A study of our Australian freshwater ecosystems and the transition to evidence based decision making. A QUT graduate project

4,568 Words

Autonomous monitoring of freshwater

BIODIVERSITY

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Executive summary

This report explores how emerging technologies, primarily acoustic monitoring can improve our understanding of freshwater environments and support more informed decisions about how we manage and take stewardship of them.

Rivers, streams, wetlands and lakes occupy a relatively small proportion of our landscape yet support a disproportionately large amount of biodiversity. Current monitoring methods are often expensive, labour-intensive and difficult to conduct continuously across large or remote areas.

This report synthesises findings from benchmarking, focus groups, interviews and observations to identify key opportunities for a product intervention that respond to the needs of decision-makers across the private and government sectors. It proposes a framework for facilitating evidence-based decision-making with the four key stages being data collection, interpretation, decision-making and action.

Authenticity Statement

This is to certify that to the best of my knowledge, the content of this report is my own work. This report has not been submitted for any subject or for other purposes. I certify that the intellectual content of this report is the product of my own work and that all the assistance received in preparing this report and sources have been acknowledged.

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AI Use Statement

I have utilised AI in this report (ChatGPT). The way I have used AI includes receive feedback on flow, academic wording and reducing word count. Please note that the wording, structure and initial research all began without the assistance of AI. AI has been used as a tool to aid ‘academic’ and ‘professional’ aspects of the following piece. MacWhisper was used in transcribing interview recordings.

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01
INTRODUCTION

Introduction

Although water covers approximately 70% of Earth's surface, only 2.5% is freshwater, with more than two-thirds of this locked up in glaciers and ice sheets (S. Mundree, personal communication, August 25th, 2026). Our own body's are 60% water and put simply "without water, life cannot occur" (Miller et al., 2021). Similarly, freshwater ecosystems support a disproportionately high diversity of species, many of which are highly specialised and vulnerable to environmental change (Reid et al., 2019). Monitoring these ecosystems can provide valuable data about the health of our water sources as well as Insights that may not be captured by conventional measures such as pH, salinity and dissolved oxygen (Vadas et al., 2022).

Accelerating environmental changes and development pressures are creating an unprecedented need for reliable and consistent environmental data. (Lento et al., 2026). Despite this need, current biodiversity monitoring can be time, cost and labour intensive. Traditional biodiversity surveys often require researchers to travel to specific locations, complete manual observations and repeatedly return to monitor changes over time. This limits the frequency and scale at which a freshwater ecosystem can be monitored (de Schaetzen et al., 2023).

Technology and innovation have been responsible for some of the most significant advances in human history. Passive Acoustic Monitoring (PAM) is a well understood and established tool for studying terrestrial and marine ecosystems, yet in the freshwater ecology space its implementation remains limited (Desjonquères et al., 2019). The demand for data plus the proven ability of PAM leaves significant potential to deliver a meaningful, needed and adoptable design solutions.

Aim

The aim of this project is to explore how Environmental Decision Makers (EDM) can better understand the effects their decisions are having on our community's water resource, and where product interventions and acoustic monitoring may facilitate this process.

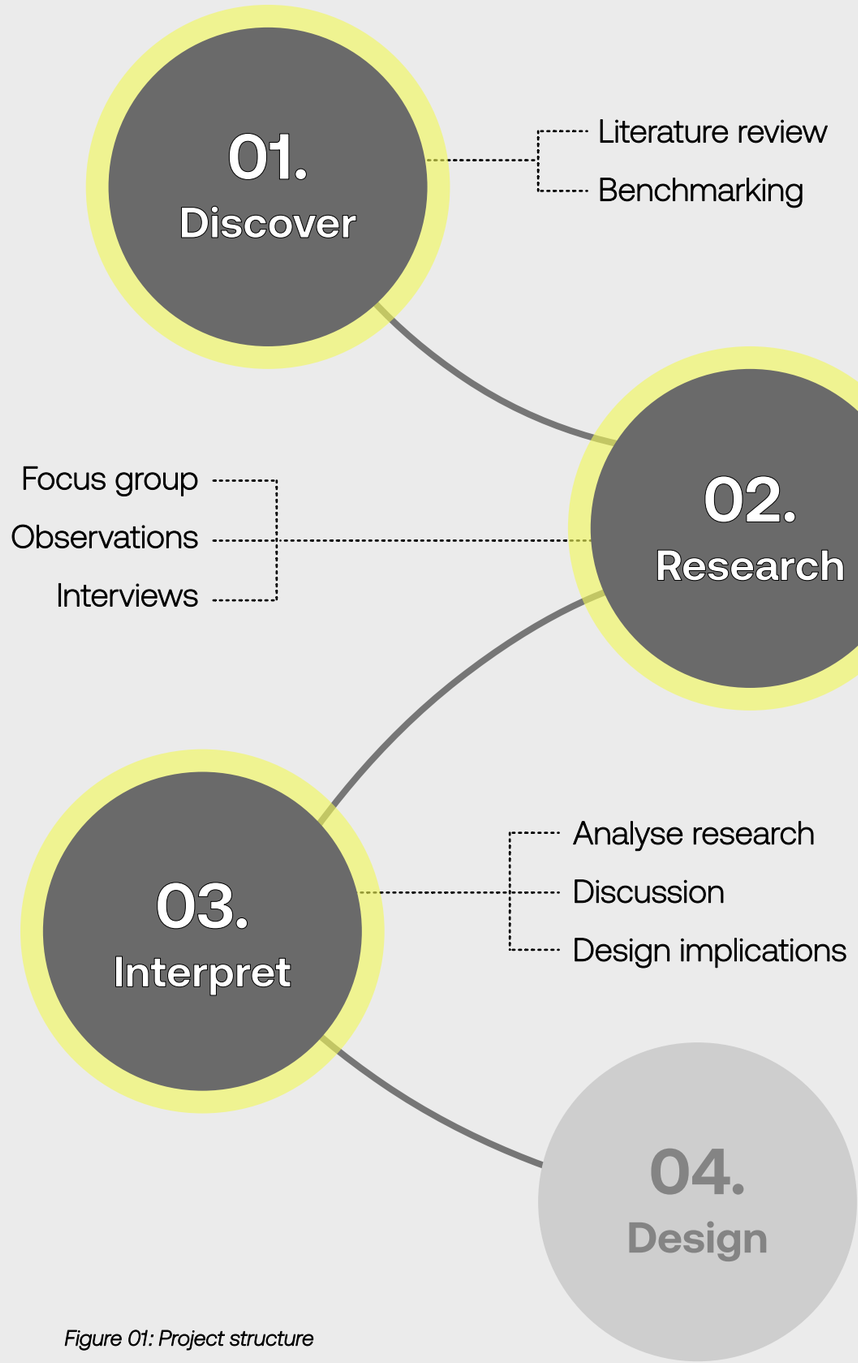


Figure 01: Project structure

Background

What is PAM?

Passive Acoustic Monitoring (PAM) offers a non-invasive approach to biodiversity monitoring. Hydrophones allows PAM devices to detect, record and analyse the sounds generated within an ecosystem. Once processed, these soundscapes can provide ecological and biodiversity information beyond what is immediately visible or measurable (Desjonquères et al., 2019).

Emerging tech or under-utilised tech?

The shallow, narrow and structurally complex nature of many freshwater environments creates challenging acoustic conditions. Additionally flow, turbulence and anthropogenic noise can obscure biological signals and affect sound propagation (Desjonquères et al., 2019). PAM's depended on sound libraries and knowledge of species acoustic behaviours further inhibits the identification and interpretation of soundscape (Gibb et al., 2019). Refer to figure 2 for how PAM operates, without quality sound recordings and accurate sound library's, meaningful ecological information cannot be inferred.

The proven success of PAM in well-studied terrestrial soundscapes, combined with technological advances is helping to push PAM applications in marine and now freshwater environments. Further advancements in AI automated classification allows for more efficient processing of large datasets and pattern detection (Hoefer et al., 2023). This AI power combined with expanding sounds libraries and ongoing ecological research creates opportunities for PAM to become a scalable approach to freshwater biodiversity monitoring (Desjonquères et al., 2019).



Figure 02: Pam operating framework

What can PAM tell us?

Freshwater environments host 4 types of soniferous (sound producing) species. PAM can detect presence, community composition and even indicators of biological activity. By deploying multiple hydrophones, recordings can also be spatially compared to identify patterns in species distribution and activity. Changes in acoustic activity can reveal behaviours including communication, mating and even feeding (Desjonquères et al., 2019). Beyond biological signals, acoustic monitoring can capture physical processes such as rainfall, water flow and dissolved oxygen which can be indicators of water-quality and conditions (Desjonquères et al., 2019).

The power of continuous recordings is that it enables changes to be observed over time. A waterway may meet acceptable water quality parameters whilst still experiencing ecological decline (Vadas et al., 2022). Biodiversity monitoring provides a complementary perspective that capturing broader impacts of our anthropogenic activity.

