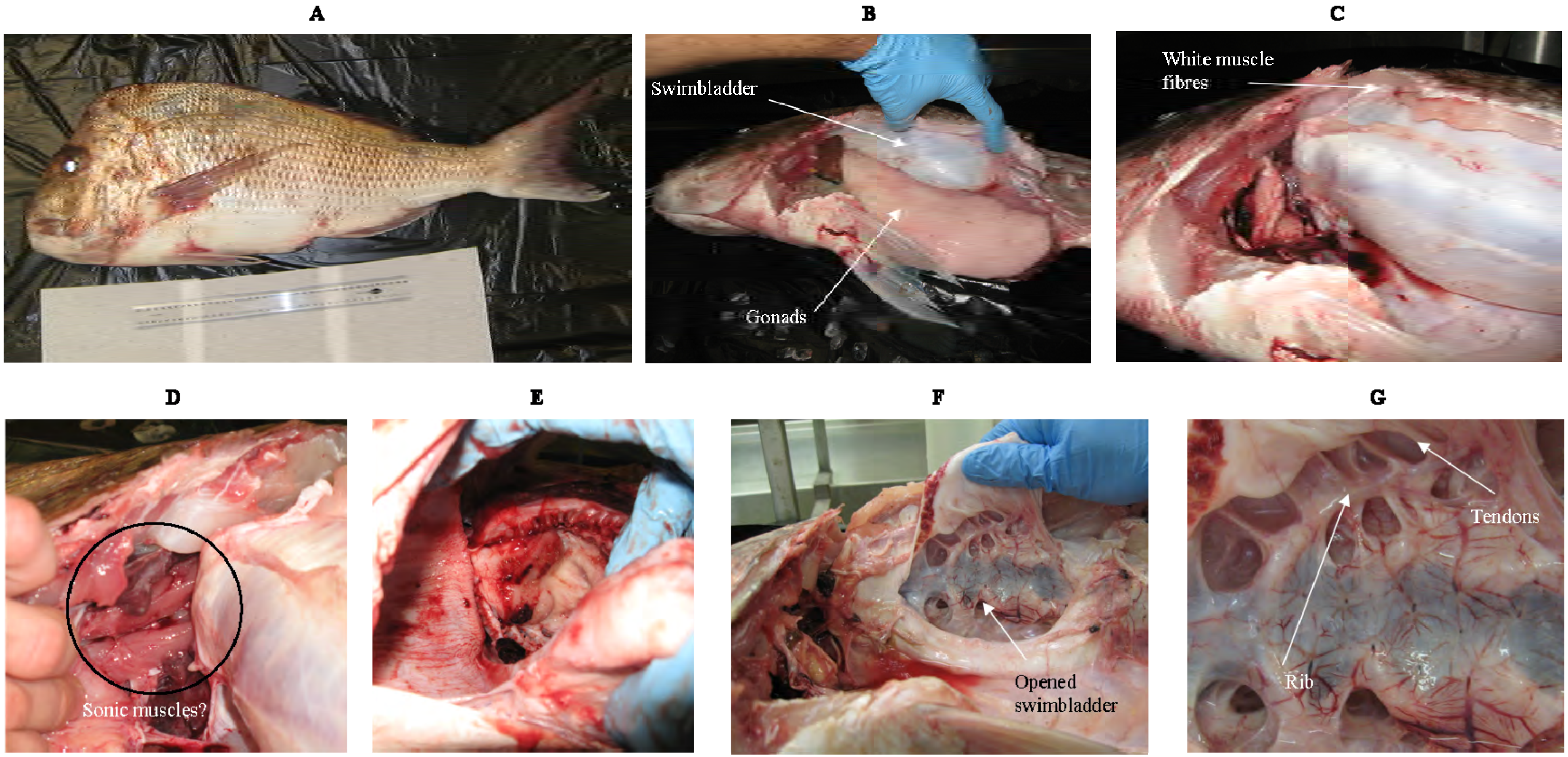

Figure 52. A 758 cm male snapper in spawning condition fro Cockburn Sound, donated by DoFWA (A). Dissection highlighting the relative size of swimbladder, gonads and internal organs within the body cavity (B). White muscle fibres found surrounding the swimbladder (C). Bi-lateral, highly vascularised muscles loosely attached to the anterior of the swimbladder (D). Anterior view from the swimbladder towards the rear of the mouth, no grinding pharyngeal plates were found (E). Swimbladder opened (F) to reveal that the ribs run through the swimbladder and are connected together by white tendons (G).

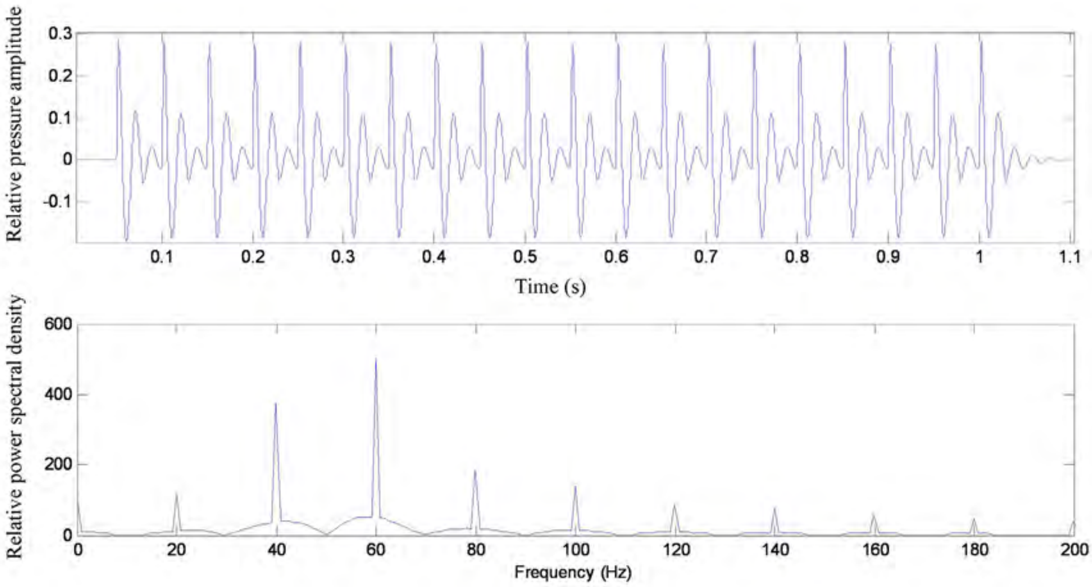

Figure 53. Modelled characteristics of a possible snapper call based on a swimbladder vibration frequency of 20 Hz and a resonant frequency of 50 Hz using CMST's SynthCall program.

7.3.3 Acoustic recordings

Acoustic recordings targeting snapper vocalisations were taken using sea-noise loggers at The Patch in Shark Bay's eastern gulf (July, 2010) and Cockburn Sound (October and November, 2010) and by mid-water boat-based recordings during DoFWA sampling in Shark Bay's western gulf (July, 2010) and Cockburn Sound (October and November, 2010) at times when spawning aggregations are known to form. During this sampling recording was conducted at the same time as the capture of 22 mature snapper in Shark Bay (16 Male, 6 female) and 5 mature snapper in Cockburn Sound (4 male, 1 female).

The eastern gulf noise logger recorded between the 11th and 14th July, 2010. At various times during the deployments individual fish calls were recorded. Examples of these calls are shown in Figure 54. Predominantly centred around 250 Hz the calls exhibited sidebands of amplitude modulation typical of a call generated by a vibrating swimbladder (Figure 54a, b and c). These calls comprised 2.71 (±1.45 S.D., n = 45) pulses and included characteristics similar to mulloway calls (Parsons, 2010). Other, less frequent sounds associated with feeding were also recorded during this period.

Stacked spectrograms from long-term recordings at the Patch in Shark Bay can be seen in Figure 55 (top plot), together with times of sunset (orange circles) and new moon (white circle). The mean and maximum wind speeds can also be seen (bottom plot) for comparison with SPLs. In Shark Bay there was a significant increase in SPLs below 300 Hz in the hours around sunset each day. However, audio scrutiny of the recordings suggested that this increase was due to an increase in wave action. There was also an increase in wind levels recorded at Denham airport prior to the SPLs increase suggesting the possibility of wind-driven waves increasing low-frequency ambient noise.

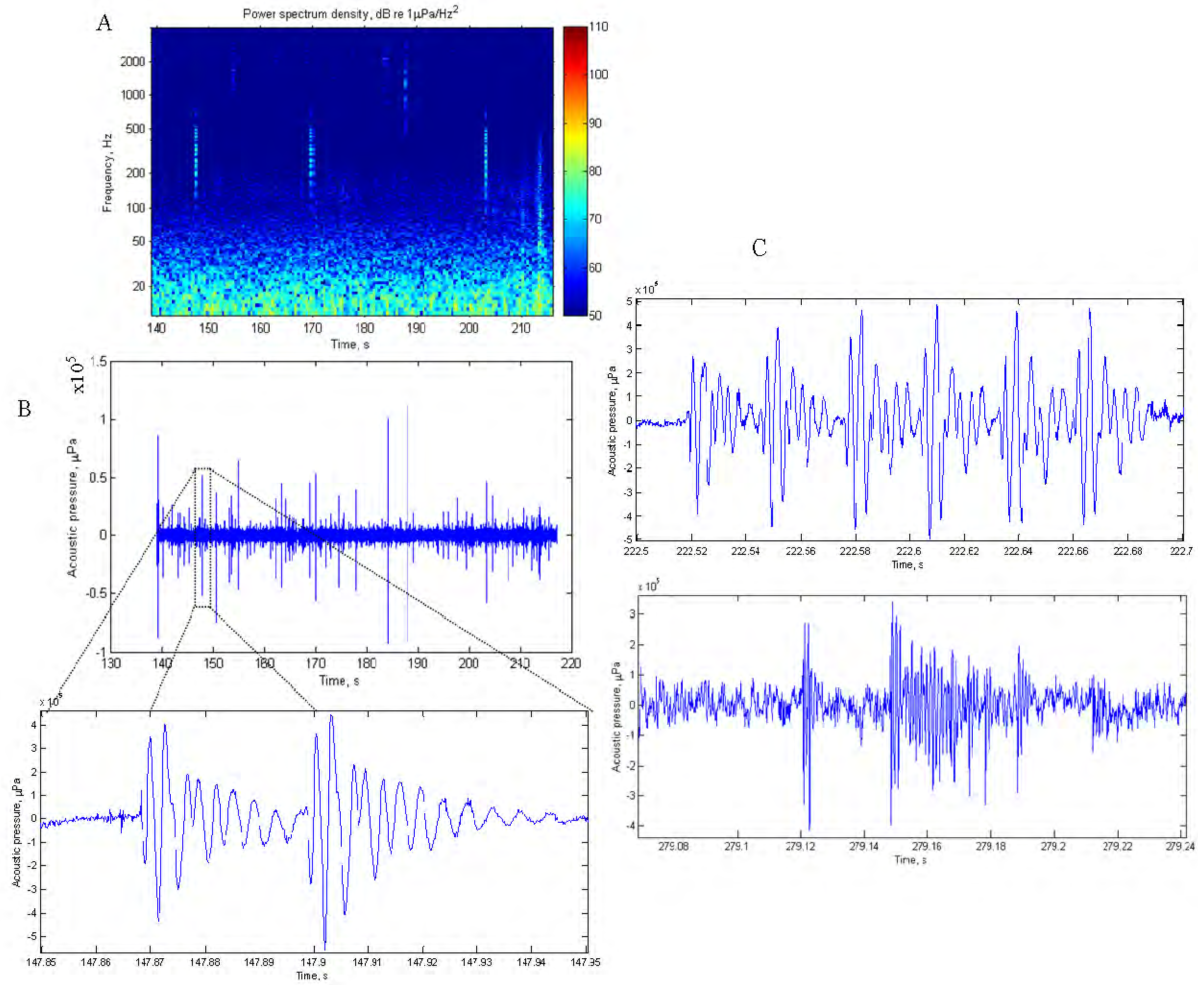

Figure 54. Spectrogram (a) and respective waveforms (b) of short, two pulse swimbladder driven calls and example waveforms (c) of swimbladder driven calls, recorded in Shark Bay's eastern gulf, at 'The Patch' at approximately 14:00, 12th July, 2010.

This lack of detected fish chorus in data from 'The Patch' was also observed in Cockburn Sound recordings (Figure 56). There were also similar increases in SPLs below 200 Hz on a daily basis, although the relationship between low frequency noise and wind was less evident in the Cockburn Sound case. There was also significant system noise in the Cockburn Sound recordings which may have masked biotic sounds (see Figure 56, below 60 Hz). At both sites the recordings taken during the capture of mature male and female snapper displayed no evidence of sound produced by the fish.

