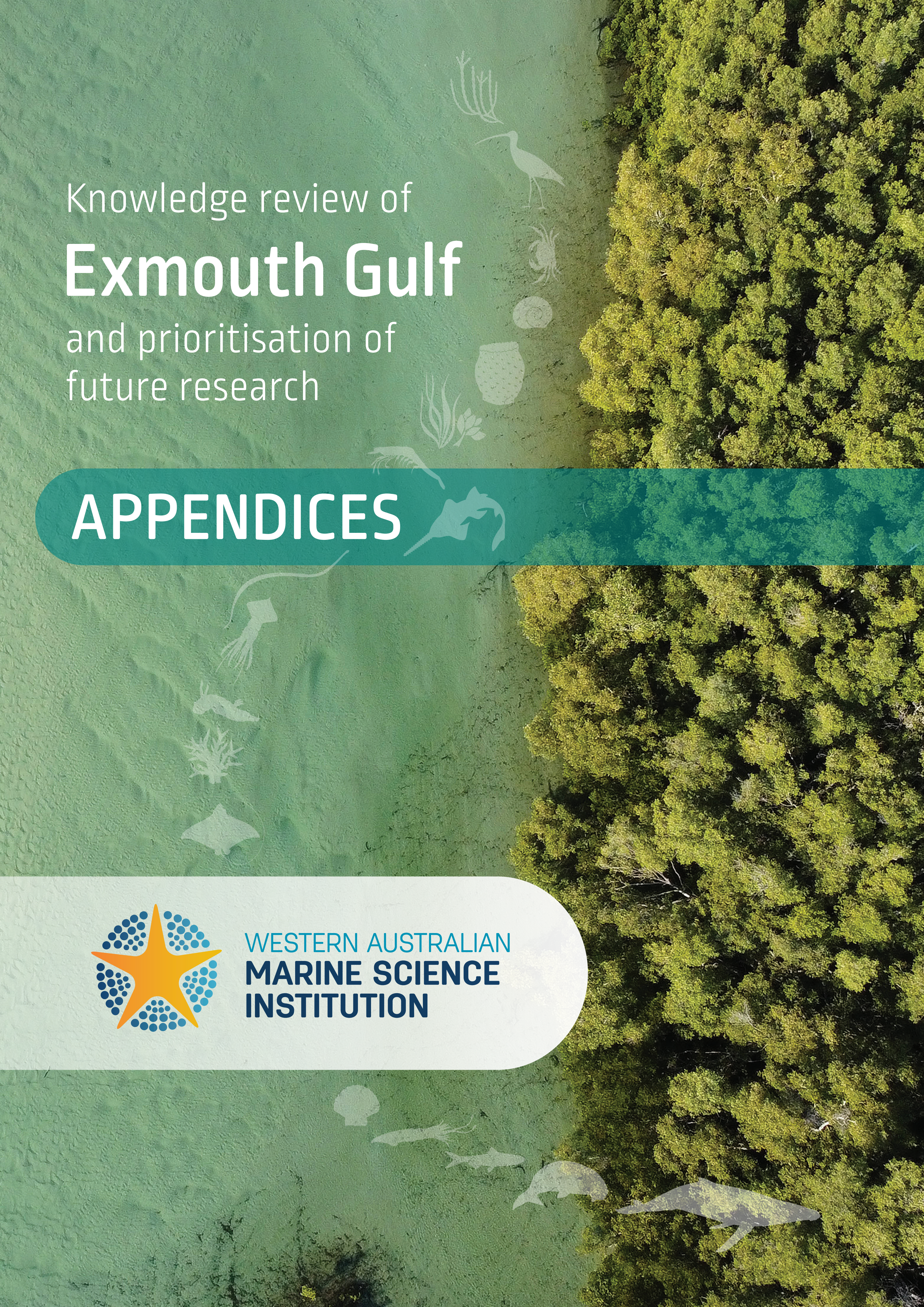

Knowledge review of

Exmouth Gulf

and prioritisation of future research

APPENDICES

WESTERN AUSTRALIAN MARINE SCIENCE INSTITUTION

This appendices document provides supplementary information to the WAMSI report **Knowledge review of Exmouth Gulf and prioritisation of future research***,* produced May 2025.

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North-west region of Australia

North-west region of Australia

Legend

- Town
- Point of Interest
- Regional Development Commision Boundaries
- Major Rivers
- Major Roads

SOURCE DATA
Proponent: Exmouth Gulf Taskforce
Basemap: ESRI Topographic

DWER GIS Section
Date: 31/03/2025, Map Version: 1
Ministerial Statement: / File No: SR-0190109

Disclaimer:
This map is intended as a generalised interpretation of environmental issues. The information contained on this map is to be considered indicative only and in no event shall the Department of Water and Environmental Regulation be liable for any incident or consequential damages resulting from use of the material.