Limitation of current data collection methods

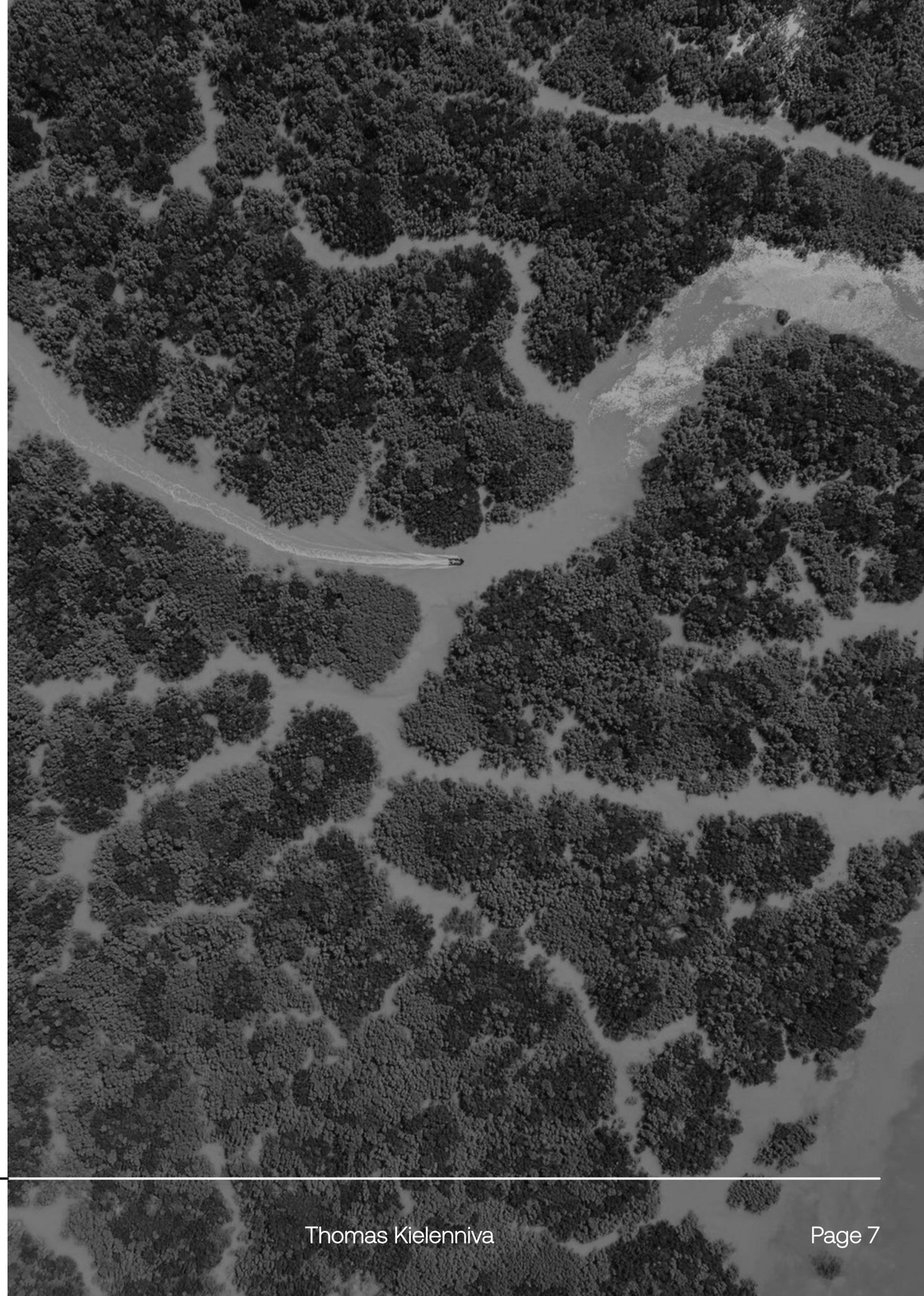
"Traditional labour-intensive sampling methods … result in data of low temporal and spatial resolution" (de Schaetzen et al., 2023, p. 1). Although automation and remote sampling can reduce repeated site visits, there applications are more established for measuring physical and chemical water parameter. Common biodiversity monitoring methods include water sampling, eDNA, electrofishing, tagging and visual surveys (Elliott et al., 2026). These methods are all either invasive, labour-intensive or time consuming.

Autonomous monitoring has the distinct advantage of not triggering the observer affect. As a researcher enters an environment they alter the natural state, subsequently affecting the reliability of data gathered (Crofoot et al., 2010). Additionally, manual sampling only captures a snapshot and is unable to capture short-term or rapidly changing ecological events without repeated visits (Elliott et al., 2026). Increasing the continuity of data is important for supporting better informed environmental decisions.

Challenges of effective PAM

There are serval technical and workflow challenges with PAM that affect the quality and consistency of results. PAM's success is often dependant on researchers determining and finalising the research objective before deployment. This allows for recording schedules and deployment location to be tailored for specific detection parameters (Teixeira et al., 2024). Whilst continuous recording will provide a more comprehensive dataset it comes with storage, battery capacity and post processing drawbacks that affect deployment lifespan. Furthermore, changes in detection parameters and environmental decisions cannot be made until the device and data is collected by researchers (Hill et al., 2019).

Environmental factors further complicate reliability. Rainfall, humidity, turbulence, sediment movement and flooding all effect sound propagation. Such conditions are often amplified in remote locations, where maintenance and monitoring is difficult (Whisson et al., 2021). The dynamic nature of water means the study site may change or devices may need to be repositioned over time, reducing the consistency of sampling conditions.



Benchmarking

Overview:

Understanding the current landscape of acoustic products is vital in identifying gaps and opportunities for innovation. A 2025 study by Worldwide Soundscapes compiled 416 PAM datasets across 12,343 sites, of which only 26 were freshwater based (Darras et al., 2025). To reflect the distribution of PAM applications 12 recent Australian based case studies were selected and used to examine how PAM is being applied across different environments and sectors. See appendix for case studies.

Given the limited application of PAM in freshwater, a variety of terrestrial PAM devices and water quality sensors were evaluated. This gave insights into what the demands and needs of environmental decision makers are. The products evaluated are representative of the current approaches of acoustic biodiversity data collection. Refer to appendix for assessed criteria.

Current PAM environment deployment:

Current application of PAM are still heavily rooted in terrestrial and marine environment. The majority of freshwater PAM devices are built upon existing terrestrial systems with a very small percent designed and manufactured for the sole use in freshwater environments. less then 10 percent of case studies analysed were based in freshwater environment, as seen in figure 3.

Current PAM sector deployment:

PAM is currently most established within the ecological research and conservation space (Sugai et al., 2020). Most of these projects are funded through governmental department or grants but tend to have secondary flow on commercial affect. However, growing adoption within the private sector is being observed as seen in figure 4.

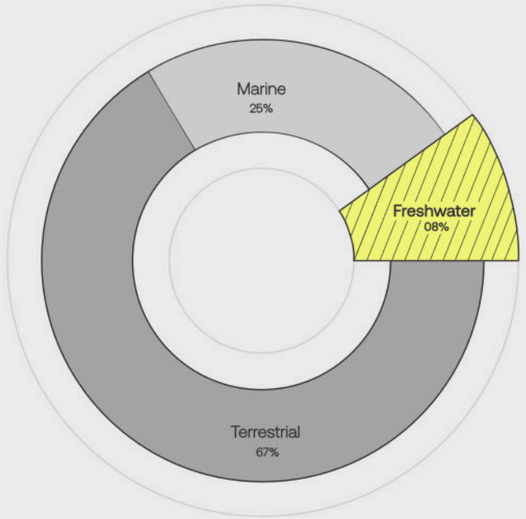


Figure 03: Distribution of PAM use in environments

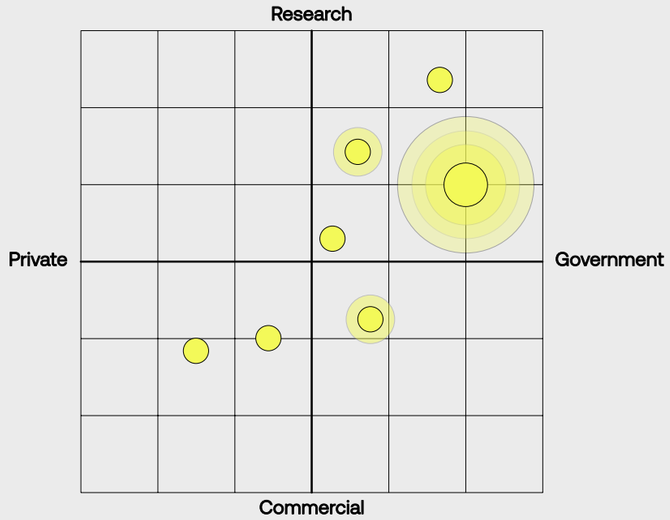


Figure 04: Distribution of sectors using PAM
Circle rings = occurrence from case studies

Product matrix:

Figure 6 evaluates 8 PAM devices that were deployed in the previously mentioned case studies. Evaluation criteria can be seen in figure 5 were. The criteria was derived from insight found in the literature. Total scoring for all devices can be seen on the far right.