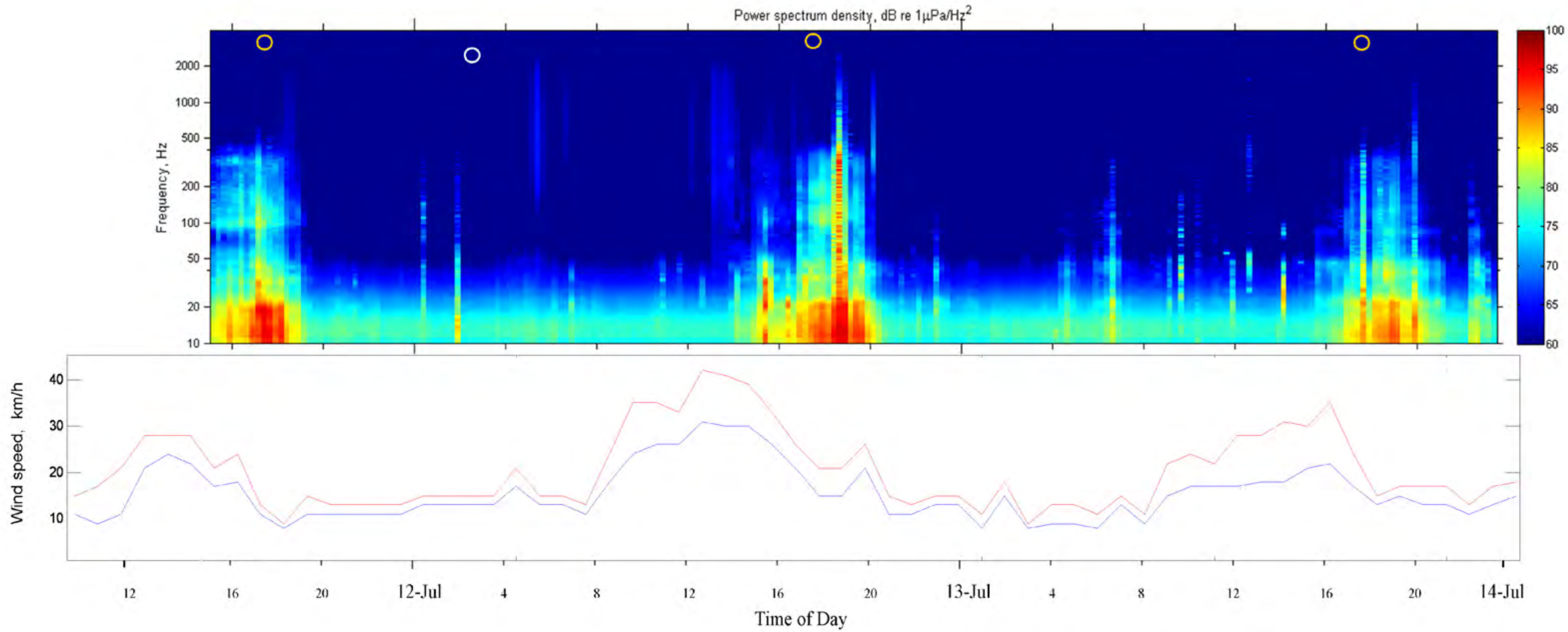

Figure 55. Stacked spectrograms of acoustic recordings taken in the Eastern Gulf of Shark Bay, together with the hourly mean and maximum wind speeds (blue and red lines of bottom plot) measured at Shark Bay airport provided by the Bureau of Meteorology. Orange and white circles in the top plot represent time of sunset each day and of the new moon, respectively. Points of interest have been highlighted and are explained in the text.

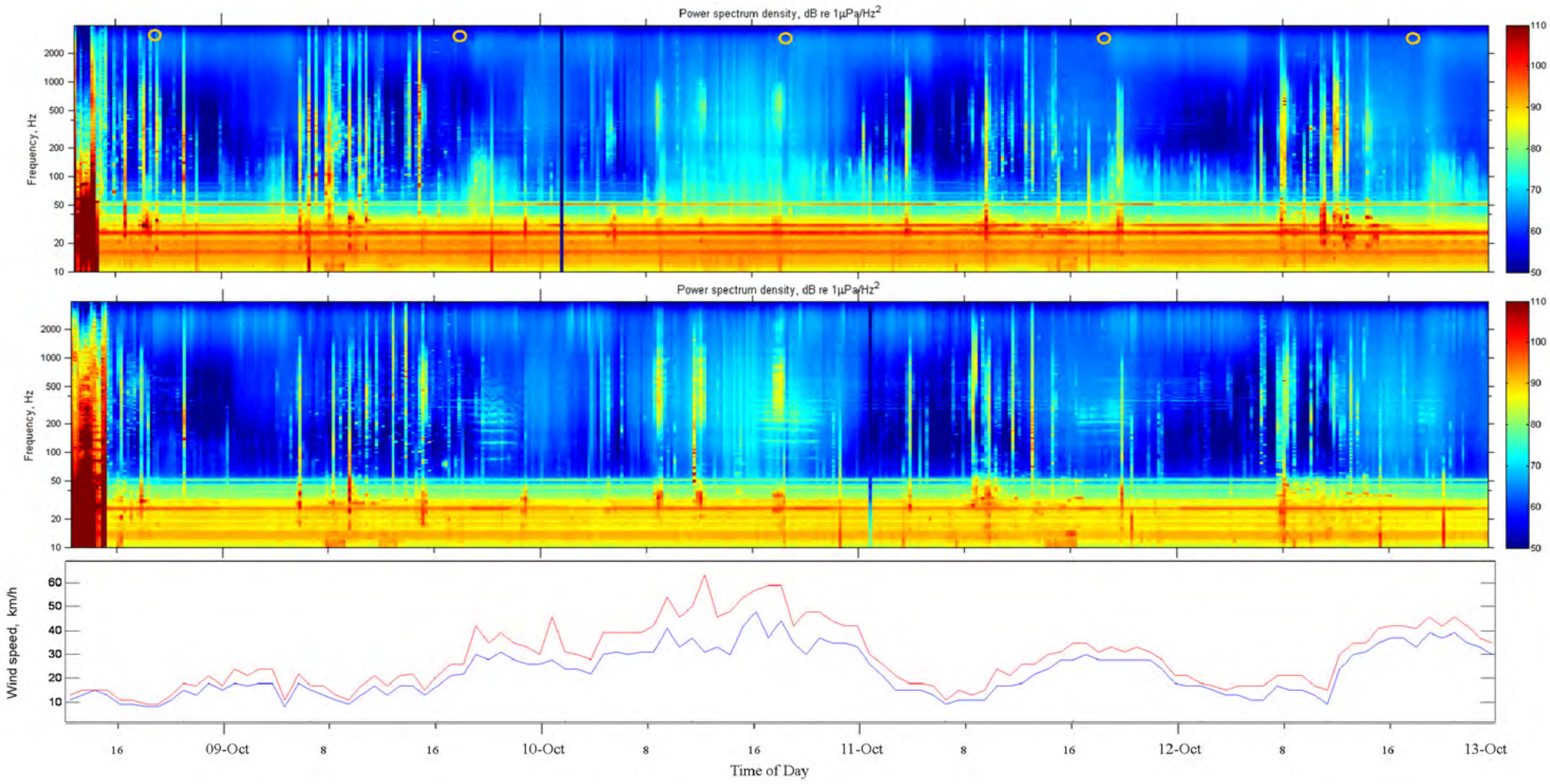

Figure 56. Stacked spectrograms of acoustic recordings taken at two sites in Cockburn Sound together with the hourly mean and maximum wind speeds (blue and red lines of bottom plot) measured at Garden Island provided by the Bureau of Meteorology. Orange circles in the top plot represent time of sunset. Points of interest have been highlighted and are explained in the text.

7.4 Black Bream

7.4.1 Anatomy

Dissections of mature male black bream donated by recreational fishers did not reveal any specialised mechanism of sound production. Figure 57 illustrates the positions and size of black bream swimbladder, gonads, internal organs and related musculature of a 27 cm black bream. Only white muscle fibres were observed surrounding the swimbladder, the volumes of which were 12 and 14 $cm^3 \pm 1$ cm^3. While they appeared to hang loose within the body cavity the gonads and internal organs filled a substantial part of the body cavity, leaving little room for vibration. No evidence of pharyngeal teeth capable of noise production was observed

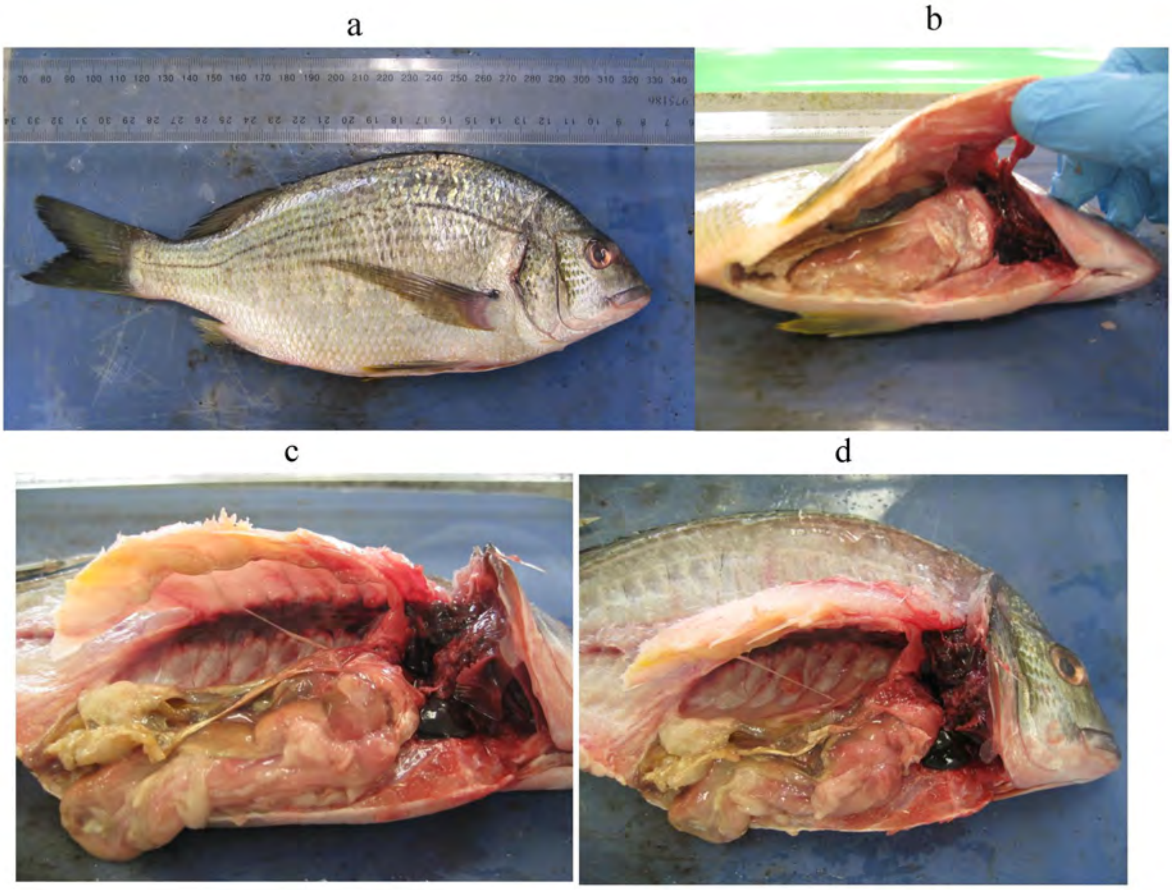

Figure 57. Stage VII spawning maturity, 25 cm male black bream donated by a recreational fisher during SwanFish (a), captured near Kent St Weir, the Swan River. Dissection highlighting the relative size of swimbladder, gonads and internal organs within the body cavity and lack of sonic muscle (b). White muscle fibres found surrounding the swimbladder (c) and lack of pharyngeal teeth likely to produce sound.

7.4.2 Theoretical modelling of call characteristics

Combined with the lack of associated specialised muscle tissue surrounding the swimbladder, a volume of approximately 15 cm^3 could create resonant frequencies at 10 m depth of approximately 300 Hz when assuming the swimbladder vibrates as a gas-filled bubble. As no evidence of sonic muscle was found and there was little area in the body cavity to vibrate, it is unlikely that this species produces calls of frequency greater than a 500 Hz. For modelling purposes, a contraction repetition frequency of 25 Hz has been assumed and the swimbladder has thus far been modelled as a prolate spheroid allowed to vibrate freely. The characteristics of a possible call, as generated by SynthCall, can be seen in Figure 58.

The acoustic recordings taken in the Frankland River raised the possibility of high frequency sounds produced via stridulation, perhaps the snapping of the jaws together. Sparids have been anecdotally reported as producing sound via stridulation of pharyngeal teeth (Luczkovich, pers. comm.). Parmentier *et al.* (2007) characterised the sound of the Clarkfish (*Amphiprion clarkii*) which while a member of the Pomacentridae family (in comparison with the black bream, sparid) produces sound through a series of jaw snaps. Without considerable biological analysis of the jaw structure of the black bream it would be difficult to model these calls. The biological examination did not provide evidence that black bream produce sound in this way.

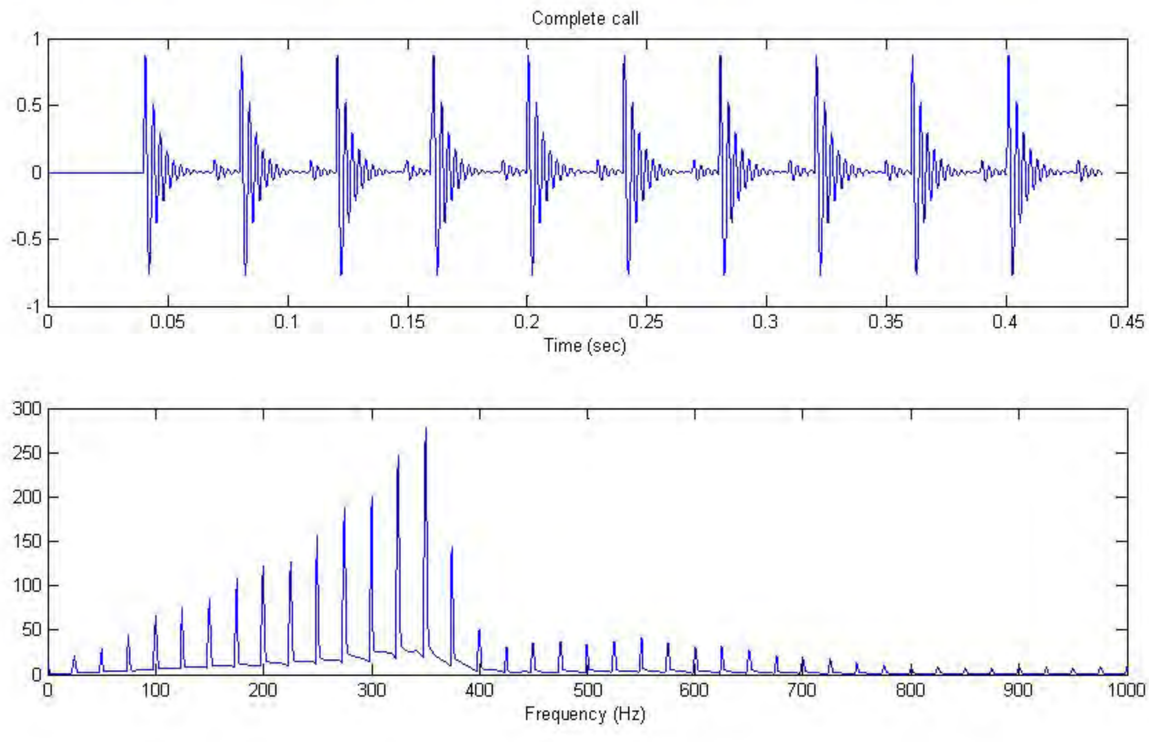

Figure 58. Predicted waveform (top) and power spectrum (bottom) of a black bream call of 10 pulses.