GOVERNMENT OF WESTERN AUSTRALIA

N

0 50 100 200
Kilometres

Coordinate System: GDA2020
Scale: 1:4,000,000 at A3

LOCALITY MAP

Exmouth Gulf nutrient sources and pathways workshop report

WESTERN AUSTRALIAN MARINE SCIENCE INSTITUTION

Exmouth Gulf nutrient sources and pathways workshop report

October 2024

Workshop date:

Thursday 15 Aug 2024

Location:

Indian Ocean Marine Research Centre (UWA)

Acronyms and abbreviations

Acronyms	Definition
AIMS	Australian Institute of Marine Science
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DBCA	Department of Biodiversity, Conservation and Attractions
DWER	Department of Water and Environmental Regulation
EG	Exmouth Gulf
ECU	Edith Cowan University
EPA	Environmental Protection Authority
IOMRC	Indian Ocean Marine Research Centre
UQ	The University of Queensland
UWA	The University of Western Australia
WAMSI	Western Australian Marine Science Institution

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Exmouth Gulf nutrient sources and pathways workshop summary

WAMSI was engaged by the Exmouth Gulf Taskforce to undertake a knowledge gaps review of Exmouth Gulf, which includes gaining a better understanding of terrestrial and marine nutrient sources and pathways. On 15 August 2024, WAMSI facilitated a workshop with 15 researchers and managers from seven organisations who have historically or currently worked on nutrients in Exmouth Gulf.

The purpose of this workshop was to 1) document all available data and literature on nutrient sources and pathways, 2) review a draft conceptual model of nutrient sources, pathways and nutrient budget estimates and 3) identify knowledge gaps for future research.

Workshop participants provided updates to current projects and identified some additional historical data that could be useful for better understanding the nutrient dynamics in Exmouth Gulf. Much of the workshop was spent discussing the draft conceptual model and the suitability of a static conceptual model for representing the nutrient budget in Exmouth Gulf.

Recent reporting on nutrient budget estimates in Exmouth Gulf suggested that over 90% of nutrients entering the Gulf were from offshore sources. There was a unanimous vote of no confidence in these estimates. It was recommended that such estimates should not be used to represent the nutrient budget of the Gulf overall and should not be used by managing bodies or decision makers when assessing impacts to nutrient sources of the Gulf and surrounding habitats.

Exmouth Gulf is a dynamic system and has daily and seasonal influences as well as different 'states', such as pre- and post- cyclone and flood events, and climatic phases (La Niña and El Niño). More nuance is needed to genuinely inform management decisions. Participants believed we still do not know enough about nutrient sources, pathways and fluxes in Exmouth Gulf in order to provide robust guidance and advice. It was suggested, and generally agreed, that a gap analysis was needed to clearly outline what is known and unknown for nutrient sources fluxes and flows in Exmouth Gulf.

The next steps following the workshop include 1) delivering a draft workshop report to the Exmouth Gulf Taskforce, 2) producing a conceptual model or series of models (without quantification) to demonstrate nutrient sources and pathways in different seasons and during different states (e.g., pre and post cyclone), 3) developing a database and gap analysis to highlight available and missing data and 4) scoping the feasibility of a combined hydrodynamic and biogeochemical modelling project.

Purpose of the workshop

In 2021, the EPA delivered strategic advice to the Minister for Environment under Section 16(e) of the Environmental Protection Act 1986 on the potential cumulative pressures of the proposed activities and developments on the environmental, social and cultural values of Exmouth Gulf. Following this advice, the Exmouth Gulf Taskforce was established as a Ministerial Advisory Body under s.25 of the EP Act. Under its Terms of Reference, the Taskforce is to provide advice to the Minister for Environment, including knowledge gaps and options to inform terrestrial and marine planning processes.

A priority for the Taskforce is to gain a better understanding of nutrient sources and pathways into Exmouth Gulf and what key knowledge gaps may still exist following a review of the literature and expert consultation. To date, most literature and data collection has focused on the intertidal habitats (e.g., mangroves, cyanobacterial mats) of the southern and eastern margins of Exmouth Gulf.

The purpose of this workshop was to bring together researchers and managers who have historically or currently worked on nutrients in Exmouth Gulf in order to 1) document all available data and literature on nutrient sources and pathways, 2) review a draft conceptual model of nutrient sources, pathways and nutrient budget estimates and 3) identify knowledge gaps for future research.

Workshop attendees

A total of 15 people attended the Exmouth Gulf Nutrient Sources and Pathways Workshop on 15 August 2024. Participants represented seven organisations: WAMSI, DBCA, DWER, UWA, ECU, AIMS and UQ. A list of attendees is provided in Appendix 1.

The agenda for this workshop is provided in Appendix 2 and informs the structure of this workshop report. Several attachments were also provided prior to the workshop and discussed by participants (Appendices 3-7).

Workshop participants were provided with the opportunity to review this workshop report to make amendments as needed.

Existing datasets and knowledge on nutrient sources and pathways

Workshop participants were provided with a list of existing data sources and literature on nutrient sources and pathways in Exmouth Gulf prior to the workshop (Appendix 3). One aim of the workshop was to expand on this list, particularly to identify data that may not be publicly available.

Participants provided updates to current projects and identified some additional historical data that could be useful for better understanding the nutrient dynamics in Exmouth Gulf (Table 1), which revealed some additional information not included in Appendix 3.

Table 1: Details of past and current projects relating to nutrient sources and pathways shared by workshop participants. Bolded text indicates new sources of information arising from the workshop, which have been added to Appendix 3.