A	B	C	D	E	F	G
Autonomy	Durability	Data quality	Maintenance	Ease of use	Accessibility $	Deploy / retrieve

Figure 05: Benchmarking criteria

PAM Device	A	B	C	D	E	F	G	Total
AudioMoth 1.2	3	1	3	2	8	10	4	31
Frontier Labs BAR-V2	5	7	7	9	9	7	5	49
Frontier Labs BAR-LT	6	6	8	9	8	5	6	48
Cornell SwiftOne	1	7	5	7	6	6	4	36
Song Meter Mini 2	3	7	6	4	5	8	4	37
Song Meter SM3BAT+	3	5	7	3	7	3	4	32
Loggerhead LS2	4	4	9	3	1	2	2	25
JASCO AMAR G4	6	8	10	2	1	1	1	29

Figure 06: PAM device benchmarking

Opportunities and gaps:

The combined analysis of figures 3,4 and 5 highlight several key opportunities within the acoustic monitoring field. The primary limitation of current acoustic monitoring are as following:

Gap 1: Autonomy. Although existing recorders can operate autonomously for extended periods, most still require site visits to physically check or alter the devices operation. The lack of feedback loops between the device and researcher means faults can go unnoticed possible costing months or years worth of data (Heath et al., 2024). Devices like the BAR v2 do adapt their recording in keeping with GPS data (Frontier Labs, n.d.), however, the opportunity for remote control over adaptive monitoring is underdeveloped.

Gap 2: User experience. The ability to accurately set up and capture data is often dependant on technical knowledge. Deployment errors are one of the leading causes for data loss (Dudzinski et al., 2011). Devices are often designed with data collection as a higher priority as opposed to the user experience of those setting them up. The lack of standardisation means ecologist struggle with the configuration process when using a new or unfamiliar device. Consistency between users interfaces is curial for increasing data consistency between sites.

Gap 3: Adaptation vs Integration. The majority of PAM devices with 'freshwater capabilities' are terrestrial first devices with hydrophone adaptors. This limits the deployment locations of many devices to creek banks or areas where the PAM recorder can remain out of the water. Adaptation rather than integration means that external hydrophone cable leading into water are an increase failure risk. Terrestrials devices are not designed to reliable handle the complicated and dynamic environment of freshwater.

The product matrix provides further demonstrated that products like the JASCO AMAR G4 which scored well in the durability and data quality were offset by ease of use and cost/accessibility. Conversely, simpler cost affective and easy to use device such as the AudioMoth were offset significantly by maintenance and data quality. A key opportunity is balancing ease of use/ affordability with durability and quality data.

Summary:

Addressing these gaps, particularly usability and autonomy in remote contexts emerged through as a critical innovation area. Decision makers rely on the fidelity of large data sets to develop accurate insight. As such a product led innovation much balance quality data at an accessible scale with standardisation

02
RESEARCH

Primary research

Overview

Primary research was undertaken to validate and further explore findings found in secondary research. Qualitative research was conducted to gauge end user experiences, alongside manufacturing and decision-maker perspectives.

Methodology

Interviews, focus groups and observations were used to compare perspectives and identify recurring themes. These methods were chosen to allow for triangulation, ensuring higher quality, more reliable, and defensible data (figure 7) (Carter et al., 2014).

This strategy leveraged different perspectives to province a holistic view that accounted for the development, deployment and application of PAM data (figure 8). The driving research objective is not just to explore the physical needs that the product must adhere to, but also how the product can suit the needs of environmental policy and decision makers.

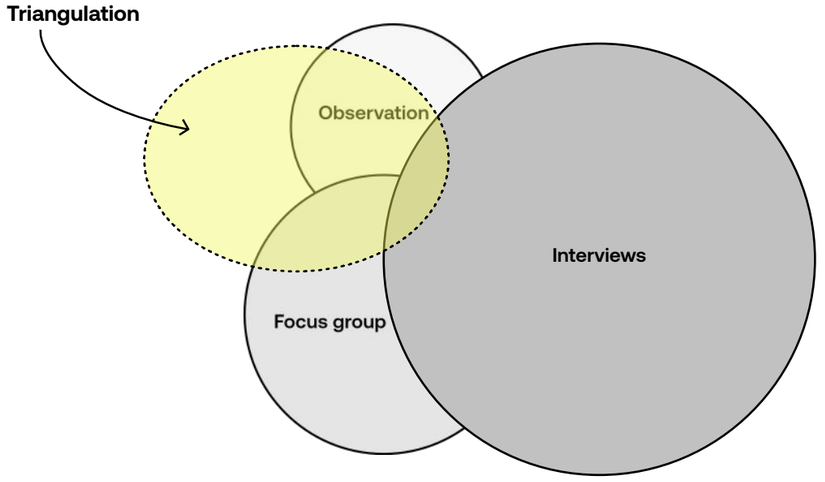


Figure 07: Triangulation research method

Participant recruitment

This study utilised 6 expert opinions spread across, 3 semi-structured interviews, 1 focus group and 1 observation session. All but one interview was conducted in person to capture richer contextual and non-verbal information. Interest was distributed via a combination of cold emails and phone calls.

Provided to participants was a project synopsis outlining the aims of the project, an information sheet explaining how collected data would be used, as well as a consent form to confirm agreement to audio recording and in some cases image release.

Focus group and observation participants were selected to provide a compressive understanding of conventional practices and technological innovation in the PAM field. Conversely, Interviews participants were selected to help understand the needs and demands of decision makers. See summary of methods and participants involved in figure 8.

Observations	P1: Field Ecologist	**Frontier Labs** audio acoustic manufacturers
Focus group	P1: Field Ecologist	
	P2: Designer	
	P3: Engineer	
Interviews	P4: UQ Academic researcher	
	P5: QLD Environmental department representative	
	P3: CEO of Queensland Futures Institute	

Figure 08: Distribution of expert knowledge

Methods focus group / observation

The focus group was conducted in a semi-structured manner with 3 industry experts to discuss and demonstrate practical aspects of biodiversity monitoring, equipment uses and fieldwork. Combined with the focus group was an observation segment where the process of setting up a terrestrial PAM device was shown by an ecologist (BAR v1). The flexible nature allowed for a collaborative dynamic to be built where all experts could build upon each other's statements adding unique point of views.

Organised in collaboration with Frontier Labs, a class leader in manufacturing terrestrial PAM devices both sessions took place in person at their Brisbane studio. Involved was an industrial designer, engineer and field ecologist. Having all the major actors involved in developing, manufacturing and deploying a PAM device the one room gave incredible breadth of insights.

Limitations

The focus group / observation session was subject to some significant limitations and potential biases. Namely, the observation did not take place in context. Due to time constraints, it was unfeasible to travel, however observations still gave valuable insights into the process of setting up PAM devices. Additionally, the understudied nature of freshwater PAM meant the interviewees expertise was with terrestrial PAM applications. This meant that many comments on aquatic PAM were based off educated assumption as opposed to experience. The focus group also presents challenges in conformity of responses, as the conversation flow depths of insights varied for each participants based of their perspective and areas of knowledge

Participant	Project value	Duration
P1	The set up and field work require to conduct a effective PAM site study	1 hour 10 minutes +15 min observations
P2	Considerations as to features and function desired by the end users	
P3	Environmental factors that affect reliability and how to combat them through manufacturing	
P4	The importance of monitoring water biodiversity and current data collection methods in the academic space	30 minutes
P5	What makes environmental data useful and how PAM can better support evidence based decision making	40 minutes
P6	what direction is Queensland heading in from a government/private standpoints and how PAM data could help support these directions	1 hour 15 minutes

Figure 09: Key insights areas discussed with participants

Method interviews

The interviews were conducted in a semi-structured manner, which was chosen to allowed the interviewees to explore and unpack nuanced insights beyond what might have been possible with structured formal interview. The flexible nature allowed the expertise of interviewees to be fully explored beyond topic that were derived from secondary research. 3 participants were interviewed providing context on, government needs and policy making, private sector environmental responsibility's as well as academic research and publication directions

Each participant was recruited specifically to provide specific insights on the 3-end user group identified in secondary research. Consent forms were signed and returned prior to commencing interviews and all interviews were recorded on two devices for redundancy

Limitations

Although valuable date was gathered there were three key limitations identified. Firstly, not all participants possessed specialised expertise in PAM. Although, all had heard of it and helped make decision based of the data it provided. This meant that topics directly realting to PAM could not be effectively explored and interview direction was more focused on the application of PAM data. Secondly, the small sample size, whilst adequate for the time contrasts of this project provide a relatively small distribution of information which leads into the third limitation. All participants were purposively selected based on their relevance to the study which introductions participant selection bias. Although PAM limitations were address in the interviews, all interviewees had experience with PAM success were already in support of the technology.