7.4.3 Acoustic recordings

Specific fish sounds were not detected in the Frankland River in 2010. However, anecdotal evidence from fishers suggest that spawning occurred early in the 2010 season and the black bream may have departed the sampled area of the river prior to the recordings. Spectrograms of the recordings taken in the Frankland River can be seen in Figure 59 for the 7 m deep hole (top plot) and the 11 m hole (bottom plot). Both recordings displayed increases in sound pressure levels below 250 Hz every day between 4 pm and 7 pm around the lead up to sunset. Broadband, high-frequency clicks (centred at frequencies greater than 2 kHz) of short duration, thought to originate from crustaceans were evident in both recordings. An expansion of 250 seconds from the recording at the 11 m deep hole can be seen in Figure 60. These sounds were most likely created by an invertebrate. In the deeper hole there was an increase in the high-frequency sounds in the late morning. Vessel noise was present in both datasets, but more prominent at the deeper hole which is a well known site and more accessible to local fishers. The recording from the deeper hole also displayed evidence of water movement, most likely originating from swimming fish. Low-frequency sounds (20 – 50 Hz) were evident in the early hours of the morning at both holes, and also around midday on the 24th October, 2011 in the deeper hole (Figure 59; the recording at the shallower hole had stopped by this point). Short-term low frequency sounds were also present in the deeper-hole recordings, due either to flow of water over the hydrophone or the hydrophone being knocked by something creating impulsive sounds of high energy.

Anecdotal evidence from fishers suggest that the late rain in the 2011 season delayed the arrival of the black bream into this area of the Frankland River, and that spawning may have been occurring during the acoustic recordings. During these recordings significant mooring noise up to 1000 Hz was observed for a period of 10 days (1st to 11th December, 2011, Figure 61, top image) from the early afternoon until several hours after dark (Figure 61, left hand images). These noises were due to tapping on the hydrophone (rather than wind-generated wave movement of the hydrophone), likely to be caused by an animal. As the mooring noises began, so did sounds between 100 and 500 Hz (predominantly around 200 Hz, Figure 61, right hand images). At their peak these sounds were produced throughout the day (sunrise to several hours after sunset). While the mooring noises became infrequent after the 11th December, 2011 the calls persisted for several days, at a considerably reduced rate, during hours of darkness (Figure 61, 11th to 14th December, 2011).

Aural inspection of the sounds between 100 and 500 Hz showed they were most likely generated by a vibrating swimbladder, though the mechanism of vibration and numbers of pulses within each call is unknown. Range could not be determined for the sounds, having the received levels were typically of the order of 113 dB re 1 μPa and not much above ambient noise levels. This indicates a call of low SL, a source at significant range or a combination of the two. As range could not be determined for these sounds the number of sources is unknown. Infrequent sounds (only four have been found for the entire recording period so far) most likely originating from fish and containing energy around 2000 Hz were observed (Figure 61, lower middle images).

Acoustic recordings taken during the capture and release of four black bream at various times during the course of the project have displayed no evidence of sound production.

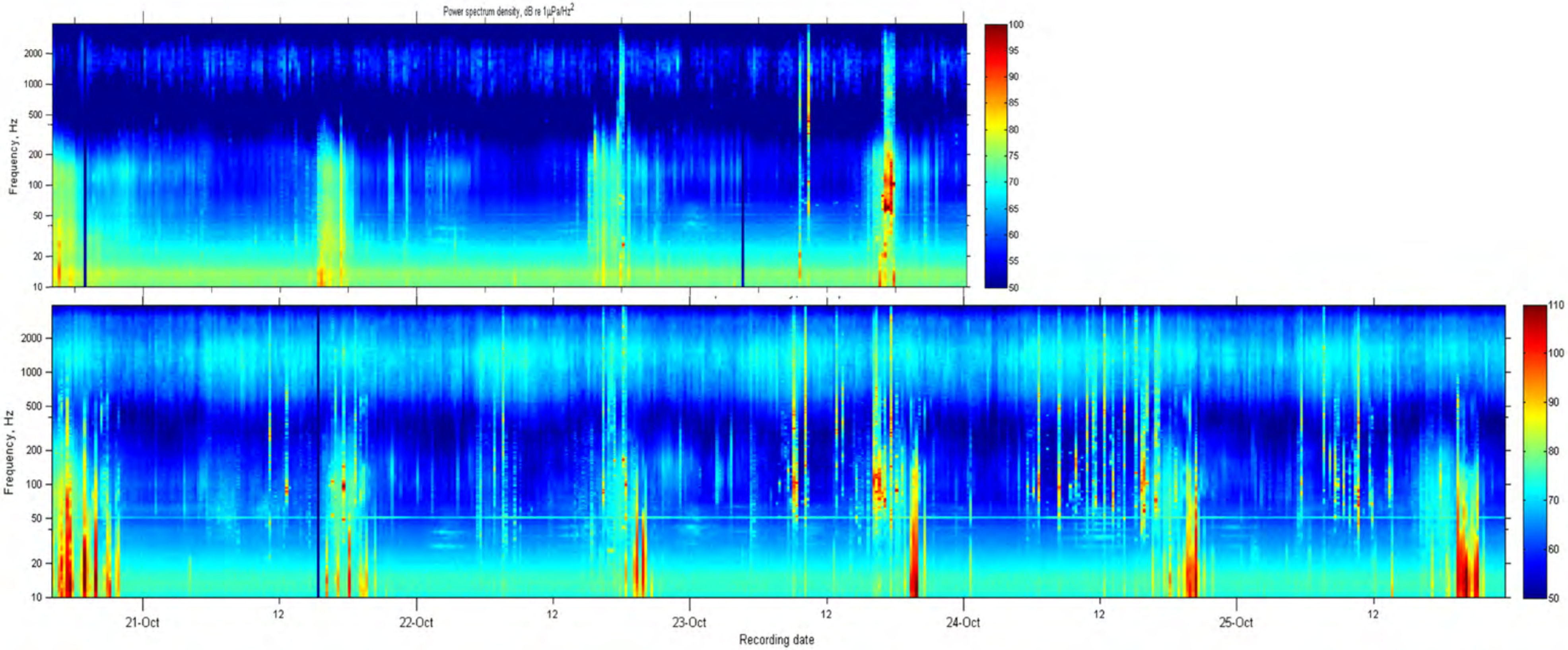

Figure 59. Stacked spectrograms of acoustic recordings taken at two sites speculated to be where aggregations of black bream form in the Frankland River.

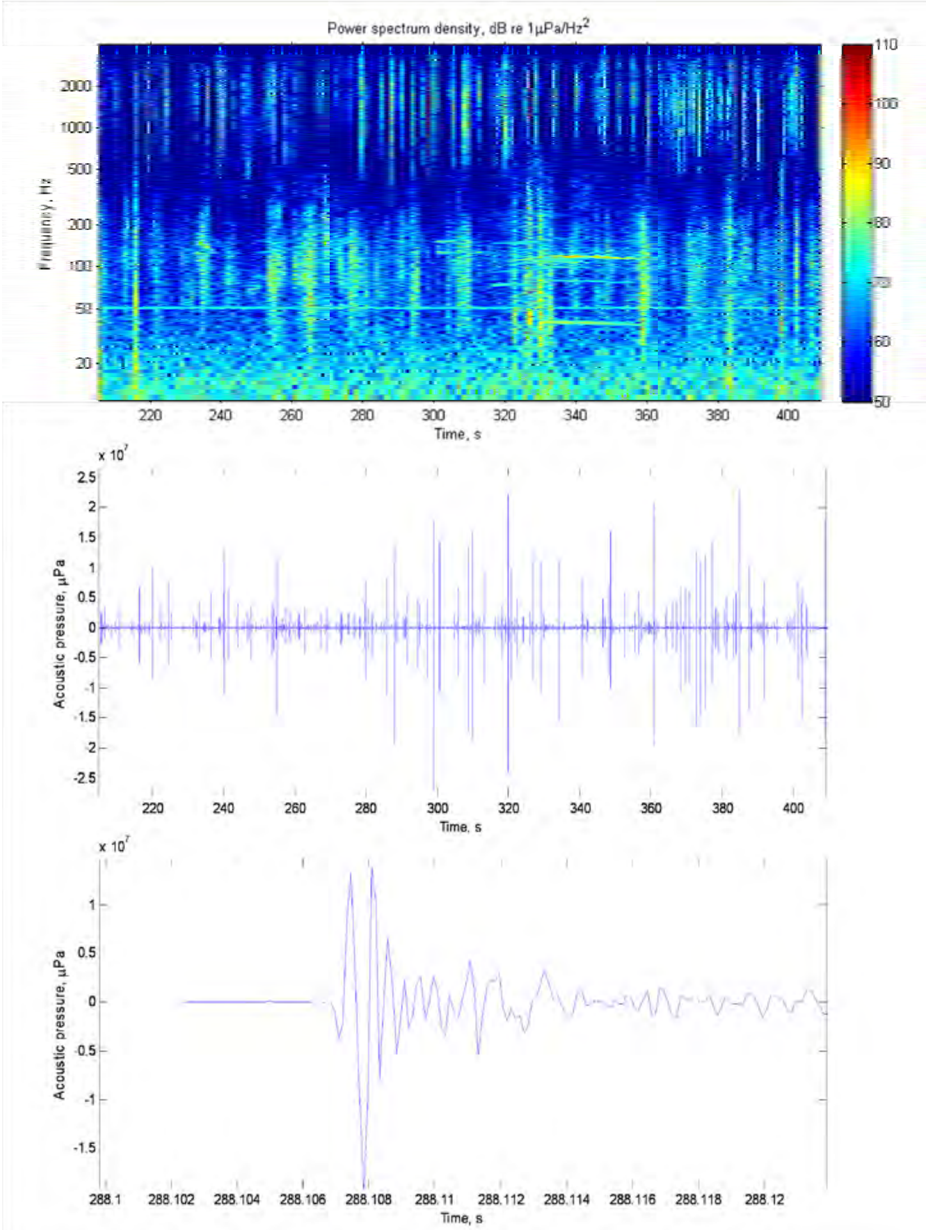

Figure 60. Spectrogram and waveforms from approximately 200 seconds of recording at 17:30 on the 22nd October, 2010 at an 11 m deep hole in the Frankland River. High frequency noises (≈1000 Hz) were observed around dusk, likely made by crustaceans.

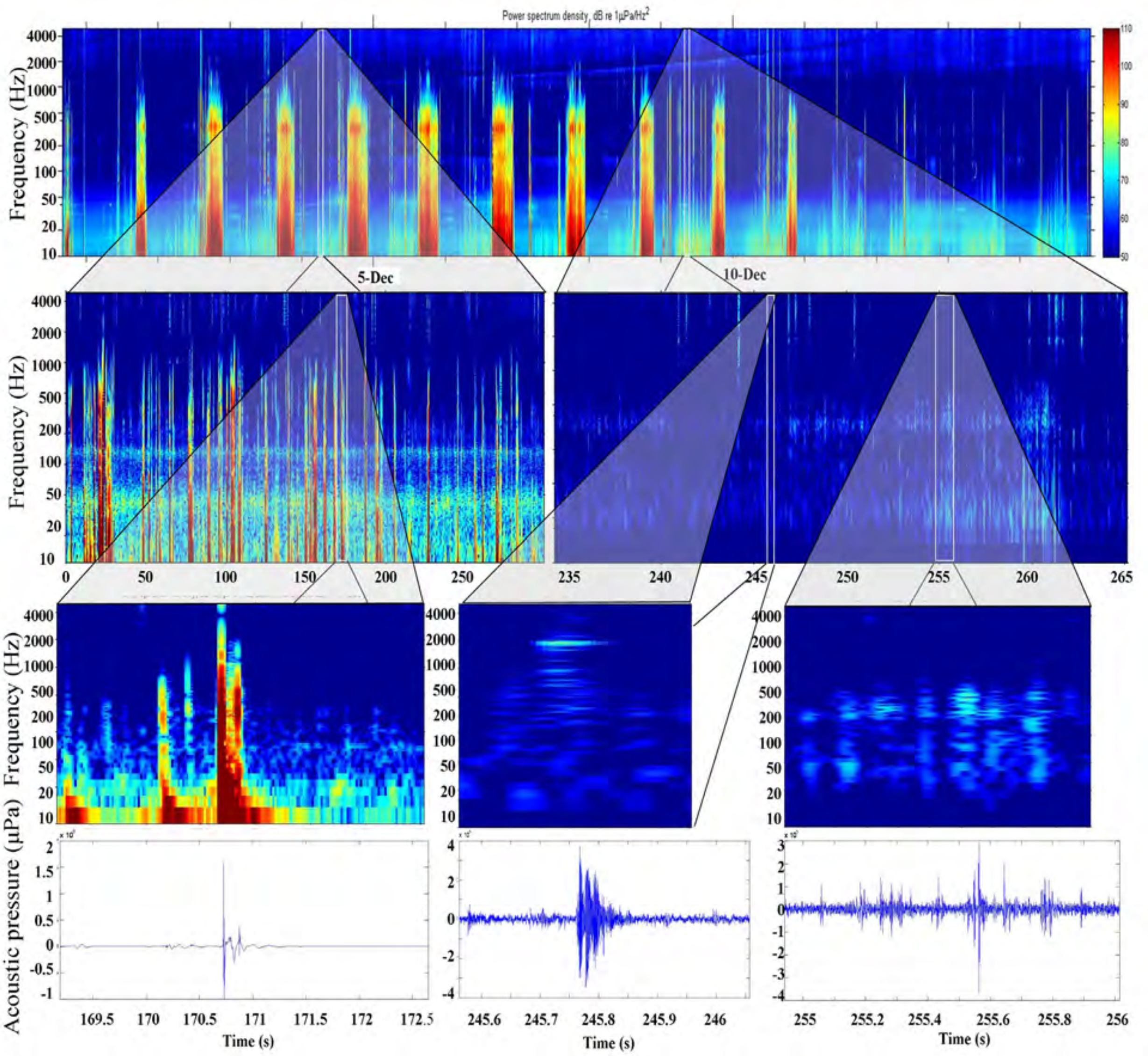

Figure 61. Stacked spectrograms of six days acoustic recordings taken in the Frankland River (top), together with expanded sections of the spectrograms (middle) and waveforms of signals of interest (bottom).

7.5 Fish calls and choruses from around Western Australia

During the course of this project numerous fish choruses and individual calls have been recorded. The choruses displayed interesting trends, providing information on the presence and timing of aggregations of vocal fish. The sources of many of these sounds remain unidentified. Some examples are described below.