Name / Organisation	Knowledge	Data availability
UWA Matt Hipsey	• Mardie Offsets Project is currently modelling selected tidal creeks on the eastern margin - Giralia and Urala, not the whole of EG • Project team is developing the tools and datasets that can then underpin a larger focus on EG e.g., how quickly are nutrients transferred and processed through the Gulf? • Current modelling could include an additional nutrient tracers component for EG if that was of interest	Project not yet complete - late 2025
UWA Sharyn Hickey	• Mardie Offsets Project has mapped 10 habitats in the tidal areas along the eastern margin of EG • Cyanobacterial mats are very dynamic and change in extent across time • Will look at satellite imagery of coastal areas across eight time points, from south of Learmonth to south of Karratha to assess change • Fine scale maps will also be produced for Giralia, Urala, and Gnoorea to examine what else can be detected with higher resolution imagery	Project not yet complete - late 2025 Report on intertidal habitats (Deliverable 1) soon to be released
UWA Ryan Lowe	• Mardie Offsets Project is investigating the hydrodynamics and sediment dynamics along the eastern Gulf –at Giralia and Urala • PhD student will also be examining hydrodynamics and the interaction with habitats • **Camille Grimaldi (UWA/AIMS) is working on a hydrodynamic model (Delft3D) for the whole Gulf that models circulation patterns, connectivity, residence times etc. spanning 1990s-present** • Very limited work has looked at potential nutrient exchange from ocean to the Gulf. **Two relevant papers that look at nutrients and primary production across ocean-Gulf interface are from historical AIMS cruises – McKinnon et al. 2003 and Furnas 2007**. But these still represent snapshots in time of concentrations and not fluxes of nutrients (dependent on flows)	Projects not yet complete - late 2025 Grimaldi et al. paper soon to be submitted
ECU Glenn Hyndes	• Mardie Offsets Project is tracing the flow of nutrients through the system/food webs using stable isotopes (carbon, nitrogen, sulfur) • The current data on how much nutrients are being supplied from algal mats is really variable across tides, regions and zones • Have yet to see a strong nutrient signal in the outgoing tides from algal mats, however, may not be sampling at the exact time when nutrients are pulsing off the algal mats • Have also yet to see a clear signal of nitrogen fixation by the algal mats – but still early days • Also investigating primary productivity, biomass, standing stock, diversity in cyanobacteria mats, functional groups of microbes • Upcoming project by Shannon Dee (ECU) will be examining the uptake of nutrients by corals in EG	Project not yet complete - late 2025
AIMS Kay Davis	• Blue Carbon Seascapes project involves taking sediment cores inside EG and offshore (off Muiron Islands) • Coring sites include benthic and intertidal habitats • Aiming to determine the extent of carbon burial and the sources of carbon	Project not yet complete - late 2025/2026.

	• Nutrient samples also being taken north of Tent Island to south Urala, and a couple of offshore sites	Data will be made freely available
AIMS Chris Fulton	• AIMS data manager currently rebuilding historical AIMS datasets from EG e.g., combining georeferenced data with other data • A lot of EG expertise within AIMS in the 90s • Undertook some ecotoxicology studies as part of the WAMSI Dredging Node • Examining *Sargassum* phenology along Gascoyne/Pilbara coasts, incl EG, in collaboration with DBCA • Working on building a connectivity model (focused on carbon). ~ 2-3 years away • Currently using eDNA to examine the deposition of organic material and how much carbon is leaving the Gulf • Future work being led by Shaun Wilson is aiming to determine the importance of different primary producers in the Gulf and how they contribute and link to key values, such as targeted fish species and higher order consumers. ~2-3 years away	Data will be made freely available
DWER Fiona Webster	• DWER provides technical expertise on proposals, such as the salt farms proposals for the eastern margins of EG/Pilbara • DWER wants to understand the impacts of salt farms on the nutrient flows in EG and gain a relative understanding of the offshore inputs vs intertidal inputs	NA
DBCA Tom Holmes	• DBCA has expanded monitoring into EG on macroalgae/seagrasses • EG has not really been a focus for DBCA until now given the EG marine park proposal and land based tenure • Understanding coastal and marine based nutrient cycling is important for the management of these tenures	
DBCA Sallyann Gudge	• Assisting with the research gathering and implementation of several research projects for the proposed EGMP • DBCA working closely with Traditional Owner partners for the proposed marine park planning process • Nutrient flows and connectivity are important to understand from both an ecological and cultural perspective	
UQ Catherine Lovelock	• **Installed instruments in 2010/11 to measure surface elevation and understand vertical accretion on mangroves, algal mats and salt flats** • **Has been monitoring mangrove tree growth in Giralia since 2007 to understand what nutrients are limiting the growth of mangroves** • **Fertilisation experiments with mangroves have been running for a long time and also has plots at Mangrove Bay to look at mangrove recovery and dieback** • **Missing from Appendix 3 is Lovelock et al 2021. Vulnerability of an arid zone coastal wetland landscape to sea level rise and intense storms. Limnology and Oceanography, 66(11), pp.3976-3989.** • **Though not EG based, Ridd et al. 1988, 1996, 1997 have published some of the few studies on outwelling from flats that could serve as a comparison**	

A conceptual model for Exmouth Gulf

A draft conceptual model was shared and discussed during the workshop (Appendix 7). The model included recent nitrogen budget figures for the whole Gulf taken from a consultancy report for K&S