Summary

A total of 3 semi-structured interviews were conducted, alongside a focus group and observation session. Three PAM industry experts and three end users of PAM data participated in the study providing a variety of qualitative insights into practices, challenges, and areas of innovation opportunity. While this approach enabled a broad depth of research limitations such as sampling size, selection bias and context are acknowledged by the researcher

Analysis & Findings

Introduction

Inductive thematic analysis was used to unpack the data. All research methods were transcribed using MacWhisper and produced into physical transcripts (see appendix) where theme's, sub-themes and codes were identified. In the second stage emerging themes were categorised and imported into Excell. This was done to consolidate overlaps and organise codes into broader categories (see appendix)

Observation

The participant was ask to conduct a talk out loud protocol as they set up the Frontier Labs BAR-v1 device and start recording. Observed actions were first broken into codes, then grouped into broader stages and then visualised as a sequence (figure 10).

Scheduling

Scheduling represents a critical point of interaction between the researcher and device set up. Simple errors during configuration and time to set up the device can directly affect the usability of data collected. Furthermore, predetermined schedules require researchers to establish fixed parameters before the device enters a dynamic environment. This raises a fundamental system flaw, if researchers must know what they are looking for before monitoring begins, it means the system has limited capacity to support the discovery of unknown ecological data

"Scheduling Is the most important part… it involves knowing a bit about your targeted species" (Participant 1)



Figure 10: Sequence of setting up BAR v1

Focus group

Having key stakeholders involved across the development, manufacturing and deployment of PAM devices meant that the focus group primarily centred on technical considerations. Thematic coding of the discussion identified several key insights into the limitations of current PAM devices and development opportunities

Workflow constraints

Participants identified a continued dependence on trained ecologists throughout the PAM deployment process. While remote PAM devices reduce limitations associated with human-based data collection, such as observer presence, its benefits are offset by its lack of self-reliance. Researchers still need to physically visit sites to verify that the device is functioning correctly, replace batteries or storage, and retrieve data. This creates a workflow that remains time, labour and cost intensive which limits the scalability of remote monitoring

"A huge limitation with human collected data is the human collecting the data" "as the act of observation can change the observed system" (Participant 1)

"If I put one batter in the recorder it will last me twenty-seven days, hence ill replace it six times to last me 157 days" (Participant 2)

Reliability

The push towards longer and more continuous PAM deployments demands increased durability to reliably handle the environmental conditions. A failure early in deployment can remain undetected for weeks or months resulting in the loss of valuable data during time constrained projects. Four key barriers to reliable operation were identified: condensation, external interference, power limitations and pressure venting. System integration presents an opportunity to improve reliability by reducing the number of interfaces and connections between components

"The biggest environmental problem is condensation…. Devices would get water damage from the moisture inside" (Participant 3)

"Its not just the fact that ive lots a year's worth of data… I may never get the chance to record those events again" (Participant 2)

Recording Quality

Audio quality is no less important than the quantity of data collected. Poor recordings can make target species and behaviours difficult to identify. Additionally environmental noise and interference can obscure biological signals and increase the likelihood of false positives or false negatives. Low-quality recordings therefore require manual time-consuming validations by ecologists or else run the risk of contributing to poorly informed environmental decisions. This highlights the importance of producing high-quality, interpretable recordings that can support reliable analysis and automated detection

"Your never detecting sound over silence. Theres always wind noise, leaves, fires and incest's" (Participant 3)

"If you've got a good recording of an animal sound that's distinctive … its easy to distinguish a true positive from a true negative" (Participant 1)

Interviews

Interviews provide a complementary perspective that helped to further explore the application of PAM and what quality make datasets useful. Thematic coding also help to reveal the way in which these datasets are already being applied in the real world

Evidence based decision making

Evidence-based decision-making was identified by all three interviewees, with participants emphasising the importance of equipping decision-makers with better information to support informed decisions. Government, private and research sectors all rely on environmental data from a range of sources. Particularly within the government sector, participants identified a need to transition from reactive data collection towards more proactive approaches. Rather than collecting environmental data when a development or policy is proposed, the environmental department is "trying to give them better information up front" and "have that database and biodiversity mapping readily available"

"Its all about evidence-based decision making… you need to be able to demonstrate your policy reasoning" (Participant 5)

"How do we take this data and make a usable decision-making tool" (Participant 4)

Consistent monitoring

The true value of environmental monitoring is realised through longitudinal data. Current manual methods provide only a snapshot of what is happening in the environment and are limited in their ability to identify the effects of anthropogenic activities. Establishing an ongoing baseline of our waterways enables changes in ecosystems to be detected and understood. This creates an opportunity for proactive intervention where emerging issues can be addressed before they escalate and become more difficult to manage

"We only have snapshots of what happening in the environment and there no consistency, we don't know what effect a minor intervention can actually have" (Participant 4)

"Help us nip things in the bud" Sags (Participant 4)

Scalability

When discussing the greatest potential of PAM all participants mentioned the ability to be deploy at scale. Unlike a single highly trained ecologist in the field PAM enables multiple sites to be continuously monitored. Furthermore, by using a distributed network of devices it can increase spatial and temporal coverage providing additional data. A low-cost, integrated system could enable larger networks of devices to be deployed across waterways, including during dynamic environmental periods when researchers may not be present

"By utilizing PAM …. You can be in many places at the same time … significantly increasing your power to answer researched questions" (Participant 1)

"A ecologist cannot be in 20 places at the same time" (Participant 1)

Summary

The focus group, observations and interviews all identified several key, critical insights into the experiences, practices and opportunity of PAM. The prioritisation of long-term self-reliant monitoring seems to be the driving factors when it comes to creating useful data sets for decision making. These results will be interpreted further in order to distil and identify potential design opportunities and implications.

03
DISCUSSION

Discussion

The aim of this report was to explore how we can equip water resource decision-makers with tools to better understand the effects our decisions are having. The initial background research, which consisted of literature studies and benchmarking indicated a significant gap in the application of PAM in freshwater settings. Primary research in the form of observations, focus groups and interviews reinforced these findings, whilst providing further depth and insight. Whilst secondary research established a market gap, primary research focused on how a design led product intervention could fill this space. The key findings are presented as following.

First and foremost, PAM is an emerging field closely associated with terrestrial devices where it is rapidly becoming a proven methods for monitor birds, bats, insects and other wildlife. Participants described how Its application in freshwater ecosystems remains relatively limited and is general confined to one off research projects which overlapped findings in the literature. When questioned it was uncovered that this disparity reflects the greater technical challenges of underwater environments, including flow, turbulence, flooding, sediment and underwater noise, something not well documented in currently literature. This presents an opportunity to adapt terrestrial PAM technologies into an product specific for the requirements of freshwater

The quantitative analysis revelled critical insights into the limitation of current methods and how PAM could offer a shift towards continuous and scalable environmental observation. Traditional monitoring provides a limited snapshot of ecosystem conditions, whereas continues monitoring establishing an ongoing baseline which lets changes be detected and understood. Furthermore, an ecologist is limited by time, travel however a scalable network of PAM devices has the ability to extend an ecologist reach and monitoring capacity. The literature often treats these opportunities in isolation however the reality is continuity and scalability are closely aligned.

The finding across both primary and secondary research closely mirrored each other when it came to the need for self-reliance. Research don't necessarily need autonomy, they need self-reliance systems that reduce the need for their ongoing dependence. Increasing the scalability of devices should not require a corresponding increase in the number of ecologists needed to operate them. Self-reliance doesn't just enable more devices, it enables devices to remain deployed for longer and in places that are difficult or expensive for researchers to regularly access. The finding hence positions the automation of device processed as a frontier for improving efficiency and reducing costs

In summary, this study confirms many barriers identified in existing research while contributing new insights into how they might be overcome. The insights identified through primary research extends current knowledge and offer a direction for where design-led solutions may have the greatest impact.

Design implications

Introduction

Following the learning from the study there are several key considerations that can help define a potential product outcome. Whilst much of the literature reinforced the need to apply PAM in freshwater settings and potential applications, the evidence gathered through research points towards the importance of promoting scalability by increasing the usability of devices and datasets. Together, these insights define priority areas for future design interventions

The product intervention needs to fit within and support the existing monitoring workflow of gather, interpret, decide, act figure. By creating a system-level intervention that considers the entire PAM cycle right through to the use of data (figure 11), the design can better integrate PAM into existing practices and support wider adoption. This can enable more informed decision-making and meaningful environmental action.