Figure 62 illustrates three types of chorus which were observed on regular occasions in the Geographe Bay datasets; these images in particular were recorded at the HMAS Swan wreck. While these calls did not appear every day, they were often present for several consecutive days. The calls all appear around the time of sunset and on occasion at dawn. The coloured ellipses in Figure 62a shows increased spectral levels over three different frequency bands. The first types of calls to appear in the evening were at around 500 Hz (Figure 62b, black ellipse). These were short grunts which displayed sidebands of amplitude modulation, typical of a call from a fish possessing a swimbladder and very similar to those in Figure 44. Preliminary analysis suggests these calls appeared predominantly in December and January, but were present on occasion, through until April. Later in the evening calls centred around 1000 Hz occurred (Figure 62c, orange ellipse). The waveforms and aural characteristics of these calls are similar to noises produced by fish while eating, though this is speculation. Likely invertebrate noise followed these calls each evening (Figure 62d, green and orange ellipses).

There were also several different types of less frequent sound, as illustrated in Figure 63 and Figure 64, highlighting that numerous different sounds exist over the same frequency band. Those sounds of Figure 63 were found sporadically throughout the dataset and Figure 63b showed a striking resemblance in spectral content to that of Figure 49, recorded at the site where dhufish have been captured this season. Figure 64 presents a sound which has so far only been found once throughout the HMAS Swan wreck dataset, recorded in waters off Dunsborough, on the 10th December, 2012. The sidebands of amplitude modulation and lack of reverberation in the waveform suggest that this call originated from a nearby fish which produced sound via vibration of a swimbladder.

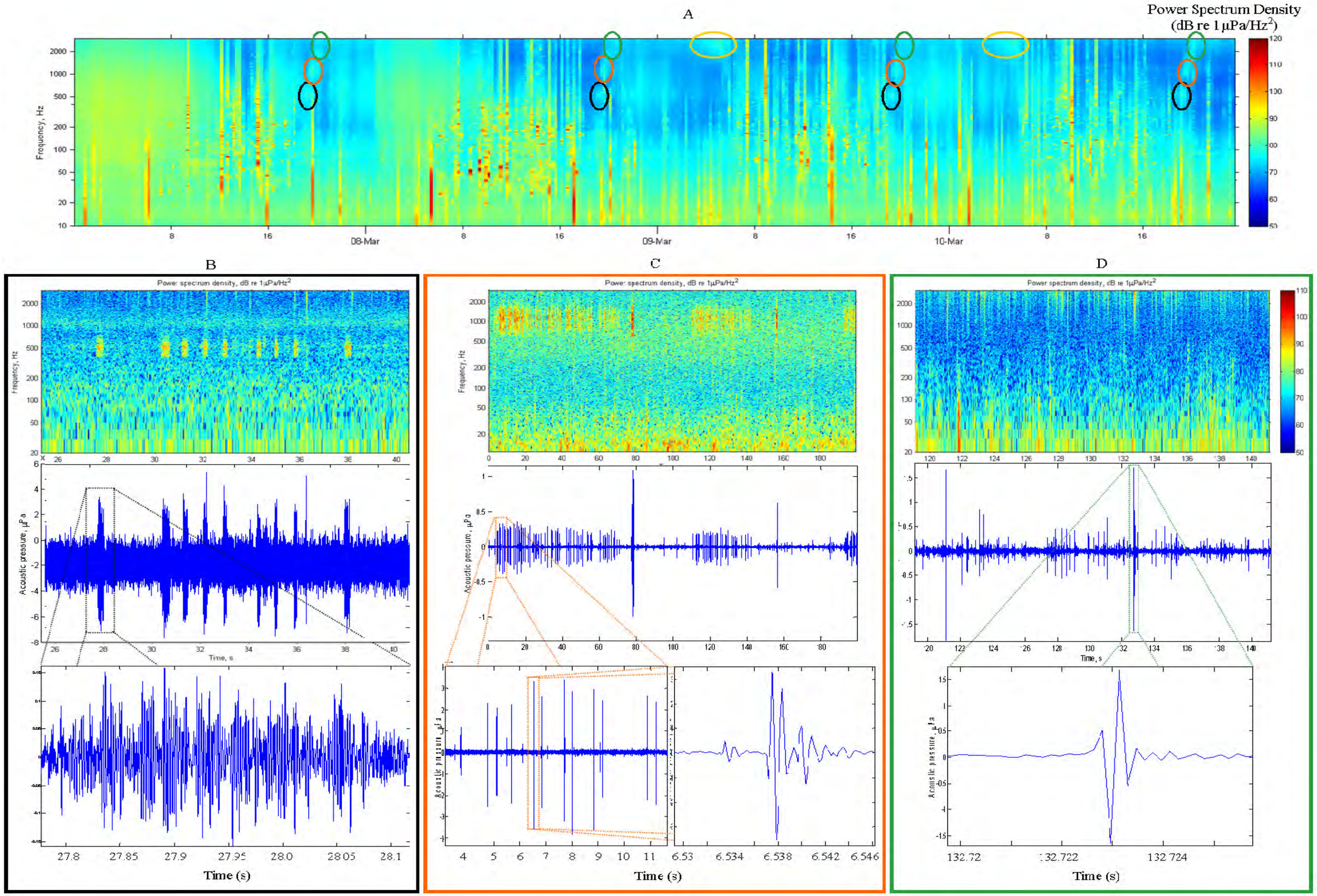

Figure 62. Spectrogram of three days acoustic recording in Geographe Bay (A). Magnified example spectrograms and waveforms for three types of recorded calls centred around 500 Hz, 1000 Hz and greater than 2000 Hz (B, C and D, respectively). Points of interest are explained in the text. Image taken from Parsons et al. (2013a).

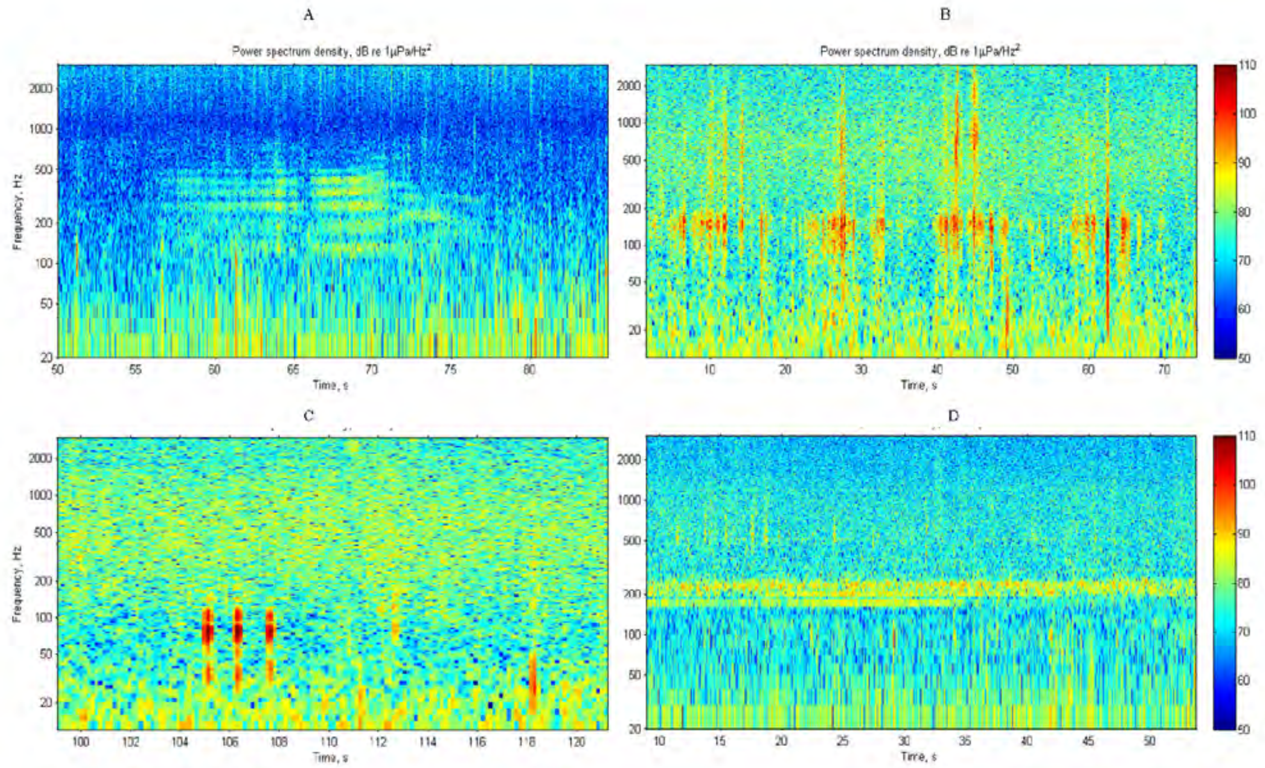

Figure 63. Spectrograms of four types of unidentified sounds recorded in Geographe Bay, 2009/10.

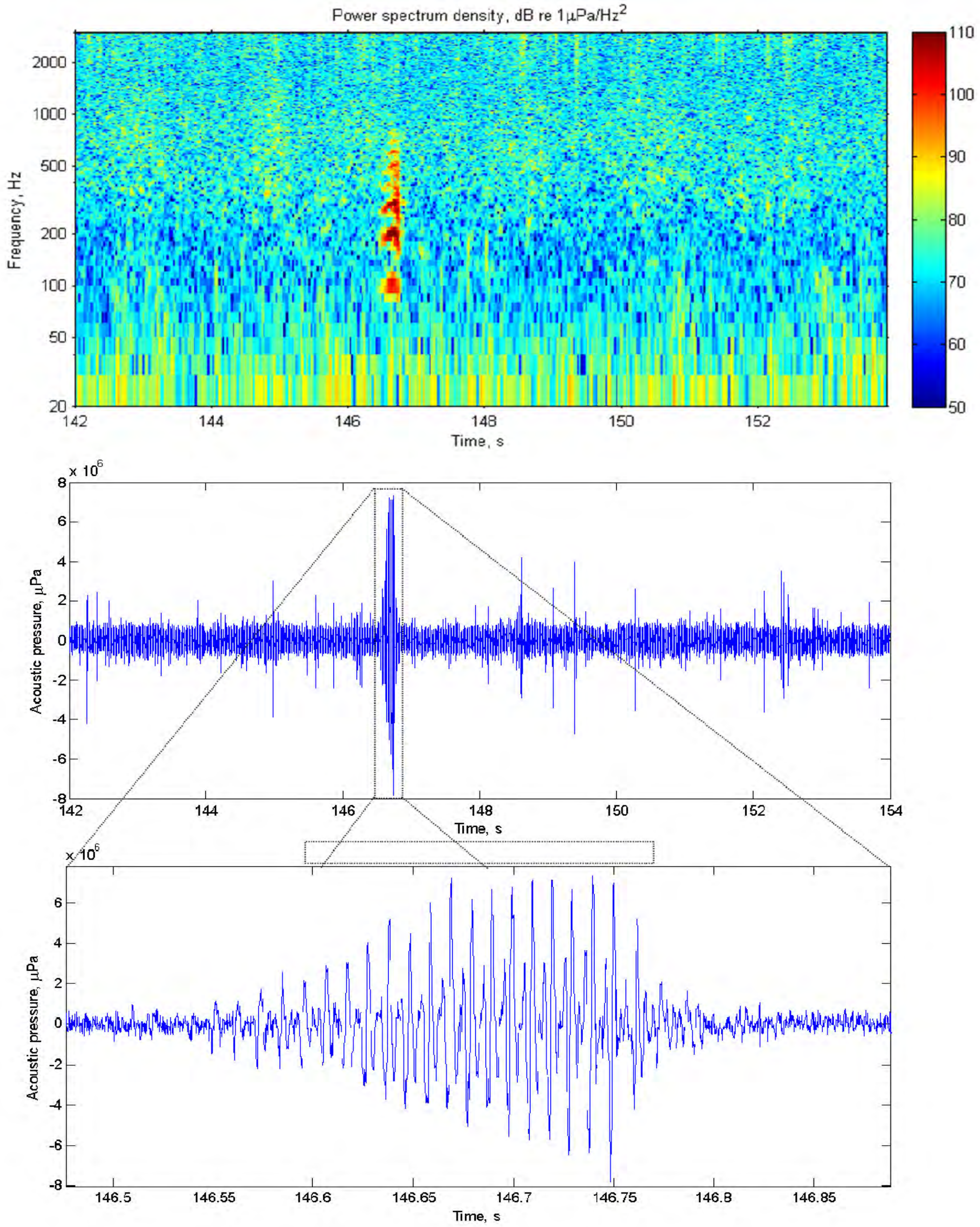

Figure 64. Spectrogram and waveform of an unidentified call recorded on 10th December 2010 at approximately 10:15 in Geographe Bay.

Figure 65, Figure 66 and Figure 67 illustrate spectrograms and waveforms of several calls taken from recordings acquired at two sites in Geographe Bay and one in waters off Cowaramup. All three types of sound possess acoustic characteristics to suggest they are produced via vibration of a swimbladder.