Salt's Ashburton Salt project (Water Technology 2021)(Appendix 5 and 6). This report estimated that 93% of nutrients (nitrogen) entering the Gulf were from offshore sources. All participants in the workshop unanimously agreed they had no confidence in these budget estimates. While these estimates may reflect the nutrient budget at some point in time, it is not reflective of the nutrient budget overall as there could be orders of magnitude of variation. The lack of confidence largely comes from the predominant use of data from historical literature that is spatially and temporally limited, lack of field validation and lack of inclusion of all nutrient sources. Presenting a simplified view of a nutrient budget, without confidence, uncertainty estimates or validation to decision makers was advised as being 'dangerous' as it could mean the difference between a considered and fully informed decision and a decision based on inaccurate data. The latter decision could possibly result in unintended consequences or detrimental irreversible environmental outcomes.

Workshop participants questioned whether a static conceptual model is best for representing the nutrient sources, pathways and budgets in Exmouth Gulf. Such a model has value for communicating with a non-scientific audience, and a relative understanding of where most nutrients are coming from will help to inform advice and decisions around coastal development and impacts to nutrient dynamics. However, there are concerns that a model would not represent the natural and varied states of Exmouth Gulf. The major concerns for a static conceptual model of nutrients in Exmouth Gulf are:

- Exmouth Gulf is a dynamic system and has daily and seasonal influences as well as different 'states', such as pre and post cyclone and flood events, and climatic phases (La Niña and El Niño). This cannot be shown on a single model. More nuance is needed to genuinely inform management
- We do not have enough data to generate accurate nutrient budgets for the Gulf. Existing budgets draw heavily on historical literature with spatially and temporally patchy sampling efforts
- A lot of trophic levels can be ignored in simplified models, though they are important for understanding the true dynamics of a system
- The Gulf should not be presented like a 'bucket' where nutrients only flow one way into the Gulf

If a nutrient budget was to be developed for Exmouth Gulf, it should consider the following:

- Pools of high nutrient water can form in algal mats and behind mangroves which would be flushed with outgoing tides and floods. These pools are not spatially or temporarily resolved
- 10 classes of coastal/tidal habitat have been identified and mapped, and should be accounted for in productivity and nutrient budgets
- To have net import of nutrients into the Gulf, the offshore nutrient concentrations should be much higher and consistently higher. Is this true? Would there be periods where Exmouth Gulf has higher nutrients than offshore waters? Import also depends on how effective hydrodynamic processes transport nutrients within the Gulf, i.e. whether ocean-derived nutrients only influence the entrance region of the Gulf or the whole extent.
- During floods and cyclones, high volumes of particulate matter can be flushed into the Gulf, and this needs to be better understood and accounted for in nutrient budgets
- Benthic and intertidal habitats can change significantly within and between years. For example, the extent of cyanobacterial mats can double or halve. Likewise, seagrass habitat area and locations can dramatically shift in the Gulf, such as the apparent lack of seagrass

coverage in NE Gulf (according to 1990s systematic surveys) compared to contemporary surveys indicating a vast seagrass meadow between Tent Island and South Urala Creek

- Seasonal growth and decay of many primary producers (e.g., *Sargassum*) is important for understanding episodic use and flux of nutrients through the ecosystem
- Concentrations of nutrients entering the Gulf from offshore exchange in the north is likely not reaching further south into the Gulf. Therefore, nutrient concentrations should not be viewed as uniform across the whole Gulf
- Tiny micro creeks are doing a lot of work in terms of nutrient fluxes and flows but they are not included in models because they are hard to see and obscured by mangrove canopy
- All sources of nutrients, including seagrasses, major groups of macroalgae like *Sargassum*, diatoms, *Trichodesmium* etc. need to be considered
- There is a division of fauna that occurs in the Gulf that needs to be better understood in terms of links to nutrients, energy flows and connectivity, e.g., many species observed off the Pilbara are also observed for much of the Gulf, whereas the species observed from Bundegi around the North West Cape to Jurabi are different
- Trawling efforts for the Exmouth Gulf Prawn Managed Fishery would have an impact on nutrient availability
- A % range for nutrient budget sources could be presented to account for the variability and uncertainty

Key knowledge gaps and future research

There was general agreement by workshop participants that not enough is known about nutrient sources, pathways and fluxes in Exmouth Gulf. Some of the gaps specifically mentioned include (but are not limited to):

- A better understanding of sediment-water interactions and habitat-water interactions
- Determining whether atmospheric deposition of nutrients is significant in the Gulf
- Improving our understanding of nutrient fluxes for cyanobacterial mats

It was suggested and generally agreed that a gap analysis was needed to clearly outline what is known and unknown for nutrients in Exmouth Gulf to help guide future research.