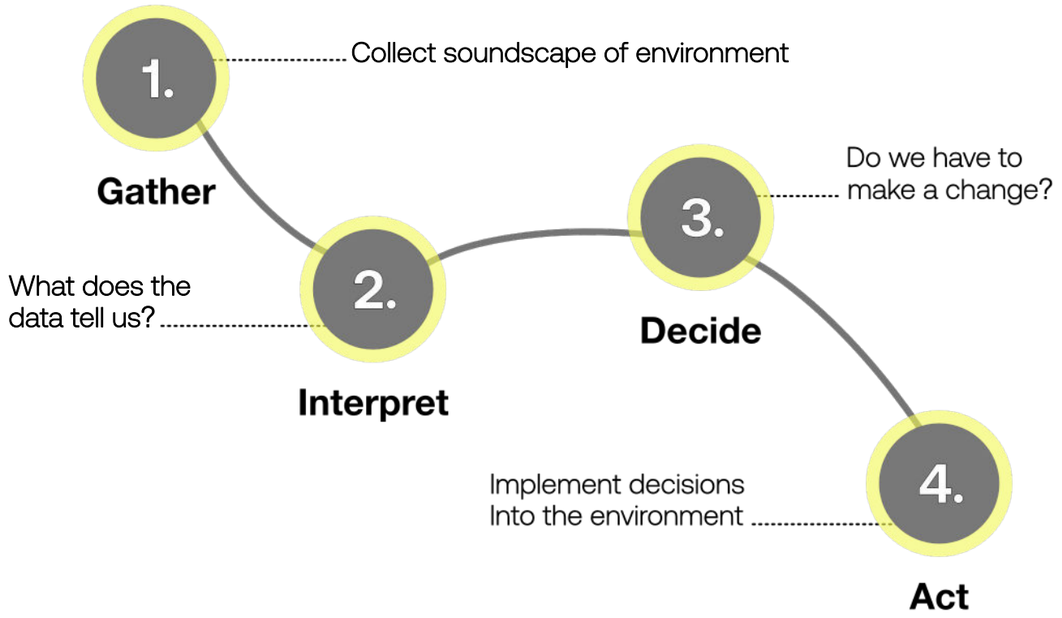


Figure 11: Enviromental decision making framework

1. Deployment

The product must account for the dynamic nature of freshwater environments. For self-sustained deployment to be achieved, the device must withstand environmental factors such as changing water levels, algal buildup, animal interference, and anthropogenic activity. Deployment methods should remain consistent across sites to support data consistency and enable straightforward installation and retrieval by a single ecologist with limited time and resources

2. Creating feedback loops

Although remote data downloading remains challenging, simple feedback loops could improve device management whilst providing more adaptable datasets. Information on whether a device is active, recording, storage and power, could allow researchers to identify problems without physically accessing the site. This is particularly valuable in remote deployments where routine checks are time-consuming and difficult for small research teams. Providing feedback allows issues to be addressed before valuable data is lost. It can also enable recording schedules and device behaviour to be adjusted in response to deployment conditions or monitoring needs.

3. Dedicated freshwater devices

A recurring theme in the research was the drawbacks of adapting terrestrial devices for freshwater applications. Adaptation inherently results in a compromise of both deployment and reliability. A common approach is to isolate electronic components from the water by keeping them on a creekbank, however this can constrain deployment methods and limit the type of data that can be collected. Improving durability requires better component integration within the product, with careful consideration of how the device interacts with its environment. Integrating components can reduce potential points of failure better supporting longer term deployment

4. Depth of datasets

The value of PAM in supporting decision-making lies in its ability to extend the capabilities of ecologists. Increasing the scale of monitoring can add depth to datasets by revealing the spatial and temporal distribution of biodiversity. This can be combined with consistent monitoring which can establish environmental baselines against which changes can be identified. This allows a shift in environmental management from a reactive approach towards a more proactive approach, where emerging changes can be identified earlier and informed action can be taken. The design intervention should support scalable monitoring through self-reliance, low-cost deployment and consistent data collection.

5. Ease of set up

The aesthetics and interactions with PAM devices are often highly technically and rely upon a preexisting understanding of the device. Complex setup and deployment processes can increase the likelihood of user error, potentially resulting in incorrect positioning, missed recordings or data loss. Industrial design is uniquely positioned to bridge the gap between research functionality and user experience. By creating a balance between technical requirements and intuitive interactions It could lead to clearer deployment processes and a more accessible system

Summary

In summary, the design opportunity's supports a shift from a technically focused recording device towards a user-centred, freshwater-specific monitoring system. The product intervention should prioritise consistency and scalability in order to enhance the data generated through PAM to support more informed environmental decision marking

Conclusion

This report explored how passive acoustic monitoring (PAM) could be applied within freshwater environments to generate higher-quality datasets and support more informed environmental decision-making. Given the scarcity of freshwater and current rates of ecological decline, there is an urgent need for accurate biodiversity insights.

Informed by secondary research, one focus group, one observation and three interviews were conducted with industry and water management stakeholders. The research explored barriers preventing the use of PAM in freshwater environments, as well as what constitutes meaningful and usable data. Advancements in terrestrial applications have established PAM as a reliable and respected monitoring method, creating opportunities for its application across other environments. Benchmarking further identified a lack of freshwater-specific devices and a reliance on adapting terrestrial equipment for freshwater monitoring. This creates an opportunity for products designed specifically around the demands of freshwater environments.

The findings indicate that increasing the scale and consistency of monitoring is key to generating deeper and more useful datasets. This is due to it providing a more holistic view of our environment allowing us to better monitor anthropogenic activity and their environmental affects. However, scalability requires long-term self-reliance, supported by low-cost deployment, durability and ease of use. A product intervention addressing these factors could extend the capabilities of ecologists and improve the quality and continuity of biodiversity data. Ultimately, PAM has the potential to support more informed decisions about the management of our freshwater resources.

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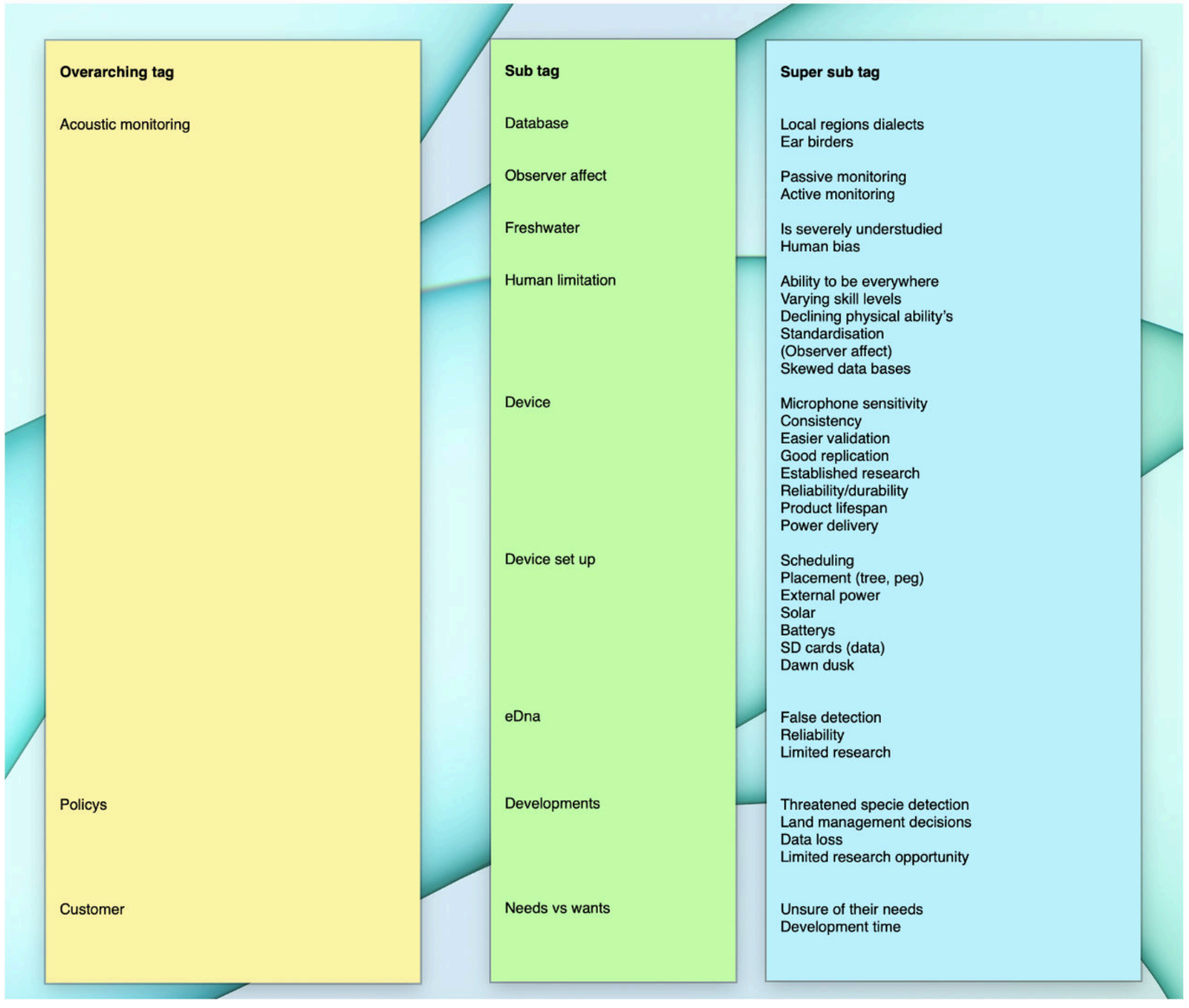
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Note: Appendix has been heavily redacted due to privacy and ethics approval