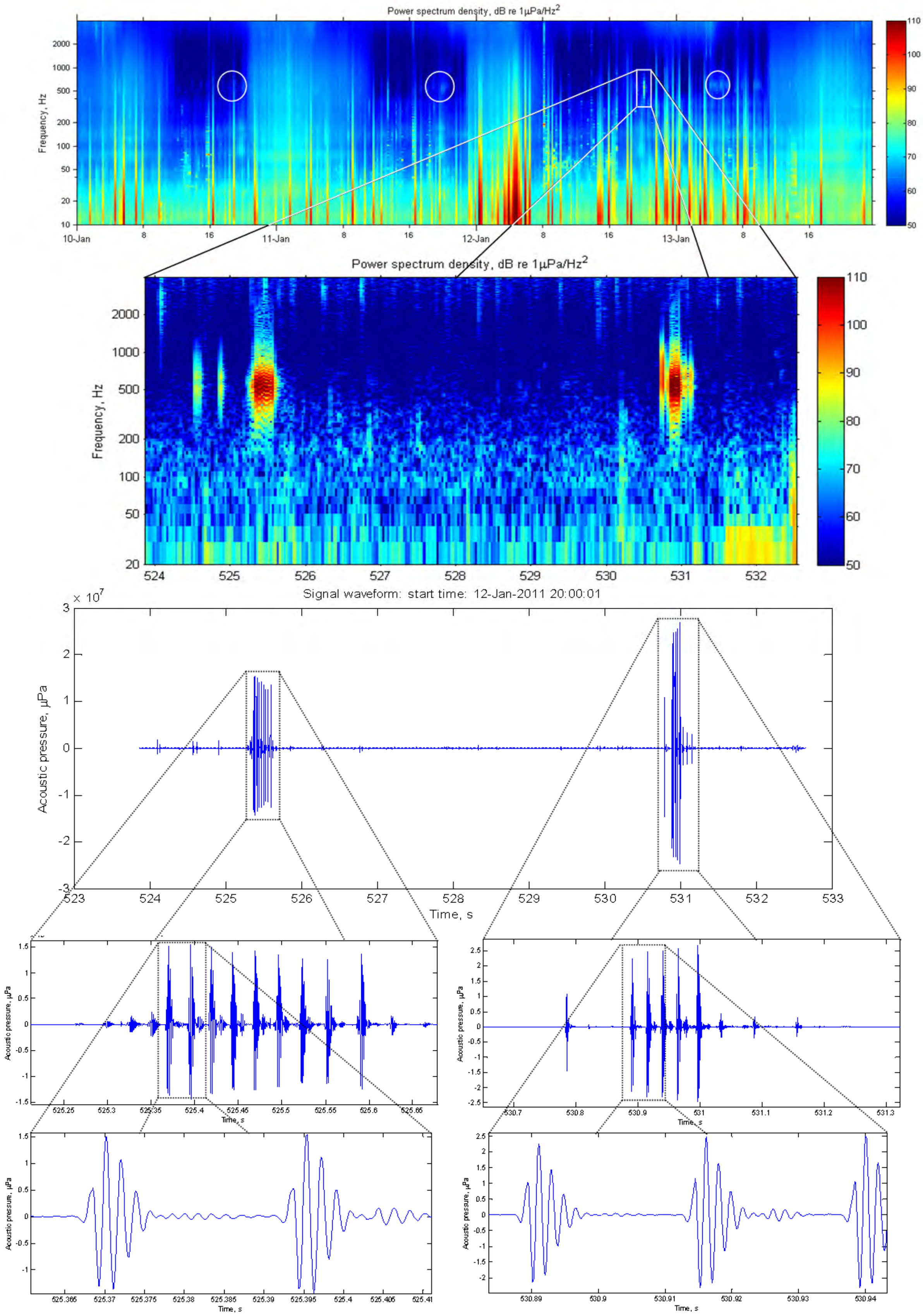

Figure 65. Spectrogram of 4 days recording in Geographe Bay with a magnified spectrogram of 10 s at approximately 20:00 hrs on the 12th January, 2011. Waveforms of two recorded calls are shown with swimbladder pulses magnified. Circles in the top spectrogram highlight periods at dawn and dusk when similar calls were observed.

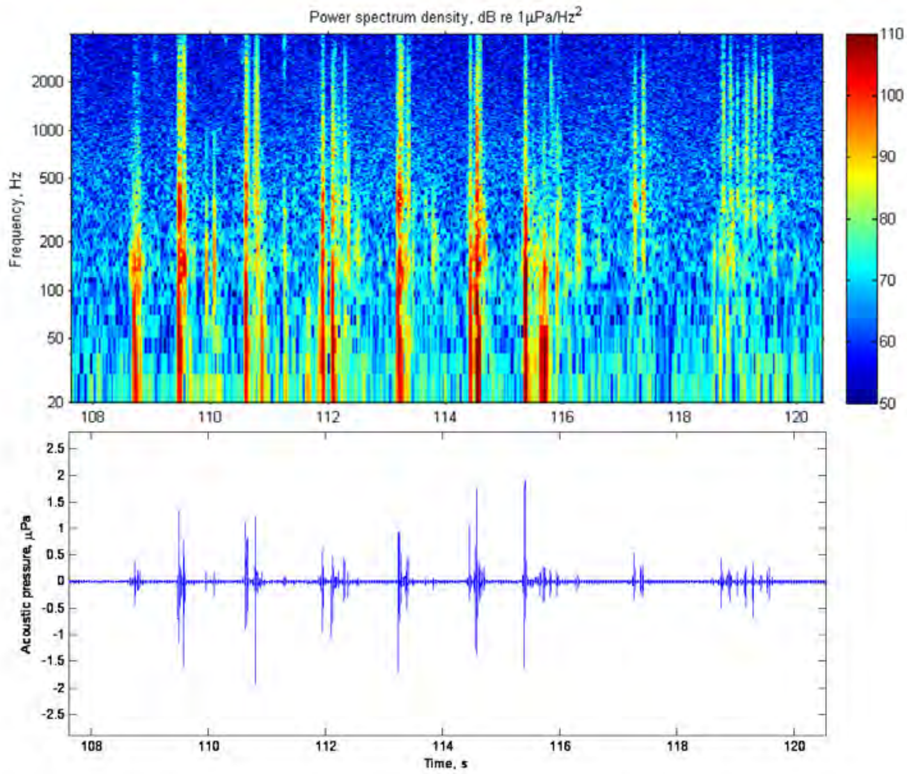

Figure 66. Spectrogram and waveform of 13 s recording at a possible 'lump' occupied by a WA dhufish, in 27 m of water, Geographe Bay on the 14th January, 2011 (location supplied by local recreational fisher). Note signals between 116 and 120 s.

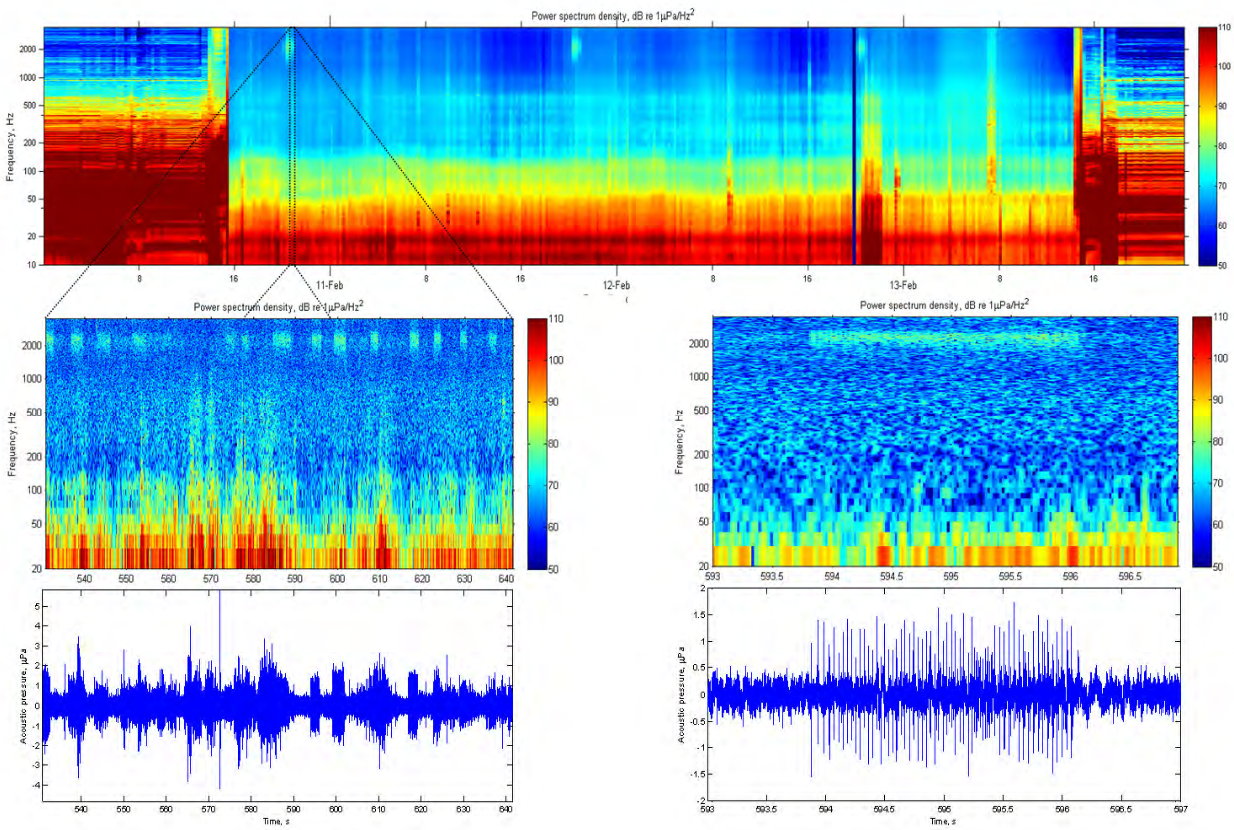

Figure 67. Spectrogram of three days recording on 2nd Feb 2010 in 40 m of water off Cowaramup Bay.

Through this and other projects over 30 different types of fish calls and over 15 fish choruses have been detected around Western Australia by CMST (McCauley, 2012, Parsons *et al*., 2009, 2010, 2012a, c, 2013a, b, c).

7.6 Summary

The following findings for each of the target species have been confirmed:

Mulloway

- Source levels of three categories of mulloway call have been confirmed;
- Significant variation in frequency within individual mulloway calls has been detected. Whether this frequency change is voluntary has not been determined. While the frequency range of the variation is of an order that can be detected by some species, whether mulloway can detect this frequency change and whether an intended recipient could detect the variation within the short time of a single call has not been determined. If voluntary, the behavioural implications of these variations could provide information on the species spawning;
- Spatial mapping of mulloway in the Swan and Canning River systems has been conducted confirming calling fish between Mosman Bay and Blackwall Reach, at Rocky Bay, Fremantle Port and upstream as far as Riverton Bridge and Canning St Weir;
- No sounds were detected at the Causeway Bridge although anecdotal evidence from fishers show that mulloway have been caught at this site. It is likely that the timing of spot recordings was not sufficient to record sounds at all sites;
- Temporal variations in mulloway calls along the Swan River show that the mulloway move along the river and that for a full picture of how many are in the river at any given time it is necessary to simultaneously conduct long-term (longer than one month) deployments at numerous sties along the Swan.
- A chorus of mulloway was detected and temporally mapped at Garden Island and mulloway calls (to few to meet the criteria of being a chorus) were detected in Cockburn Sound, Abrolhos Islands, Shark Bay, Myalup Beach, Geographe Bay, Augusta;
- Long-term trends in sound production at Mosman Bay have shown seasonal, lunar, semi-lunar and 3.97 day trends in the intensity of sound pressure levels. In order of effect the intensity of calling has been related to temperature, salinity, sunset, lunar phase, pH and O_2 levels. The timing of peak spawning has been related to sunset, lunar phase, salinity and temperature;
- While only simple propagation methods have been employed it has been shown that noise from passing vessels can restrict the detection of mulloway calls from hundreds of metres to tens of metres or less. The impact on courtship behaviour and spawning success has not been evaluated;
- A method for estimating the number of calling fish detected by a single hydrophone has been laid out. This adapts a method used by Sprague and Luczkovich (2012) designed for a compact aggregation of low SL fish to account for more dispersed callers emitting sounds of greater SL. This method requires ground truthing. One possible way of ground-truthing is to study an aggregation of mulloway in a sea cage;

West Australian dhufish

- Sonic muscles attached to the anterior of the swimbladder and the rear sides of the brain casing have been identified;
- This study has confirmed that mature and juvenile WA dhufish produce sound, both in their natural environment and during capture;
- While it is confirmed the species calls in distress, the functions behind calls produced in the wild have yet to be determined.
- *In situ* calls have been detected in recordings taken at a site where recreational fishers catch WA dhufish in significant numbers each year, at a time when they are predicted to be spawning. Both individual calls and an increase in SPLs over a frequency similar to that of the species calls over a period when anecdotal evidence suggest WA dhufish were present in increased numbers at that time.
- The species produce calls at a maximum SL of 137 dB re 1 μPa which means that in waters of ambient noise levels less than 87 dB re 1 μPa, if producing sound, the fish could be detected by a sea noise-logger at ranges of up to >250 m.
- This provides an autonomous tool with which a large area (up to 0.2 km^2) can be remotely sampled for presence of WA dhufish.

In comparison with the 2011-12 season, the 2012-13 deployment off Cape Naturaliste showed evidence of few dhufish calls. However, anecdotal evidence suggested that a limited number of dhufish were caught during the period of the deployment. It is worth considering that the strong surge/current, as detected by the regular surge noise and mooring noise observed on each of the three loggers, could influence spawning behaviour of dhufish.

Snapper

- No specialised mechanism for sound production was identified on biological examination of mature males and females;
- No direct evidence of snapper calls has been detected in recordings taken around spawning or captured snapper;
- The volume of the snapper swimbladder suggested that it is feasible that vigorous swimming could cause vibration at resonant frequency and produce energy in the region of 50-100 Hz;
- Spectral levels below 200 Hz increased in Shark Bay and Cockburn Sound recordings shortly after sunset each evening, however, this typically occurred 3-5 hours after an increase in local wind levels, which was most likely to be the cause of increase in ambient noise;

It is suggested therefore that snapper are not soniferous and not suitable for passive acoustic monitoring.

The DoFWA frequently use a Humminbird sidescan sonar to locate snapper in Cockburn Sound for sampling. While sidescan sonar may help locate snapper, it is believed that a sideways mounted MBS system would be able to map the volume of the school while maintaining sufficient range to limit vessel avoidance and therefore monitor the numbers of snapper. Unfortunately, no MBS system was available for this study to confirm these hypotheses. This has therefore been deemed future work for the CMST to complete and is anticipated to be conducted in November, 2013.

Black bream

- No specialised mechanism for sound production was identified on biological examination of mature black bream;
- No direct evidence of black bream calls has been detected in recordings taken in the Frankland River or during capture;
- Mooring sounds increased and possible fish calls were detected around a period when recreational fishers were catching black bream. While biological sounds were of low received levels it is possible that these noises could be used to detect the presence of black bream in their spawning area.

Investigation of the sounds detected in the Frankland River to confirm whether they originated from black bream would require significant investigation and therefore it is currently deemed that passive acoustic techniques, while possibly capable of gleaning indirect information on the presence of black bream, this is not an efficient way to collect data.

Other fish sounds

A variety of fish sounds, many from as yet, unidentified sources have been recorded across Western Australia and numerous choruses have been found to occur on a regular, predictable basis, in temperature and tropical waters, (McCauley, 2012, Parsons *et al*., 2012a, c, 2013a, b).