Next steps

The next steps following the workshop include:

1) delivering a draft workshop report to the Exmouth Gulf Taskforce
2) producing a conceptual model or series of models (without quantification) to demonstrate nutrient sources and pathways in different seasons and during different states (e.g., pre and post cyclone). This can be used to understand different nutrient stocks, transformations and fluxes and potential for seasonal and interannual variation in stocks, transformations and fluxes.
3) developing a database and gap analysis to highlight available and missing data
4) scoping a combined hydrodynamic and biogeochemical modelling project

Appendix 1: Exmouth Gulf Nutrient Sources and Pathways Workshop participants: 15 Aug 2024 IOMRC

Name	Affiliation	Attended
Luke Twomey	WAMSI	In person
Jenny Shaw	WAMSI	In person
Alicia Sutton	WAMSI	In person
Sharyn Hickey	UWA	In person
Matt Hipsey	UWA	In person
Ryan Lowe	UWA	In person
Mick O'Leary	UWA	Not available
Kathryn McMahon	ECU	Not available
Glenn Hyndes	ECU	In person
Shannon Dee	ECU	Not available
Catherine Lovelock	UQ	Online
Chris Fulton	AIMS	In person
Kay Davis	AIMS	In person
Shaun Wilson	AIMS	Not available
John Keesing	CSIRO	Not available
Mat Vanderklift	CSIRO	Not available
Wendy Thompson	DWER – EG Taskforce	Online
Naomi Rakela	DWER – EG Taskforce	Online
Fiona Webster	DWER	In person
Hans Kemps	DWER	Not available
Tom Holmes	DBCA	In person
Sallyann Gudge	DBCA	Online

Appendix 2: Exmouth Gulf Nutrient Sources and Pathways Workshop agenda

When: 9.30 – 11.30am, Thurs 15 Aug 2024

Location: IOMRC UWA, Level 5 Board Room

Parking can be difficult around UWA, so if it suits you to come earlier, please come at 9am for tea, coffee, fruit and pastries.

Agenda:

1. What are we hoping to achieve: DWER and WAMSI
2. Existing datasets and knowledge. Please bring along any data or maps for show and tell
3. Review of draft conceptual model
4. Do we have enough data to quantify nutrient sources and pathways?
5. Best outcome for DWER
6. Key knowledge gaps and future work

Attachment 1: Compiled table of known literature and data on nutrients to assist discussions

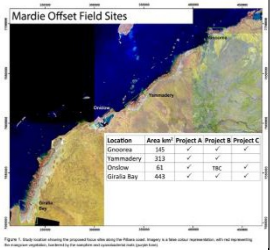
Attachment 2: Existing conceptual models taken from publicly available sources

Attachment 3: Water Technology 2021 Nutrient Pathway Assessment and Modelling Report

Attachment 4: Table extract from Water Technology report on % nutrient sources for the Gulf

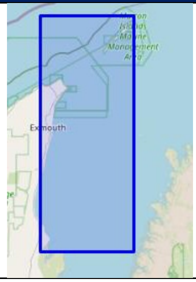
Attachment 5: Draft conceptual model for nutrient sources and pathways in the Gulf

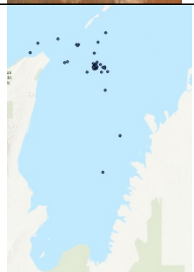
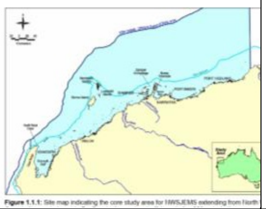
Appendix 3: Existing sources of data to inform discussion on nutrient sources and pathways in Exmouth Gulf

Source	Project	Timeframe	Location	Methods/data	Links	Access
ECU Kathryn McMahon Glenn Hyndes	WAMSI Mardie Offsets Program	~Jan 2023 – Sep 2025	Giralia Bay (and Gnoorea and Onslow) 	• Net primary productivity estimates of cyanobacterial mats, mangroves and saltmarshes across two seasons (late wet and late dry) • Nutrient and energy pathways – sampling dissolved and particulate nutrients across different habitats over a tidal cycle, and freshwater (if present) in the creeks and rivers that form the downstream end of the catchments • Rates of nitrogen fixation of cyanobacteria mats • Role of cyanobacteria mats in the cycling of nutrients; identification of "species" using DNA extraction • Food web structure: Stable isotopes and gut content analysis • Feeding ecology of birds will be examined using direct observations and dropping analysis • Field and lab experiments to assess key physical drivers of cyanobacterial mat productivity, nutrient cycling including nitrogen fixation and the flow of nutrients with events	https://wamsi.org.au/research/programs/mardie-project/	Projects still underway
UWA Matt Hipsey Ryan Lowe	WAMSI Mardie Offsets Program	~Jan 2023 – Dec 2024	West Pilbara (Giralia Bay, Gnoorea, Yammadery, and Onslow sites for validation and testing)	• Collation and analysis of available environmental data and revised conceptual models relevant for the region • High-resolution and sub-regional coastal models for the complex West Pilbara Coast, including intertidal areas • Understanding of environmental controls on intertidal BCH, and projections of future habitat areas in response to climate change • Understanding of the sensitivity of intertidal BCH to developments within the intertidal zone • New fit-for-purpose coastal modelling capability for the region that will be available for future environmental assessments	https://wamsi.org.au/research/programs/mardie-project/	Projects still underway
UWA/UQ Sharyn Hickey Mick O'Leary	WAMSI Mardie Offsets Program		Giralia Bay, Gnoorea, Yammadery, and Onslow	• Map intertidal habitat extents and track environment change across space and time (i.e., seasonal to multidecadal timescales) using satellite imagery and Indigenous knowledge	https://wamsi.org.au/research/programs/mardie-project/	Report soon to be released on intertidal habitats (Deliverable 1)
UQ Catherine Lovelock	ARC	2004 - continuing	Giralia	• Monitoring of tree growth rates within a long-term fertilisation experiment (growth assessed annually) • Monitoring of porewater salinity (annually)	See scientific publications, SET data will be available through	Projects are on-going