04 APPENDIX

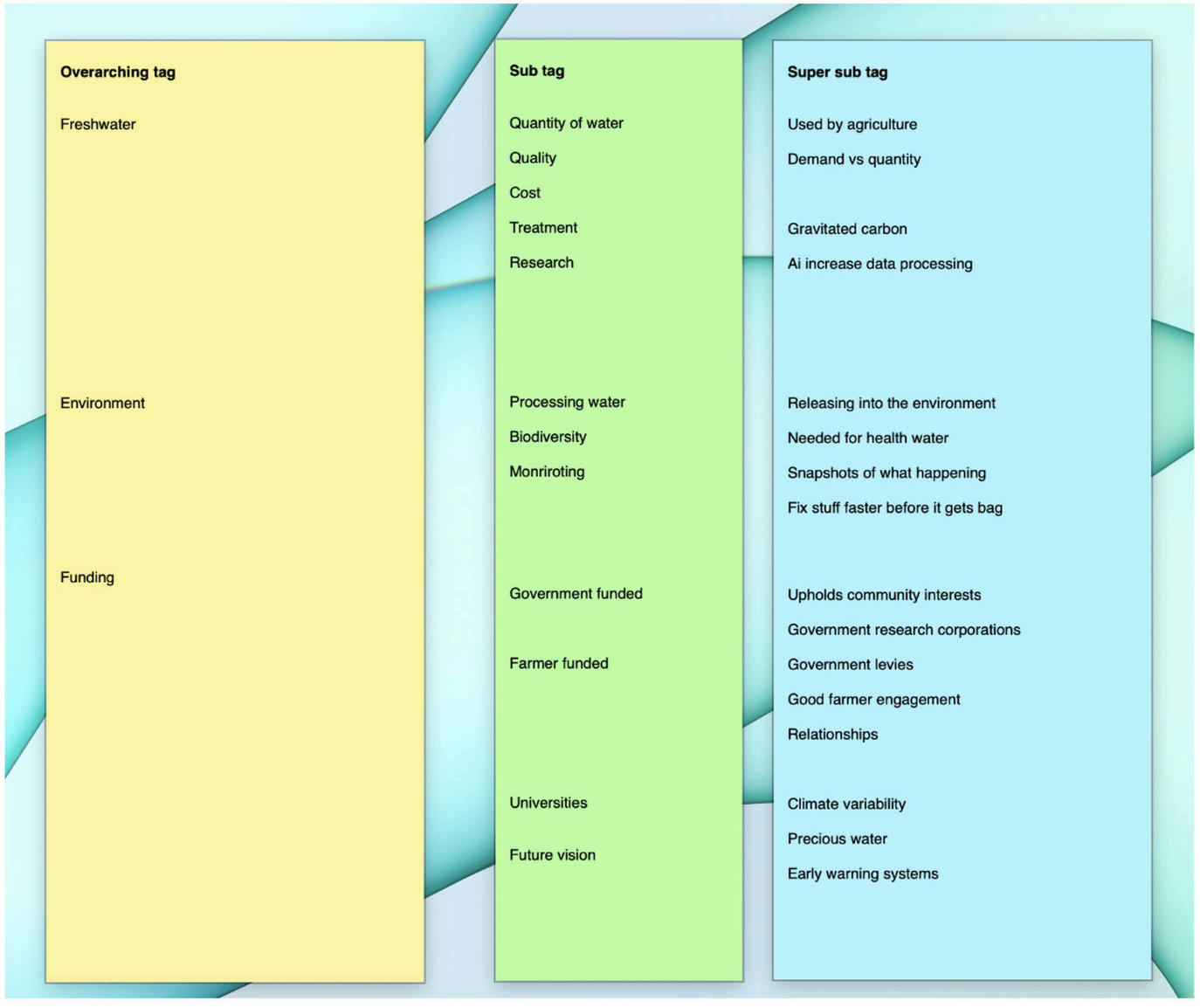
Excerpts From Focus Group coding

Overarching Core	Code	Subcodes
Biodiversity & Monitoring Challenges	Biodiversity monitoring	Species detection; Threatened species; Biodiversity measurement; Ecological monitoring; Land-management decisions
	Detectability	Difficult-to-detect species; Probability of detection; Rare species; Improving detection
	Observer effect	Human presence; Disturbing the environment; Non-representative data; Minimising observer influence
	Sampling limitations	Human limitations; One location at a time; Limited field coverage; Limited observation time
	Environmental conditions	Floods; Fires; Night-time monitoring; Difficult-to-access environments; Dynamic events
	Monitoring scale	Multiple locations; Simultaneous monitoring; Long-term monitoring; Landscape-scale monitoring
Acoustic Technology & Data	Passive acoustic monitoring	Non-invasive listening; Environmental sounds; No interaction with environment; Acoustic landscape
	Active acoustic monitoring	Call playback; Provoking animal responses; Experimental monitoring; Species recolonisation
	Acoustic detection	Diagnostic sounds; Distinctive calls; Species identification; Call detection
	Acoustic limitations	Species must produce sound; Similar calls; Local dialects; Regional variation; Mimicry
	Human expertise	Skilled listeners; Expert identification; Ecological knowledge; Species knowledge
	AI & automated recognition	Automated recognition; AI processing; Species recognisers; Large quantities of audio; Rare-call detection
	AI limitations	Missed detections; False positives; False negatives; Need for human validation
	Data validation	True positive; False positive; True negative; False negative; Expert verification
	Acoustic vs eDNA	Detection differences; Validation; Cost; Technology maturity; Method limitations
Device Design & Deployment	Autonomous recording	Remote operation; Long-term deployment; Scheduled recording; Continuous recording
	Deployment	Field installation; Multiple devices; Site selection; Tree mounting; GPS
	Power	Batteries; External power; Solar power; Power consumption
	Recording schedules	Species-specific schedules; Sunrise/sunset; Intermittent recording; Continuous recording
	Storage & processing	Large audio datasets; Storage capacity; Data volume; Processing requirements
	Hardware	Microphones; Multiple microphones; External power connection; Waterproofing; Protective housing
	Environmental durability	Waterproofing; Humidity; Outdoor exposure; Environmental protection
	User requirements	Target species; Monitoring objectives; Site conditions; Scheduling requirements
	Monitoring efficiency	Less fieldwork; More locations; Longer monitoring periods; Increased ecological research capacity