- Over 30 individual types of fish sounds and over 15 different choruses have been detected in Western Australian waters in CMST projects over recent years;
- Deployments in this project have detected at least 12 types of calls, eight of which have not been previously described and four choruses which have also not been previously described;
- The detected choruses in Geographe Bay overlapped in frequency band and time, however, spectral peak frequencies were significantly different;
- Choruses detected off Cape Naturaliste were similar to others recorded around WA;

Further effort is required to determine which species produces each sound and thus whether these choruses originate from commercially or recreationally important fish. The chorus regularity and variation in intensity show that changes in aggregations can be detected and passive acoustic recording provides information on a number of species of fish on the WA coast.

7.7 Application of passive acoustics to fisheries monitoring

The collapse of multiple fisheries around the globe, through overfishing of spawning aggregations, has made their sustainable management a high priority worldwide. For some (aggregating) species this can be done through management of the spawning aggregations. In Australia, stock depletion and collapse has been noted for various species (Jackson, 2007, Phelan *et al*., 2008) and awareness of the need to manage aggregation fishing has been increasing (Sadovy and Domeier, 2005, Mackie *et al*., 2009). For some species measures have been put in place to help avoid overfishing, such as the temporal closures for fishing snapper in Shark Bay (Anon. 1999) and

Cockburn Sound (Jackson, 2007), which have been noted as one of the most effective methods of sustaining stocks of such species (Jackson, 2007). However, given the variations in aggregation timing and location such closures need to be sufficient to allow for annual variation. Early aggregation of a snapper in Cockburn Sound, for example, could result in a large increase in catch immediately prior to the closure, and thus depletion of stocks just before spawning.

In recent years the change in ethos from single-species management to incorporate a more ecosystem based fisheries management approach has been developed by the DoFWA, alongside the use of 'weight of evidence' approaches in assessments, that support management decisions (Wise *et al*., 2007, Mackie *et al*., 2009). In addition to current traditional sampling techniques, a complementary data source, such as that from acoustic recordings of underwater 'soundscapes' and the sounds produced by fish, could significantly enhance knowledge of aspects of the behaviour of data deficient species or particular aggregations of a species (Parsons *et al*., 2012a, b, c). So far, over 800 species of fish from 109 families around the world have been shown to produce sound via different mechanisms (Kaatz, 2002, Slabbekorn *et al*., 2010), including some which support commercially important invertebrate fisheries (Fish, 1964, 1966, Moulton, 1963). In Western Australia, new fish sounds and choruses are being detected and characterised each year (McCauley, 2012, Parsons *et al*., 2009, 2012a, b, c, 2013a, b). The timing, intensity and location of fish choruses and the regularity with which they form can provide insights into the ecology of the source species.

A prime example of passive acoustic aiding management of important fisheries is the Nassau grouper (*Epinephelus striatus*), which once formed large, predictable aggregations, but due to over-fishing is now officially classed as endangered in the Caribbean and tropical western Atlantic (Sadovy and Domeier, 2005). Having been shown to be soniferous during spawning (Hazlett and Winn, 1962, Sharer *et al*., 2012), considerable effort has gone into characterising the Nassau grouper calls and applying passive acoustic recording to monitoring individuals and movement patterns and size of some aggregations (Rowell *et al*., 2010) to adapt management of the stocks. In temperate waters the Atlantic cod (*Gadus morhua*) has undergone similar depletion and it is the study of their vocal behaviour during courtship and spawning aggregations which is helping understand more about their ecology to improve management decisions (Brawn, 1961a, 1961b, 1961c, Nilsson, 2004, Fish and Mowbray, 1970, Hawkins and Rasmussen 1978, Nordeide and Kjellsby, 1999, Finstad and Nordeide 2004).

This section will describe the applications of passive acoustic recording of fish sounds in studying fish species and their potential for providing management advice with particular regard to the target species of this project. The steps involved in conducting passive acoustic studies in themselves illustrate some of the applications to monitoring a population of fish.

7.7.1 Identifying vocal species and characterising calls

Since the 1950s researchers have been recording sounds produced by fish and producing catalogues to identify a species by sound (Moulton, 1964, Fish, 1953, Fish and Mowbray, 1970). Many species produce species-characteristic sounds at a constant frequency, call rate and SL, allowing them to be discerned from other calling fish in the area (Mok and Gilmore, 1983). The mulloway in the Swan River, for example, emit three categories of calls via trains of swimbladder pulses at modulation and resonant frequencies of 60 and 275 Hz, respectively, where no other fish emits a similar signal (Parsons, 2010). Confirming a species is soniferous can be done in two ways:

1) In captivity, such as the WA dhufish in this study (captured in the wild and recorded at the side of the boat) and the mulloway recorded in aquaculture at the Challenger Institute of Technology (Parsons, 2010), or;
2) *In situ*, such as the recording of a weakfish passing by a hydrophone array and underwater video system (Sprague and Luczkovich, 2004).

Each method has its drawbacks. Captivity not only affects behaviour, but if recordings are taken *in aquaria* it requires consideration of reverberation effects on the tank (Okumura *et al*., 2002). By comparison, *in situ* recordings do not affect natural behaviours, but are often difficult to ground-truth (for example, visual confirmation of species or collection of eggs to confirm spawning behaviour), especially in dark or turbid waters (Parsons, 2010).

The production of sound by fishes is most commonly associated with spawning, territorial displays and distress, but also with feeding, exploration and other associated functions (Winn, 1964). Characterising the associated behavioural functions with calls means that in future surveys, biologists and managers can glean significant insights into fish behaviour from remote recordings. Some species have limited vocal repertoire whilst spawning, emitting one type of call for prolonged periods such as the Atlantic cod or mulloway, while others, such as the haddock, produce different calls at different stages of spawning (Hawkins, 1986, Hawkins and Rasmussen, 1978, Nordeide and Folstad, 2000, Parsons, 2010). Thus passive acoustics can offer fine-scale information on spawning times and possibly an insight to whether courtship has been successful.

For a given fish species, sounds produced by vibrating a swimbladder generally decrease in spectral peak frequency and modulation frequency with increasing fish size (Connaughton *et al*., 1996, 2000, 2002a, 2002b). Thus, once calls of a species have been characterised the frequency of other calls recorded *in situ* can provide information on the relative size of the calling fish, possibly leading to a coarse estimate of size distribution. Call frequency can be a significant cue for mate selection in courtship (Myrberg and Spieres, 1972, Emlen and Oring, 1977). In addition, some species produce a large repertoire of calls (Nilsson, 2004), some of which vary in frequency content within a single call (Section 4.1.1.3). Understanding if these variations are voluntary, whether the recipients can detect these variations and whether there are any implications for associated behaviours, such as mate choice, is important information for biologists (Myrberg and Spieres, 1972, 1980 Myrberg *et al.,* 1993). For example, if discernible to female of a spawning species, the suite of acoustic descriptors above would provide a call recipient with information on the size, health and possibly spawning capacity of a calling male, i.e. some of the attributes required to select a male for spawning. Characteristics of fish calls can vary with environmental conditions, e.g. increases in call frequency or SL have been recorded with increasing water temperature (Connaughton *et al*., 2000, Section 4.1.4). Thus it is important for biologists to understand how the conditions can affect call characteristics before assessing how they can inform the researcher.

7.7.2 Locating vocal fish

The identification of Essential Fish Habitat (EFH) is one of the most fundamental steps in fisheries management. At its most basic description EFH is simply a habitat where fish are present, with the complete definition in the Magnuson Stevens Fishery conservation and Management Act being "those waters and substrates necessary for fish for spawning, feeding or growth to maturity". Even with historical knowledge supplied by experienced fishers, scientists often exert considerable effort to identify habitats and locations where a particular species can be found. Locating a habitat and time where those fish are aggregated in sufficient number to study effectively can be even more time consuming. Traditional Chinese fishermen have been using sound to locate EFH for hundreds of years, by listening to the sounds of spawning sciaenids through the hulls of their wooden boats (Moulton, 1964).

Once a species' sound(s) have been identified it becomes a case of locating those sounds. This is conducted routinely to delineate EFH, such as spawning areas and feeding grounds (Hawkins, 1986, Mok and Gilmore, 1983, Rountree *et al*., 2002, 2006) using towed or fixed arrays of hydrophones (Gilmore, 2002, Barimo and Fine 1998, Mann and Jarvis, 2004, Parsons *et al*., 2009) or multiple deployments of a single hydrophone such as in the Swan River. Delimiting areas of EFH is of particular use to management decisions such as fishery closure zones or marine reserves, particularly when considering endangered species like the Nassau grouper (Rowell *et al*., 2010). Within these areas, fine-scale localisation of calling fish using an array of hydrophones can be used to observe natural behaviour of individuals (Parsons *et al*., 2009), though once choruses reach calling density where sounds overlap discerning a single caller becomes problematic.

7.7.3 Temporal and spatial patterns

Many species are vocal for specific periods, sometimes only a few hours a day (Rountree *et al*., 2006). Alternatively they may move around a broad area vocalising in more than one place, such as the mulloway moving along the Swan River. When these calls or choruses are associated with spawning the delimiting of the aggregation timing offers information to fisheries researchers and managers in designing sampling regimes and determining the timing of closures to fishing. Some Sciaenids and Gadids, for example, exhibit crepuscular or nocturnal soniferous behaviour (Hawkins and Rasmussen, 1978, Mok and Gilmore, 1983). Ueng *et al.* (1998) noted mulloway sound production and spawning at low light levels and compared the behaviour to that of other species, describing mulloway vocalisation after dusk and pre dawn as nocturnal. In contrast, sound production during the several hours prior to sunset in Mosman Bay, and the lack of dawn chorus showed that mulloway is not purely nocturnal, thus spawning and chorus behaviour can be site specific. Barrios (2004) linked sound production patterns from black drum to tidal patterns. Lunar spawning in Sciaenidae has been regularly reported, occasionally using point data of sound production as confirmation (Holt *et al.*, 1985, Aalbers, 2008, Lowerre-Barbieri *et al.*, 2008). Semi-lunar spawning, at new and full moons has been reported in spotted seatrout (*Cynoscion nebulosus*), as well as other marine and estuarine fishes (Takemura, 2007, Manabe *et al.*, 2008). The daily timing and relative size of an aggregation may be related to a number of environmental drivers interacting at different temporal scales. For example, in Mosman Bay the daily chorus times were related to time of sunset (seasonal) and the moon phase (monthly), while the SPLs and by proxy the size of the aggregation was also related to water temperature, salinity, dissolved O_2 and pH. Peak mulloway chorus levels in Mosman Bay and egg abundance in aquaria have shown cycles on 3-4 day timescales. Season-long deployments of acoustic loggers enable the response of fish to ecological drivers to be teased out of the data and modelled so that the timing of any temporal closures can be designed around known environmental conditions.

7.7.4 Abundance

Estimating the abundance of fish in an aggregation, at any given time, is one of the ultimate goals of fisheries science (Rountree et al., 2006).

During periods where individual calls can be discerned, the number of calls can be related to the number of callers. Alternatively, callers may be separated and counted individually, such as the Mosman Bay mulloway. However, an aggregation of considerable size will include overlapping calls, so numerous that individuals cannot be distinguished. Up to 15 callers were counted at any one time in Mosman Bay, however, once more callers contributed to the chorus, they could not be separated.

If each fish calls at a species specific SL, then through partial pressure theorem it follows that the overall SPL of an aggregation is related to the number of fish calling at that time (McCauley, 2001, Sprague and Luczkovich, 2004, Parsons *et al*., 2012b). Luczkovich *et al*. (1999) determined a relationship between SPLs of weakfish choruses and the abundance of eggs, suggesting that the SPLs related to the number of fish in the aggregation.

One of the first steps of determining an individual fish's contribution to SPLs is to establish the SL of its calls (Parsons *et al*., 2012b). In an ideal world this is done by recording and visually ground-truthing a fish behaving naturally, calling at a range of 1 m from the hydrophone. However, this is an exceptionally fortuitous event and not often reported (Sprague and Luczkovich, 2004). An alternative is to locate a fish at a known range and location, typically by using a hydrophone array (Parsons *et al*., 2009, Locascio and Mann, 2011). To relate the RLs recorded to the SL of the fish requires identifying the energy lost as the sound propagates from source to receiver (McCauley, 2001). This requires knowledge of the acoustic characteristics of the area (bathymetry, substrate properties, temperature, salinity) and accurate positions of the fish and hydrophone in three dimensions. If enough localised calls are recorded it is possible to determine the transmission losses of an area through regression of the RLs of all the calls (Parsons *et al*., 2012b).

Given a known SL and mean rate of calling for the fish the contribution to average SPLs over a given period can be calculated (Section 4.1.5). However, not all calling fish are located 1 m from the hydrophone and the distribution of the callers must be estimated. The simplest technique is to assume a random distribution of fish (Sprague and Luczkovich, 2012) and set an outer limit on the range of the callers. Sprague and Luczkovich (2012) used a finite difference time domain model to predict the SPLs that would be recorded from a randomly distributed aggregation of calling weakfish up to a range of 30 m, in <10 m of water, compared with that of a single weakfish at 1 m range. This provided results very similar to the recordings they acquired North Carolina and results suggested up to 1000 fish within a 30 m radius of the hydrophone (i.e. 0.12 m^{-3} per fish), compared with a density of up to 0.5 m^{-3} volume specific density detected for weakfish by echosounders in the same region. However, this modelling is for a species call of SL 127 dB re 1μPa (Luczkovich *et al*.,

1999) over a small area. In this study, mulloway produce calls of up to 172 dB re 1μPa and have been detected up to 500 m away from the receiver. If callers produce sounds of high SL and are separated over a broad area, callers at significant range (>100 m) can still contribute energy to the overall SPLs. A single caller at close range (<10 m) would substantially skew abundance estimates and overestimate the number of fish present. However, unusually close range callers can be detected from the amplitude of their calls compared to the rest of the chorus. For example, three different conditions could produce the same SPLs: a single caller at 2 m; one caller at 30 m range, three at 60 m and four at 120 m or; thirty six callers at 100 m range, all produce the same SPLs over a two minute calling period. It is possible to detect the 2 m and 30 m callers from the pressure waveform. Once these callers have been removed confidence levels in the revised abundance estimate would be considerably improved.