Source	Project	Timeframe	Location	Methods/data	Links	Access
Ruth Reef				• Monitoring of surface elevation tables (SETs, changes in elevation over time) across the intertidal zone • Monitoring groundwater depth and salinity • Soil carbon stocks, soil microbial communities and other observations on a campaign basis	TERN https://www.tern.org.au/tidal-wetland-monitoring/	
AIMS Chris Fulton Kay Davis Shaun Wilson	Blue Carbon Seascapes	2023-2025	NE Exmouth Gulf: Test Island to South Urala Creek 	• Soil/sediment cores in the intertidal, seagrass beds and bare sediments (15 sites), offshore from creeks • Tissues/biological samples, eDNA • Testing for TC, TN, TP, with TC being the focus to understand where carbon is coming from	https://www.aims.gov.au/information-centre/news-and-stories/could-seaweed-help-save-planet-blue-carbon-solution-be-investigated-aims	Projects still underway
UWA, AIMS Camille Grimaldi	Oceanographic modelling in Exmouth Gulf	1990s to present	All of Gulf	• Hydrodynamic model (Delft3D) – modelling of circulation patterns, connectivity, residence times, etc.		Need to request
UWA/UQ Sharyn Hickey Catherine Lovelock	The Salt Flats of Exmouth Gulf: Ecological Functions and Threats	Various	Southern and eastern Exmouth Gulf	• Review • Case studies	https://research-repository.uwa.edu.au/en/publications/the-salt-flats-of-exmouth-gulf-ecological-functions-and-threats	Report freely available
UWA/UQ Sharyn Hickey Amy Stone Catherine Lovelock	Brief: Carbon and Productivity Calculations in Exmouth Gulf Region		Southern and eastern Exmouth Gulf	• Estimates on primary productivity, carbon sequestration, and nitrogen fixation, based on previous reports, and mapping	https://research-repository.uwa.edu.au/en/publications/brief-carbon-and-productivity-calculations-in-exmouth-gulf-region	Report freely available

Source	Project	Timeframe	Location	Methods/data	Links	Access
UWA/UQ Sharyn Hickey Amy Stone Catherine Lovelock	The Cyanobacterial Mats of the Exmouth Gulf, Western Australia: Mapping Report	2013, 2019, 2020, 2021, 2022	Southern and eastern Exmouth Gulf 	• Comprehensive assessment of cyanobacterial mats and the high intertidal salt flats in the Exmouth Gulf • Developed a technique to construct a representative habitat model of the cyanobacterial mat area in the high intertidal zones of the Exmouth Gulf across 5 timepoints (single-time-points) using Landsat 8 and Random Forest remote sensing modelling techniques • Preliminary model using tides, wind and water (observed from space) to project presence/absence of cyanobacterial mat (Masters project)	https://research-repository.uwa.edu.au/en/publications/the-cyanobacterial-mats-of-the-exmouth-gulf-western-australia-map	Report freely available Manuscripts in prep.
Gascoyne Gateway	Single Jetty Deep Water Port & Renewable Hub	2023-2025?	Eastern margin or whole Gulf?	• Required work: Characterise the baseline hydrological and hydrogeological regimes and water quality and quantity, both in a local and regional context (including a characterisation of the water exchange between the beach dune system and the Cape Range), including, but not limited to, water levels including the fluctuation of the aquifer system in response to tides and storm events, water chemistry, presence of acid sulphate soils, stream flows, flood patterns, spatial characteristics of the fresh/saline groundwater interface, aquifer characteristics and recharge potential.	https://www.epa.wa.gov.au/proposals/single-jetty-deep-water-port-renewable-hub	
Water Technology	K&S Ashburton Salt Project	2017-2021	NE Exmouth Gulf - *in-situ* sampling Exmouth Gulf – nutrient modelling 	• Oceanographic and Marine/Creek Water Quality, including nutrients • Surface Water Quality • ADCP transects • Nutrient model for the whole Gulf based on collected field data above and values in the literature	https://www.epa.wa.gov.au/proposals/ashburton-salt-project	Reports freely available Data included as appendices
CSIRO/WAMSI Mat Vanderklift	WAMSI 2 - Dredging Science Node - Project 5.3 -	Aug 2013 – Mar 2015	South Muiron, Bundegi, SE Exmouth Gulf.	• Water quality (light, conductivity, temperature, salinity, nutrients, suspended particulate matter and chlorophyll). • Sediment grain size • Stable isotope ratios (13C and 15N) of seagrass leaf tissue	https://data.csiro.au/collection/csiro:17632v4?redirected=true	Data freely available