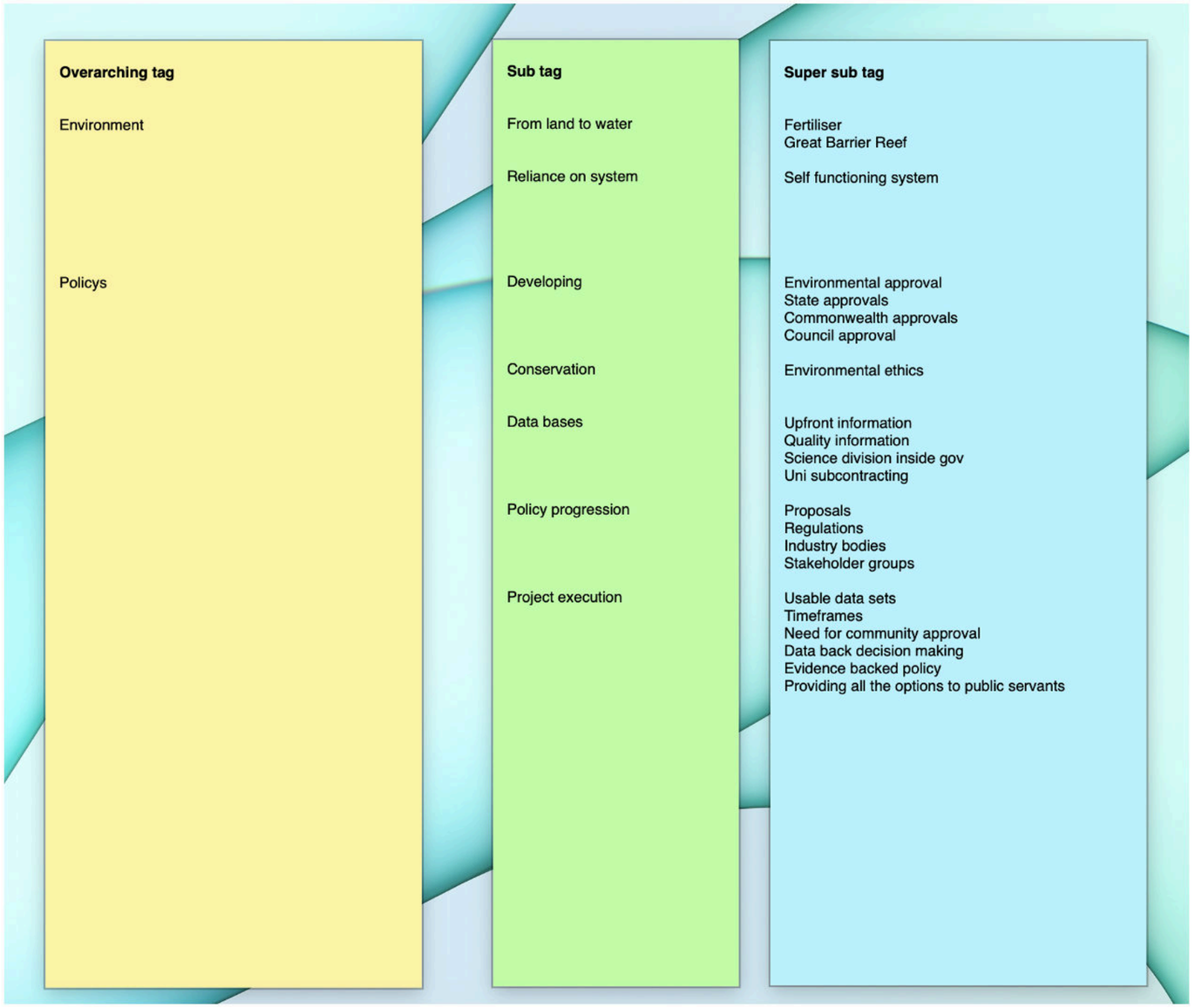
Excerpts From P4 Interview Coding

Overarching core	Code	Subcodes
1. Water & Environmental Challenges	Climate & water availability	Climate variability; Climate change; Freshwater scarcity; Water availability; Precious water
	Agricultural water demand	Agriculture's water use; Demand vs quantity; Water-use efficiency; Irrigation
	Water quality	Pollution; Contaminants; Agricultural runoff; Fertilisers; Herbicides; Pesticides
	Environmental health	Aquatic life; Ecosystem health; Environmental impacts; Biodiversity
	Human needs	Drinking water; Hydration; Human health; Water for communities
	Sustainability	Sustainable water management; Future generations; Resource conservation
2. Monitoring & Technology	Water monitoring	Water quality; Water quantity; Environmental monitoring; Water-quality assurance
	Continuous monitoring	Autonomous monitoring; Regular monitoring; Real-time/ongoing data; Snapshots vs continuous data
	Biodiversity monitoring	Biodiversity as an indicator; Aquatic species; Animal activity; Ecosystem health
	Data collection	Number of samples; Large datasets; Long-term data; Data consistency; Data precision
	AI & data processing	AI; Machine learning; Processing large datasets; Faster analysis; Decision-making tools
	Early intervention	Early warning systems; Detecting problems; Preventative action; "Fix things faster"; Reactive vs proactive
	Treatment & processing	Water purification; Filtration; Graphitate carbon; Sewage treatment; Recycled water; Energy efficiency
	Technology limitations	AI validation; Human interpretation; Technology as a tool; Diagnostics
3. Research, Stakeholders & Implementation	Research ecosystem	Universities; Government; Industry; Research organisations; Government research
	Research funding	Government funding; Farmer funding; Farmer levies; Commonwealth matching; Co-investment
	Research priorities	Government priorities; Industry needs; Farmer needs; Environmental concerns; Stakeholder engagement
	Industry & farmer engagement	Farmer participation; Industry partnerships; Relationships; Trust; Demonstrating value
	Co-design & adoption	Co-design; Benefits to farmers; Benefits to environment; Practical demonstration; Technology adoption
	Community interests	Community benefit; Environmental benefit; Public understanding; Shared resource
	Future vision	Sustainable future; Long-term water management; Technological advancement; Intergenerational responsibility; Shared vision



ExcerptsFrom P5 Interview Coding

Overarching Core	Code	Subcodes
Water, Environment & Land Use	Water quality	Catchment water quality; Fertiliser runoff; Soil erosion; Agricultural impacts; Waterway pollution
	Biodiversity & ecosystem health	Biodiversity; Species protection; Wetlands; Natural capital; Nature positive; Environmental outcomes
	Agriculture & environment	Productive land use; Farming; Fertiliser efficiency; Environmental impact; Farm outcomes
	Development & environment	Development impacts; Environmental approvals; Land-use planning; Minimising environmental impact
	Environmental sustainability	Conservation; Sustainable development; Future environmental outcomes; Balancing productivity and conservation
Data, Monitoring & Decision Making	Biodiversity data	Biodiversity mapping; Species distribution; Environmental information; Regional information
	Environmental monitoring	Wetland monitoring; Water monitoring; Scientific monitoring; Environmental studies
	Data availability	Existing information; New studies; Large datasets; Information upfront; Accessible information
	Centralised data	Central repository; Shared database; Reusable data; Data accessibility; Avoiding duplicated studies
	Spatial mapping	Biodiversity mapping; Regional mapping; Priority areas; Development-area mapping
	Data-informed decisions	Better decisions; Evidence-based policy; Development planning; Environmental decision-making
	Early information	Information upfront; Early identification of environmental constraints; Planning before development
Government, Policy & Stakeholders	Government role	Policy; Legislation; Regulation; Environmental protection; Government responsibility
	Policy development	Cabinet; Ministerial direction; Interdepartmental consultation; Policy formation
	Stakeholder engagement	Industry; Farmers; Conservation groups; Regional stakeholders; Community interests
	Competing interests	Agriculture vs environment; Development vs environment; Regional differences; Stakeholder priorities
	Collaboration	Government departments; Industry bodies; Universities; Private researchers; Consultation
	Regional variation	Local environmental priorities; Regional needs; Different stakeholder concerns; Local implementation
	Implementation & adoption	Broad policy; Regional implementation; Stakeholder support; Practical implementation
	Funding & research	Government-funded studies; University research; Private research; Commissioned research
Future & System Improvement	Efficiency	Faster approvals; Reduced duplication; Reduced study costs; Streamlined processes
	Shared information	Publicly accessible data; Reusable research; Information sharing
	Proactive planning	Planning before development; Predicting impacts; Avoiding problems
	Balancing outcomes	Environmental protection; Economic development; Agricultural productivity; Community benefit



Thematic Coding (collated all 6 participants)