This provides an estimate of the number of calling fish within the aggregation, however, it is necessary to note that passive acoustic recording can only describe the fish that are vocal within an area. There are several considerations which must be accounted for before an estimate of caller numbers can be converted to an absolute abundance estimate. For example, does a caller maintain their calling throughout the entire spawning cycle? If they cease calling it is not always possible to locate them again (Parsons *et al*., 2009), thus it is not always possible to determine whether the fish leaves the aggregation, having completed its role, or if it restarts calling at the same place, or another location. While in many species sonic muscles are a sexual dimorphic trait and only males call, this is not always the case. It is necessary to discern whether females produce sound, at what times and, what proportion of the sound is produce by females compared with males (Lagardere and Mariani, 2006, Ueng *et al*., 2007). If it is only males which call, do adults and juveniles both contribute to a chorus, or can a ratio of calling males to non-calling males be determined?

The effort to ground truth this distribution is non-trivial. If the detection of fish were simple then the ground-truthing sampling would be the method of choice to estimate abundance. Sidescan sonar surveys have shown the difficulty in detecting individual mulloway, positioned on the riverbed. One possible method of ground truthing is the use of large sea cages with significant numbers of fish. While behaviour may be affected by captivity, the number of males and females would be known allowing the caller number models to be checked against recorded SPLs.

7.7.5 Summary

As a complementary (often remotely collected), non-extractive and non-interactive method of obtaining data, passive acoustic studies of vocal fish species may be able to provide the following information to benefit the understanding of behaviour and potentially inform some management decisions:

- Locating and delineating Essential Fish Habitat;
- Characterisation of spawning behaviours;
- Fine-scale movement patterns of individual fish;
- Base impression of size distribution of the calling fish;
- Fine-scale timing of spawning;

- Relative abundance of callers and, by proxy, aggregation size (given a range of conditions and collected background data);
- Relationship between environmental drivers and relative aggregation numbers;
- Relationship between environmental drivers and the timing of aggregation formation;
- Impacts of anthropogenic activity (such as vessel noise) on fish behaviour, communication ranges and possibly spawning success (if, for example, a particular sound associated with the act of spawning is identified the number of times this is detected can be monitored);
- An estimate of absolute number of callers at a given location. Methods still require development to improve confidence limits and ground-truthing numbers is problematic, however, this provides considerable information to fisheries management if perfected. Note that for mobile aggregations an array of hydrophones would be required to sample the area likely covered in the aggregation movement;

7.7.6 Recommendations for monitoring vocal fish species in Western Australia

The advantage and value of passive acoustic methods for studying highly vocal species such as mulloway ranges from the ability to identify spawning grounds and delineate their spatial and temporal boundaries, through identifying and monitoring the behavioural responses of an aggregation to environmental and anthropogenic drivers (e.g. temperature, salinity, lunar patterns, vessel presence, ambient noise), to the estimation of relative and possibly absolute abundance. This can only be applied to the detection range of the hydrophone, thus for mobile aggregations an array of acoustic loggers would be required to track their movement over time. The area covered by the aggregation and the transmission properties of the area would denote the number of loggers required to monitor any chorus present and, as a result, determine whether passive acoustic techniques is an economically viable method to acquire data on that aggregation.

For species which are more diffusely distributed, such as WA dhufish, once vocalisation has been confirmed and characterised passive acoustic methods are a remote sampling technique that could possibly be used to determine when the fish are present within a given area and what their behaviour might be. If vocalisation occurs during spawning behaviours this could be extended to detecting spawning fish. However, this project has already shown that in some species significant effort may be required to characterise calls and indeed confirm the ability to produce sound. Using passive acoustics alone to identify fish calls and choruses along such a long coastline as Western Australia would take an unfeasible amount of effort, thus targeting particular locations noted for high abundance of the target species is recommended. From there the sampling may be expanded to less surveyed sites.

This would be combined with data mining of the decades of passive acoustic data already collected along the coast to search for calls with similar acoustic characteristics to those of the target species. The capability of remotely sampling, over extended periods with a non-extractive technique has significant benefits.

The following are recommendations for how passive acoustic techniques could be applied to help monitoring vocal species in Australia:

- Passive acoustic recording of fish calls is a useful complementary tool to acquire data on vocal fish species and should be used in conjunction with other, traditional sampling methods as a suite of techniques that are pertinent to the behavioural and biological characteristics of not just the species, but the local population of fish;
- To accurately estimate relative or absolute numbers of mobile vocal aggregations at any given time, such as mulloway in the Swan and Canning River system, it is necessary to know fine-scale movement patterns around the various spawning sites. This requires the long-term (minimum one month) deployment of an array of loggers around the river. This then helps identify whether the same, or different fish are being recorded. This technique of mapping a river or estuary system could be applied to other vocal species of fish. Similarly, some fish choruses have been shown to move along a coastline (Parsons *et al*., 2012c), which can be mapped in the same way. The importance the Swan River aggregation has to the west coast population is currently unknown, thus these data collected would provide a history of the mulloway in this river system while other studies identify the link with the rest of the local population;
- After accounting for local sound transmission propertiesSPLs observed in Mosman Bay can be used as a coarse estimate of relative abundance of mulloway at alternative spawning locations (e.g. Augusta);
- Further studies into the acoustic characteristics of mulloway calls and their specific associated function (i.e. courtship) could provide further ecological information. For example, Parsons (2010) speculated that Category 3 mulloway calls could be associated with courtship, while similar observations have been made of the haddock (Hawkins and Amorim, 2000). If so, the number of times this type of call is detected each evening could provide information on spawning success. It should be noted that significant effort would be required to identify whether a call is associated with the act of spawning;
- Ongoing studies of WA dhufish in waters around Cape Naturaliste and Augusta could provide information on whether their sounds are associated with reproductive behaviour, such as courtship of the act of spawning (especially if long-term video systems are deployed to the Augusta site where visibility is good). If so, then perhaps assessment of temporal/spatial presence of WA dhufish could be aided by passive acoustic studies. This may be relevant given the marine parks along the southwest coastline. Identifying specific spawning locations would also require proof of an absences of spawning elsewhere or an understanding of the relative importance of the different areas, which can be time-consuming and expensive in the short-term, though if successful can be very fruitful in the long-term;
- Numerous unidentified fish calls and choruses have been detected along the Western Australian coastline, some of which may originate from economically important species. Prime candidates for investigation of passive acoustic

techniques are the black jewfish, known to be highly vocal, and Bight redfish (*Centroberyx gerrardi*) for which biological and behavioural traits observed suggest it may be soniferous (Mackie *et al*., 1999, Vu, 2008);

- For a given species of commercial importance, acoustic sea-noise loggers could be deployed at primary locations where significant numbers have been caught (for example, one or two sites where aggregations are known to form). Long-term deployments at these sites (together with ground-truth visual sampling where possible and complementary *ex situ* study on individual fish of the species) will help determine whether each species is vocal, characterise any calls recorded and help identify whether passive acoustics could be used to study the species;
- Once a species has been confirmed as vocal and the calls characterised, the authors propose that a combination of call counting techniques and call contributions to overall SPLs be used to estimate maximum caller numbers (between set range limits) during chorus levels of a soniferous aggregation. However, it is noted that significant work is needed to further this.
- Produce audiograms of vocal species of fish to help define the hearing thresholds at calling frequencies to accurately estimate the ranges at which recipients can detect callers and understand the impact vessel noise has on spawning success of members of the aggregation. This could be applied to all vocal species around WA. Understanding the hearing thresholds of fish is also paramount to determining ranges at which anthropogenic activities such as seismic testing will affect fish behaviours and biology. Examples of this are the investigation of seismic exploration on the scallop and crayfish industry in Tasmania and the concerns of commercial fishers about the effects of seismic work off south-western Australia on the health of WA fish both of which prompted the development of proposals for FRDC projects to study the respective fisheries;

8.0 BENEFITS AND ADOPTION

The project has helped improve our understanding of the occurrence of soniferous (sound producing) species of fish and aspects of their behaviour in West Australian waters. Via recording of spatial and temporal patterns in vocal behaviour, passive acoustics has provided information on how environmental parameters may influence movement patterns of mulloway during their spawning period, in particular. The project has also improved knowledge on how ambient and anthropogenic noise can impact communication, which may, in turn have the potential to influence spawning success. This information is relevant to scientists monitoring these species and thus may be useful to managers when making complex decisions to maintain sustainable fisheries.

The joint efforts made by local and international research groups, government agencies, recreational fishers, volunteer community groups and industry has proven that this project is a good example of collaboration across multiple sectors. Each of these sectors has benefited from the project through developing on-going relationships to further research, both in passive acoustics and other fields. Numerous proposed and existing research and community projects have stemmed from this collaboration, driven not only by CMST, but originating from all contributors to this project.

The research conducted here has provided information for numerous educational talks, seminars and an interactive display that has benefited the general public and school children through learning about communication in the marine world and the impacts of human activity on marine wildlife.

The project has provided recommendations for future monitoring of mulloway and which are applicable to other prolific calling species, such as black jewfish (*Protonibea diacanthus*). It has also suggested further investigation of WA dhufish and their vocal behaviour may be a means to understanding their ecology and monitoring their presence and spatial distribution. The DoFWA could benefit through a better understanding of an alternative data source, which may be useful in future monitoring of selected vocal fish species.

9.0 FURTHER DEVELOPMENT

This study, together with FRDC project 2004/051, has provided an in-depth view of the vocal behaviour of mulloway. However, further investigation is required to more fully understand both their movement patterns and the drivers behind them. For example, this project has mapped presence of mulloway at different times around the Swan and Canning River systems; however, simultaneous long-term (two month deployment for example) sampling all along the river is required to map the overall movement of the aggregation. Subject to funding, this will be a target for future spawning seasons.

The CMST now has eight spawning seasons of data from Mosman Bay, with a logger currently deployed for a ninth season. The continuation of this work is vital to produce a coherent, long-term picture of the Mosman Bay aggregation.

While modelling has provided a method of relating SPLs to the number of calling fish, ground-truthing such models to improve confidence limits is problematic. The additional variable of relating calling fish to non-calling fish requires investigation. However, the reason behind the success of the passive acoustic study of mulloway in FRDC project 2004/051 was the difficulty in acquiring data from alternative sources. A test of this method with a contained aggregation of mulloway such as those established in sea cages off China is proposed to help validate the abundance estimation techniques reported here.

Vocal mulloway have been detected at a number of sites along the Western Australian coastline; however, further mapping of ‘soundscapes’ along the coast will reveal the locations of more aggregations of mulloway and other species. Numerous choruses have been detected, both inshore and offshore. The source of these choruses should be elucidated as their timing, spatial extents and intensity may be indicative of the state of the ecosystem while the number of different fish sounds may illustrate the species diversity in the area. If originating from a commercially important species (for example, Bight redfish off Cape Naturaliste), these choruses may provide an additional source of information with which the stocks can be monitored. MBS surveys, which have the potential to cover greater spatial area, in the short-term, via transects may provide corroborative information on the aggregation size and numbers.

The confirmation that WA dhufish produce sound is of significant interest. The SLs of WA dhufish calls are such that, when vocal, they may be detected at ranges of up to 250 m (dependent on ambient noise levels). Understanding the associated functions behind the calls is paramount to determining call rates and number of callers. Recording these calls and identifying their range can be compared with habitat maps to provide fine-scale information on the essential fish habitat required for WA dhufish. The most likely outcome is a source of information to delimit spatial and temporal presence of WA dhufish. Estimation of relative abundance of WA dhufish using passive acoustics includes too many variables which at present cannot be evaluated.

This project has confirmed that snapper and black bream are not suitable for passive acoustic techniques as a research tool. However, the experience gained here and from FRDC Project 2004/051 has reiterated that sideways mounted MBS systems are applicable to surveying schools of fish in shallow waters. Further study in this area would be of particular benefit for mobile schools, such as the snapper in Cockburn Sound.

The interactive display "Sounds off the Sunset Coast" at the Naturaliste Marine Discovery Centre has been well received and the capability for expansion was included to incorporate further passive acoustic work on marine wildlife. The possibility of developing additional displays would be of particular benefit to educational centres, such as AQWA and Busselton Jetty Underwater Observatory and should be explored. A portable version would benefit scientific outreach programs.

9.1 Data storage and management

All data collected will be stored on a designated storage server drive at Curtin University. As with all other CMST data a copy of this drive is kept by Curtin's IT department. Back up copies of data will are also kept on portable hard drives and dvds. Upon request of the principal investigator data can be supplied to whomever requests it. Where the principal investigator is unavailable this request can be directed to CMST's administration manager.

10.0 PLANNED OUTCOMES

10.1 Anticipated outcomes

At the outset of this project five outcomes had been planned:

1. Robust data source: Assessment and development of complementary cost-effective, non-extractive tools in estimating relative (or absolute) abundance within aggregations of sound producing fishes. Dependent on the level of application along the coast these methods could provide information to assist setting sustainable harvest limits for valuable species, at minimal effort for researchers/managers.

This project has given a detailed description of how to use passive acoustic techniques to determine relative abundance of highly vocal species and to delimit the presence of less vocal species. Although scientists have known about sound production by fish for several decades its use in monitoring is still in relative infancy. The ease of deployment and autonomous long-term monitoring demonstrates the cost-effective nature of passive acoustics, but also illustrates the need to monitor an area for prolonged periods. SPLs vary significantly over time, as does the presence of the fish. When combined with external drivers, such as environmental factors (e.g. salinity and temperature) it is possible to compare the relative abundance at different times and seasons. While not without caveats, together these points make passive acoustic a complex, but valuable tool for managers of stock assessments and marine park/closure zones. This project has made significant steps towards understanding and accounting for some of these caveats.

2. Produce ecological models: Provision of spatially and temporally explicit models detailing mulloway (other study species where possible) aggregation locations, physical dimensions, timings, responses to ecological factors and vulnerability (to fishing) will aid management strategies such as closure zones/time or delineation of marine reserves.

During this project multiple temporal models have been developed for Mosman Bay mulloway aggregations identifying times when the fish are present and how they respond to environmental and anthropogenic drivers. The extent of the aggregation in the Swan River has been identified and comparisons made between spawning seasons. The application of such modelling to other aggregations and other species could greatly improve the understanding of vocal aggregations and how they vary with time. Identifying the height of calling at each location and what drives the fish to aggregate at particular times greatly aids management with decisions on spatial and temporal delineation of ‘conservation’ zones at times when the aggregation is most vulnerable.

3. Continuous multi-year datasets: The comparison of annual mulloway sound production will enable estimates of relative abundance on a multi-seasonal scale. The identification of environmental and/or anthropogenic drivers to spawning behaviour will help determine whether variations in abundance are responses to fishing pressure, climatic change (or otherwise) and aid long-term stock assessments.