Source	Project	Timeframe	Location	Methods/data	Links	Access
	Natural Dynamics			• Seagrass measurements and % cover		
AIMS	Nutrient partitioning and storage, nutrient use efficiency and below-ground decomposition of organic matter in mangroves along the arid coast of the Pilbara Region, Western Australia	Oct/Nov 1993, Sep 1994	Bay of Rest (and Mangrove Bay and Dampier) 	• Bulk sediment and nutrient sampling: samples were taken for grain size and water content; temperature, redox potential and pH were measured; samples for solid-phase nutrients and porewater were obtained. Samples were analysed for ammonium, nitrite, nitrate, silicate, phosphate, DON and DOP. Separate samples were taken for sulphate and methane, TOC, TC and TN values .	https://apps.aims.gov.au/metadata/view/d00f42a0-d537-463b-bebe-0d2cf76ef097	Need to request
AIMS		Sep 1994 –Oct 1994	Exmouth Gulf 7 sites on the eastern side and 3 on the western side	• At each station water temperature and salinity were measured at 1m depth intervals and Secchi depth recorded. • Values for Chlorophyll a, particulate carbon and nitrogen were determined	https://apps.aims.gov.au/metadata/view/5bfaaf90-753e-11dc-885e-00008a07204e	Need to request

Source	Project	Timeframe	Location	Methods/data	Links	Access
						
AIMS	AIMS - Water Quality (Marine Monitoring Program) Nutrient Data	1997-2003		• Physical and chemical water quality measurements	https://data.aims.gov.au/water-quality/	Data freely available
CSIRO, DoE	North West Shelf Joint Environmental Management Study	2000-2003		• A database of annual loadings of point source contaminants discharged into North West Shelf waters was compiled for the period 1985 to 2001 and their chemical transformations, pathways and potential biological impacts were reviewed. The contaminants included toxicants such as heavy metals (barium, cadmium, chromium, copper, lead, mercury and zinc), petroleum compounds (produced formation water and oil), nutrients (nitrogen), and organometalloids (tributyltin or TBT).	https://www.cmar.csiro.au/nwsjems/index.html	
CSIRO	CMAR Hydrology	1962 – NE Gulf 1996 – W Gulf 1999 – N Gulf More sites outside of Gulf	NE Gulf Western Gulf Northern Gulf	• Hydrology, including nutrients	https://marlin.csiro.au/geonetwork/srv/eng/catalog.search#/metadata/c1225108-233d-74e9-e044-00144f7bc0f4	Data freely available

Source	Project	Timeframe	Location	Methods/data	Links	Access
						

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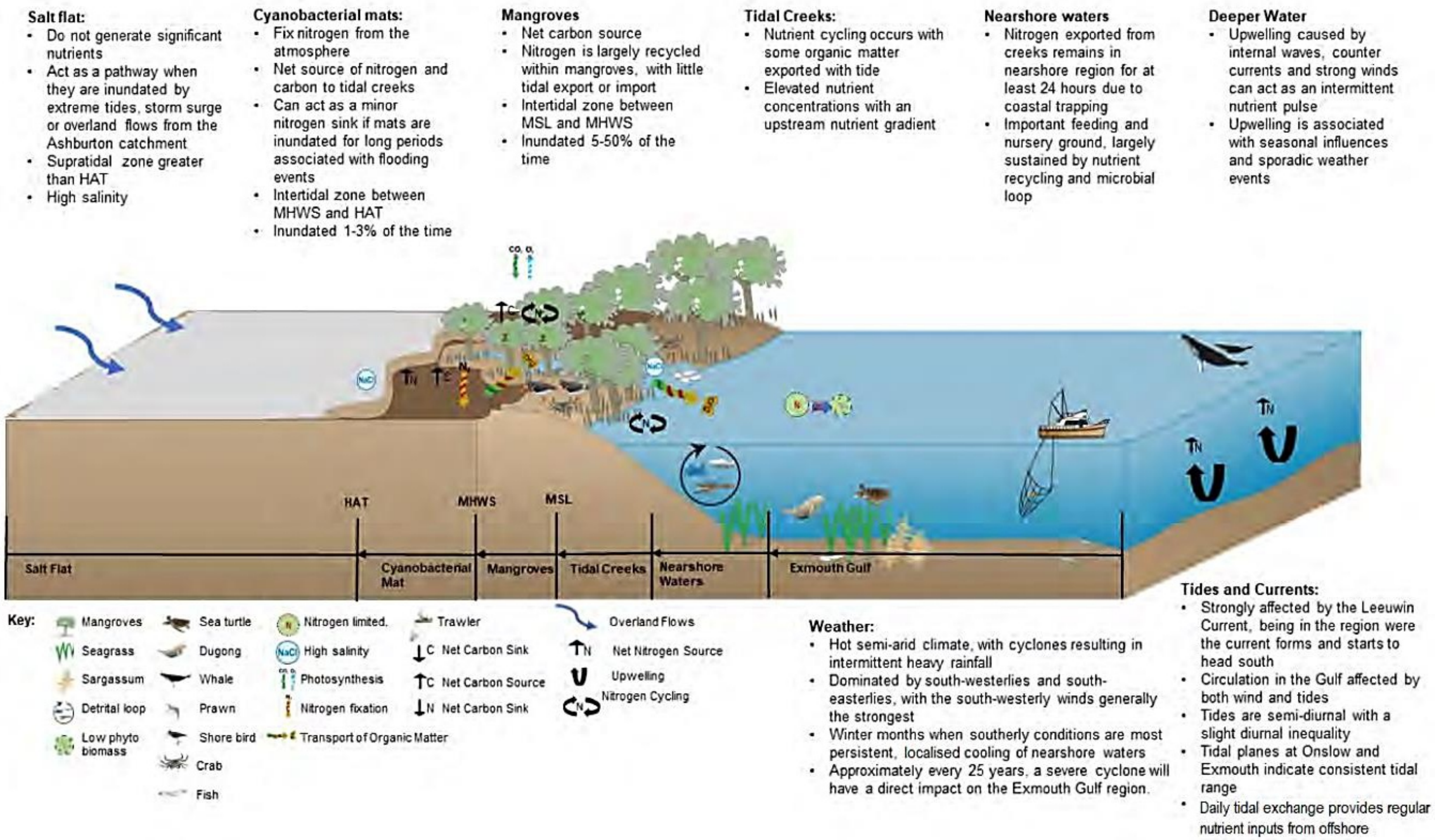
Appendix 4: Existing conceptual models taken from publicly available sources