Broad Overarching Core	Code / Theme	Combined Subcodes	Steve	Saga	Frontier Labs	Mary-Anne	Overlap	Quote
1. **Environmental** Challenges & Outcomes	Water & resource pressure	Freshwater; Water scarcity; Water availability; Water demand; Precious water	—	✓	—	✓	2/4	
	Agricultural impacts	Agriculture; Irrigation; Water efficiency; Fertiliser; Agricultural pollution	—	✓	—	✓	2/4	"Two-point five percent of the water that found on earth is freshwater… of which roughly 60 percent is used by agriculture" (SM 02:21)
	Climate & environmental change	Climate change; Climate variability; Environmental change; Long-term change	✓	✓	✓	✓	4/4	
	Water quality & pollution	Water quality; Contaminants; Runoff; Soil erosion; Pollution	✓	✓	—	✓	3/4	
	Biodiversity & ecosystem health	Biodiversity; Species; Aquatic life; Ecosystem health; Environmental indicators	—	✓	✓	✓	3/4	
	Environmental sustainability	Conservation; Sustainability; Resource protection; Future generations	✓	✓	✓	✓	4/4	
2. **Monitoring**, Data & Technology	Environmental monitoring	Water monitoring; Biodiversity monitoring; Ecological monitoring; Environmental studies	✓	✓	✓	✓	4/4	
	Continuous / long-term monitoring	**Continuous monitoring; Regular monitoring; Long-term datasets; Repeated observations**	—	✓	✓	✓	3/4	
	Data collection	Sampling; Field data; Acoustic data; Biodiversity data; Environmental data	—	✓	✓	✓	3/4	
	Large datasets	Data volume; More samples; Long-term datasets; Large-scale monitoring	✓	✓	✓	✓	4/4	
	Data storage	Storage capacity; Data repositories; Data management; Shared datasets	✓	—	✓	✓	3/4	
	Data accessibility / sharing	Shared information; Accessible data; Central repository; Reusable data	—	✓	—	✓	2/4	
	AI & automated processing	AI; Machine learning; Automated recognition; Data processing	✓	✓	✓	—	3/4	
	Human validation	Expert knowledge; Validation; False positives; False negatives; Human interpretation	—	✓	✓	—	2/4	
	Detection limitations	Detectability; False negatives; Species-specific detection; Environmental limitations	—	✓	✓	✓	3/4	
	Autonomous monitoring	**Remote devices; Autonomous systems; Reduced fieldwork; Automated data collection**	—	✓	✓	—	2/4	
	Technology limitations	Detection limitations; AI limitations; Data limitations; Method limitations	—	✓	✓	✓	3/4	
3. **Decision** Making & Action	Better information = better decisions	**Evidence-based decisions; Decision support; Better planning; Information for decision makers**	✓	✓	✓	✓	4/4	
	Early warning / early detection	Early warning; Detecting problems; Proactive monitoring; Early intervention	✓	✓	✓	✓	4/4	
	Proactive vs reactive	Preventative action; Planning ahead; Avoiding damage; Acting before problems escalate	✓	✓	✓	✓	4/4	
	Spatial information	Mapping; Site selection; Distribution; Location-based information	—	—	✓	✓	2/4	
	Efficiency	Less fieldwork; Faster processing; Faster approvals; Reduced duplication	—	✓	✓	✓	3/4	
	Cost	Monitoring cost; Storage cost; Research cost; Avoiding duplicated costs	✓	✓	✓	✓	4/4	
4. People, Policy & **Implementation**	Government role	**Government research; Policy; Regulation; Environmental protection; Decision-making**	✓	✓	—	✓	3/4	
	Universities / research	**University research; Scientific research; Researchers; Research methods**	✓	✓	✓	✓	4/4	
	Industry involvement	**Industry partners; Private sector; Industry priorities; Commercial applications**	✓	✓	✓	✓	4/4	
	Farmer / landowner engagement	Farmers; Landowners; Farmer needs; User engagement	✓	✓	—	✓	3/4	
	Stakeholder interests	Farmers; Industry; Government; Conservation groups; Community	✓	✓	✓	✓	4/4	
	Collaboration	Partnerships; Consultation; Co-design; Interdepartmental collaboration	✓	✓	✓	✓	4/4	
	Funding	Government funding; Farmer levies; Research funding; Private funding	✓	✓	—	✓	3/4	
	Policy & regulation	Legislation; Environmental approvals; Policy; Regulation	✓	—	—	✓	2/4	
	Adoption & implementation	Co-design; Demonstrating value; Practical implementation; User needs	—	✓	✓	✓	3/4	
	Regional / contextual variation	Local conditions; Regional species; Regional priorities; Site-specific monitoring	✓	✓	✓	✓	4/4	

Benchmarking Case Studies

Case	Environment / case study	Who conducted it?	What were they researching?	Sector	Device / technology used	Study duration	source
1	Australian Acoustic Observatory (A2O)	QUT, Charles Sturt University, James Cook University, University of New England & University of Queensland	Continental-scale acoustic monitoring of Australian ecosystems, biodiversity, soundscapes and environmental change	Research / conservation	Custom acoustic sensors built by Frontier Labs; solar powered; 360 sensors across 90 sites	5-year project, with ongoing data collection	Australian Acoustic Observatory – official project site
2	Eastern Australian terrestrial mammals	James Cook University & collaborators	Compared PAM with conventional surveys and camera trapping for detecting 17 vocal mammal species	Research / conservation	Autonomous acoustic recorders + automated acoustic analysis / BirdNET	Multi-year dataset; 317,410 hoursof recordings	Sensors versus surveyors – Wiley
3	Sturt National Park, NSW – arid-zone biodiversity	Charles Sturt University, QUT & collaborators	Whether acoustically detectable species could act as indicators of broader biodiversity in an Australian arid environment	Research / conservation	Wildlife Acoustics Song Meter SM2+, solar panel and battery	2014–2017	Remote Sensing in Ecology and Conservation study – Wiley
4	Grazed Queensland landscapes	QUT, CSIRO & collaborators	Used bird acoustic activity alongside satellite data to assess ecological condition of agricultural landscapes	Agriculture / research	AudioMoth + BirdNET	Approximately 1 month per farm, 2022–23	Ecological Indicators study
5	Southeast Australian biodiversity / biocredits	Australian university research collaborators	Compared PAM, eDNA, camera trapping and conventional surveys for biodiversity monitoring and biodiversity-credit assessment	Conservation / environmental markets	AudioMoth + BirdNET + amphibian acoustic model	Approximately 3 months of monitoring	Biodiversity and Conservation study
6	Powerful Owl – Southeast Queensland	BirdLife Australia, Queensland Government & citizen scientists	Distribution, breeding activity and habitat use of the Powerful Owl in urban/suburban SE Queensland	Government / conservation / citizen science	Acoustic monitoring + automated analysis	Approximately 3 years, across breeding seasons	Queensland Government – Powerful Owl project
7	Australian birds & frogs	Australian research collaborators	Tested automated acoustic identification of birds and frogs, including whether PAM could improve biodiversity surveys	Research / conservation	AudioMoth + BirdNET + VicFrogNET	Approximately 4 months, 2023–24	Ecological Informatics study
8	Southern Great Barrier Reef / Lady Elliot Island	Griffith University, Curtin University & Marine Mammal Foundation	Cetacean presence, seasonal patterns and environmental drivers around the southern Great Barrier Reef	Research / conservation	Autonomous underwater acoustic recorders	2 years	Marine Mammal Science study
9	Australian Marine Parks – NSW	Australian Government / Southern Cross University & collaborators	Underwater vessel activity and effectiveness of acoustic monitoring for marine-park management	Government / marine management	SoundTrap 300 acoustic recorders	Approximately 1 month per deployment	Marine Policy study
10	Beach Energy – Otway Basin, Victoria	Beach Energy, with JASCO Applied Sciences	Measured underwater noise from offshore gas drilling and support vessels; validated noise-propagation models and marine-mammal impact thresholds	Private sector / energy	4 × JASCO AMARs on C-Lander moorings; hydrophones	Feb–early Apr 2021 for the Artisan-1 monitoring program	JASCO – Beach Energy acoustic monitoring report
11	Woodside – Scott Reef / North West Shelf, WA	Woodside Energy, with JASCO Applied Sciences	Pygmy blue whale presence, marine mammal distribution and underwater soundscape around the proposed Browse development	Private sector / energy	JASCO ALTO autonomous long-term acoustic landers; later combined with biological echosounders	Began April 2023; initial deployments 6 months, continuing through 2026	Woodside – Underwater noise and whales
12	Gwydir River wetlands, NSW	University of New England / Australian Government / NSW environmental-water programs	Frog species richness, abundance and calling response to river flows and environmental watering	Government / research / water management	Frontier Labs Bioacoustic Audio Recorder (BAR)	Four nights before and after flow events; monitoring conducted 2019–2020	DCCEEW – Gwydir frog acoustic monitoring report

Benchmarking Matrix

Device	Use case / environment	Approx. cost	Autonomy	Durability	Data quality	Maintenance	Ease of use	Cost / accessibility	Retrieval after deployment	Total
AudioMoth 1.2	Low-cost terrestrial biodiversity and soundscape monitoring. HydroMoth configuration extends it to underwater applications.	~A$150	3	1	3	2	8	10	4	32
Frontier Labs BAR-V2	Professional autonomous bioacoustic monitoring, particularly terrestrial biodiversity surveys and long-term ecological studies.	A$499	5	7	7	9	9	7	5	51
Frontier Labs BAR-LT	Professional long-term biodiversity monitoring, including terrestrial and hydrophone-based aquatic applications.	A$930	6	6	8	9	8	5	6	50
Cornell SwiftOne	Research and conservation monitoring of terrestrial wildlife, particularly birds and other vocal species.	A$480	1	7	5	7	6	6	4	37
Song Meter Mini 2	Commercial wildlife monitoring, especially birds, frogs and other terrestrial species within the audible frequency range.	US$499 AA / US$599 Li-ion	3	7	6	4	5	8	4	38
Song Meter SM3BAT+	Specialist bat and ultrasonic monitoring, rather than general freshwater biodiversity monitoring.	US$1,599.00	3	5	7	3	7	3	4	35
Loggerhead LS2	Underwater passive acoustic monitoringof fish, marine mammals and aquatic soundscapes. Particularly relevant to freshwater applications.	Quote-based	4	4	9	3	1	2	2	26
JASCO AMAR G4	High-end scientific underwater acoustic monitoring, particularly marine mammals, fish, soundscapes and environmental noise.	Quote-based	6	8	10	2	1	1	1	31
			based on if it can be controlled remotely and how it can be configured. E.g. the frontier labs uses gps	How does the device stand up to harsh conditions	Quality of the recording. Frequency ranges, data storage capacity. Stereo vs mono recording	How easily can the product be repaired. Off the shelf components vs proprietary and ease of disassemble	How easy is it to set up and control. Is it user friendly and intuitive or do you need a scientific background	How much does the device cost and how easy is it for me to get one or a fleet of them	How easy is it to retrieve from a researcher perspective but also thief. Is it hard to find or permanent	Frontier labs Frontier Labs BAR-V2 comes out as the best over all