Through FRDC (2004/051 and 2010/004) and CMST (in-kind support and on-going work) projects, datasets covering eight spawning seasons of the Mosman Bay mulloway have been acquired and will continue to be collected with the support of CMST. This allowed comparisons of chorus levels and, by proxy, relative fish numbers between years. The temporal models developed facilitated determining whether increases or decreases in calling correlated with trends in environmental drivers and the impacts that has on comparing the same period in different seasons. This work illustrated that dominant environmental drivers can be identified through passive acoustic techniques. Multiple datasets of the same waters off Cape Naturaliste displayed evidence on increased sound levels over the same frequency band as WA dhufish calls during a period when recreational fishers suggested a significant number of WA dhufish were caught.

4. Determine vocal behaviour and suitability for further passive acoustic monitoring: If confirmed, sound production and the identification of acoustic characteristics for Dhufish, Snapper and Black bream will allow managers to identify whether these species are appropriate for passive acoustic monitoring in the future and assess the value of the data.

The study has provided one of the first reports of sound production by a member of the Glaucosomatidae family. West Australian dhufish call characteristics have been described and their call SLs identified. Detection ranges for these calls have been estimated for typically ambient noise regimes in the areas where WA dhufish occur and spawn to allow managers to evaluate the value of recording their sound and will help monitor their presence and possibly abundance in the future.

Despite the effort taken to record sound produced by snapper and black bream, the lack of evidence of confirmed sounds from these species during capture and spawning periods have already determined that the two are not appropriate for passive acoustic monitoring. The unfortunate lack of available multi-beam sonar systems to survey the Cockburn Sound snapper during spawning has meant that this project has not been able to demonstrate the effectiveness of sideways mounted systems to survey shallow water aggregations of mobile fish.

5. Promote awareness: This project will provide novel extension material to engage the local community regarding vocal fish species and spawning aggregations. Some examples include a presentation linking marine sounds to species (for use in educational centres such as AQWA or the Naturaliste Marine Discovery Centre) and a handbook outlining how to monitor vocal fish (predominantly for use by researchers).

The numerous media releases, TV show segments, magazine and newspaper articles, newsletters, public seminars/workshops and school seminars (in particular the presentation of "Sounds off the Sunset Coast" in its various forms) has helped educate and inform the wider community on the existence of underwater sound, its use by marine fauna (particularly fishes), and the ecology of marine animals (see Appendix 3 for a full list community engagement related events). These presentations have also helped promote marine science as a career for prospective young scientists. The interactive version of "Sounds off the Sunset Coast" has been developed into a permanent display at the Naturaliste Marine Discovery Centre, Hillarys used to educate the general public on marine animal sounds. This display has been produced in a format that can be updated with new marine animal sounds, as and when they are identified.

10.2 Community engagement and extension

In order to meet the objectives laid out in the extension strategy of:
'Disseminate information regarding vocal behaviour of spawning fish and the ability of passive acoustics to monitor aggregations of these species to the wider scientific community and the general public', and;

'Standardise methods and protocols for the passive acoustic study of aggregations and disseminate these processes to the wider scientific community';

The following extension outputs were identified to evaluate the performance of the project:

1) Published papers/Research Reports describing methods of passive acoustic monitoring, vocal behaviour, relationships between sound production and abundance, and possible managerial benefits of the technique from recording fish sounds.

2) Recommendations and data for inclusion in a West Coast Scalefish Fisheries database, similar to that provided by FRDC 2004/051.

3) Attendance and presentation at national and international conferences to the scientific community.

4) Articles for angling and general interest magazines detailing vocal and spawning behaviours and their relationships with environmental variables and anthropogenic activities.

5) Segments for recreational fishing shows, such as Escape with ET and Fishing WA.

6) Interviews with general interest radio and/or TV shows such as ABC radio and Stateline.

7) An interactive presentation on ‘Sounds off the sunset coast’ for use in schools and discovery centres such as AQWA and the Naturaliste Discovery Centre (NMDC) to promote awareness amongst the general public about vocal cues used by marine fauna including cetaceans, crustaceans and fish.

8) Meeting/seminars with stakeholders and community outreach to discuss the objectives, methods and results of research and how these may benefit future management.

10.2.1 Performance against extension outputs.

Current performance measured against the individual outputs is as follows:

1) A paper describing effort supported by FRDC Project 2010/004, entitled ‘Sound production by West Australian dhufish *(Glaucosoma hebraicum)*’ was published in the Journal of the Acoustical Society of America in 2013.

   A paper describing effort supported by FRDC Project 2010/004, entitled ‘Fish calls and choruses of south-western Australia’ was published in the April, 2013 edition of Acoustics Australia.

A peer-reviewed conference paper describing effort supported by FRDC Project 2010/004, entitled *'Dhu they or Don't they*' was presented at 'Acoustics' an international conference of the Australian Acoustical Society in November, 2012 and Fremantle, Western Australia.

A paper describing effort supported by FRDC Project 2004/051 and 2010/004, entitled *'In situ* source levels of mulloway (*Argyrosomus japonicus*) calls' was published in the November, 2012 edition of the Journal of the Acoustical Society of America.

A paper describing effort supported by FRDC Project 2010/004, entitled 'The effect of seabed properties on the receive beam pattern of a hydrophone located on the seafloor was published in the December, 2011 edition of Acoustics Australia.

A paper describing effort supported by FRDC Project 2004/051 and 2010/004, entitled 'A comparison of techniques for ranging close-proximity mulloway (*Argyrosomus japonicus*) calls with a single hydrophone' was published in the December 2010 edition of Acoustics Australia.

2) Recommendations associated with the findings of this project are outlined in Section 10.

3) Dr. Parsons presented findings on the sound production of dhufish, snapper and black bream at the Australian Acoustical Society conference in Fremantle, on November 21st, 2012.

Dr Parsons presented findings on long-term modelling of sound production of mulloway in relation to environmental drivers at the American Fisheries Society conference in Seattle, on September 6th, 2011.

PI Miles Parsons and CI Rob McCauley attended the Australian Marine Science Association annual conference in Fremantle 3-7th July. Dr. Parsons presented 'Are mulloway tone deaf or can the "Great One" hold a tune?: Variations in mulloway (*Argyrosomus japonicus*) calls', a paper discussing the vocal behaviour of spawning mulloway, supported by funding from the FRDC for projects 2004/051 and 2010/004.

4) On March 19th, 2011, the dhufish component of this project was promoted in 'Tracking down where baby dhufish live" as part of 'Jako's Fish Tips' column of the Weekend Australian.

The article "Parlez-vous fish?" authored by Ben Carlish (DoF), was published in the January 2011 edition of *Western Fisheries* (pp. 6-9), advertising the project.

An article covering Project 2010/004 was published on the front cover of the December 2010 edition of the CMST newsletter.

The article entitled "Sweet talk of croakers" in 'Jako's Fish Tips' column of the Weekend Australian was published on October 9th, 2010.

The article 'Scientists eavesdrop of fish' was published on-line by *Australian Geographic* on the 5th August, 2010.

5) A segment on the Channel 10 show "Escape with ET" (also aired on the Southern Cross Channel throughout Australia and SE Asia) on sound production by dhufish was broadcast across Australia on February 10th, 2012.

6) Together with DoFWA researchers, Miles Parsons was interviewed for GWN News Bunbury in February, 2011, regarding studies of dhufish in the Southwest (http://bunbury.igwn.com.au/index.php/news/prime-news/scientific-investigation-along-south-west-coast-video).

Miles Parsons was interviewed regarding passive acoustics and the FRDC project 2010/004 by Gillian O'Shaughnessy, live on ABC Western Australia radio, on the 20th September, 2010.

7) A collaboration between CMST and the Naturaliste Marine Discovery Centre has led to the design and manufacture of an interactive display on underwater sounds produced by marine animals, housed at Hillarys boat harbour in Western Australia.

8) Dr. Parsons Presented Sounds off the Sunset Coast and life as a Marine Scientist to seven groups of primary school classes at Charleville School, Buckinghamshire, UK on the 12th February, 2013.

Dr. Parsons presented Sounds off the Sunset Coast as one of the guest speakers at the Sound of Science Community Fair on Sunday 21 August, 2011 organised by the Canning River Eco Education Centre

Dr. Parsons presented passive acoustic work on mulloway vocalisations at a public seminar held at the Centre for Marine Science and Technology, on the 23rd June, 2011.

A scientific, public seminar entitled 'Passive acoustic techniques to study sound producing fish species' was advertised through the CMST mailing list and held at the CMST on September 21st, 2010.

A public seminar for all stakeholders titled 'Sounds off the sunset coast' (Appendix 1) was held on 22nd September at the Fisheries Research Laboratories, Hillarys, in conjunction with the Department of Fisheries WA and NMDC. Organisation was coordinated through the NMDC at Hillarys and as a result the seminar was advertised through the following media:

Vol. 15 September/October *On the Current* e-newsletter and NMDC website
Media Release - distributed and put on the DoFWAwebsite
ABC Radio interview and website listing (as a result of the media release)
Centre for Marine Science and Technology (Curtin University) website
Department of Fisheries - Staff FYI
Flyer at DoFWAHillary's licensing counter
Department of Fisheries - metropolitan Fisheries Volunteer program (approx. 25 volunteers) and Research Angler Program (approx. 200 volunteers)
Catalist - science teachers email network
WA Fish eNews by Jim Paparo
Flyer was sent to 46 metropolitan fishing tackle outlets (on our brochure distribution list)
Recfishwest website and networks
Science Network WA, website event listing
Into Marine website - www.intomarine.com.au/news (they picked up the media release)
AQWA (Aquarium of WA) staff and volunteers
Direct invites to project collaborators/stakeholders

11. CONCLUSION

This project has succeeded in meeting the three initial objectives and the fourth objective, which was developed during the course of the project. The collaboration between CMST, DoFWA and numerous Australian and International partners has led to data acquisition on vocal fish species from Shark Bay, along the WA coast to Denmark. The four species, mulloway, WA dhufish, snapper and black bream, have been investigated and numerous other fish calls recorded. This project has built on work conducted in FRDC project 2004/051 to developed passive acoustic monitoring of vocal fish.

SLs of mulloway calls have been confirmed at 172 dB re 1 μPa and their contribution to SPLs has been evaluated. While a technique to quantify the number of callers present from their contribution to overall SPLs has not been finalised, significant steps have been made towards this ultimate goal. The effects of behaviour, spatial distribution and SL on models of caller numbers have been identified, but still require investigation. Two different models of estimating caller numbers have been described, one developed during this study and that supported by Project 2010/004, and a second from overseas (Sprague and Luczkovich, 2012). Mulloway aggregations in the Swan River have been spatially and temporally mapped and SPLs related to the environmental drivers that affect the aggregation patterns. Multiple years of data have been collected to conduct inter-season comparisons.

This project has provided one of the first reports of vocalisation by a member of the Glaucosomatidae family, an important step which may help researchers of other members of this family. Identifying the mean and maximum SLs of 126 and 137 dB re 1 μPa was key to estimating the ranges at which dhufish calls may be detected in the wild and the effective sample area of any sea-noise loggers deployed. The detection of dhufish calls *in situ* off Augusta and Cape Naturaliste has shown how the technique can be used to detect the presence of WA dhufish within an area. DoFWA and CSIRO have been exerting significant effort using knowledge of spawning locations of dhufish to collect eggs/larvae to see if monitoring their relative abundance is feasible as a recruitment index. The detection of an increase in SPLs due to calls similar to those of WA dhufish could provide ground truth information to validate estimates of spawning ground locations and a possible way of determining whether there is fine-scale or broad-scale movement between years in the location of these spawning grounds.

The confirmation that snapper and black bream do not produce sounds that could be used effectively for studying their behaviour is a disappointing result. However, it does add to the knowledge base of each species in that alternative variables and stimuli must be used as cues for spawning and communication.

The detection of numerous different sources of fish choruses has illustrated how much is yet to be discovered off the coast of Western Australia. These choruses are likely to form under predictable timing and conditions. Not only does this provide an indicator of health and diversity for the area through the types of sounds detected and the overall SPLs, but if any of these choruses originate from a commercially important species the data may provide a complementary tool for monitoring.

The accurate determination of ranges at which fish can detect calls is an important step towards assessing the impact of anthropogenic noise on communication. This requires statistical analysis of the probability of signal detection and an evaluation of the critical hearing ratio of the fish involved. The ranges given in this study are only an identification that, at the SLs of mulloway calls in Mosman Bay, passing vessels can reduce detection, even using advanced signal processing, from hundreds of metres to tens of metres. With fish of lower SLs, such as WA dhufish the ambient noise need not be as high and yet still mask the calls. To fully understand the communication thresholds used by fish it will be necessary to produce audiograms for each species and identify the critical hearing thresholds.

From this, and concomitant CMST projects over 15 different choruses have been recorded in Western Australia and over 30 different individual types of fish call. Long-term monitoring of coastal fish choruses are being increasingly used as an indicator of health of the system as well as the response of individual species to the environmental conditions surrounding them. This project has increased our understanding of vocal fish species around WA and how to apply passive acoustic techniques to monitor them, but also highlighted how little is know about the large number of soniferous fish in our waters and how much more could be learnt by studying them.

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APPENDICES

Appendix 1. Intellectual Property

No saleable items were developed during this project

Appendix 2. Staff

Staff that were employed on the project using FRDC funds were:
CMST, Curtin University - Miles Parsons, Mal Perry, Frank Thomas, Iain Parnum, Dave Minchin

Staff involved in the project using non-FRDC funds were:

CMST, Curtin University -	Miles Parsons – Research Fellow (Principal Investigator), Rob McCauley - Associate Professor (Co-Investigator), Mal Perry - Senior Technician, Frank Thomas - Research Engineer, Iain Parnum - Research Fellow, Ann Smith – Administration, Dave Minchin - Engineer
DoFWA -	David Fairclough - Senior Finfish Scientist (Co-Investigator), Paul Lewis - Technician, Ian Beale - Research Scientist, Brett Cristafulli - Technician, Gary Jackson - Senior Finfish Scientist, Geoffrey Norriss - Technician,
SBERP -	Derek Burkholder - Assistant Researcher, Cindy Bessey - Assistant Researcher
DEC -	Alan Kendrick - Marine Scientist, Dave Holley - Marine Park Manager, Shannon Armstrong - Marine Park Manager
CARL -	Simon Longbottom - Aquaculture Manager
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