Taken from Water Technology. 2021. Ashburton Salt Project Nutrient Pathway Assessment and Modelling p. 60.



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1.0 Salt Flats

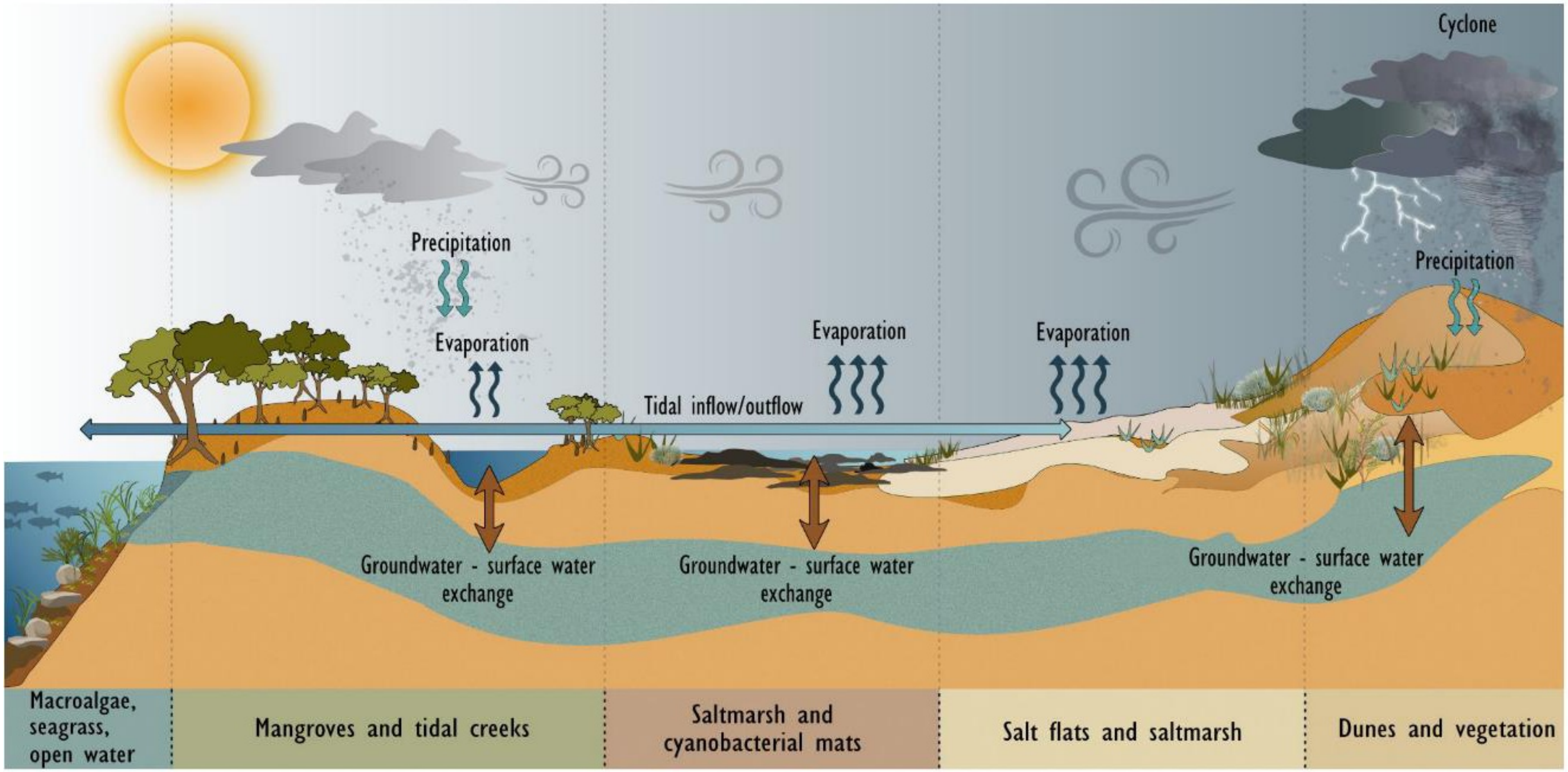

Figure 1: Conceptual model of the intertidal and supratidal zone of the Exmouth Gulf. Likely hydrological processes including tidal flow and groundwater and surface water exchange are shown based on Babel 2004 and Mernagh, 2013. Design: OOID Scientific

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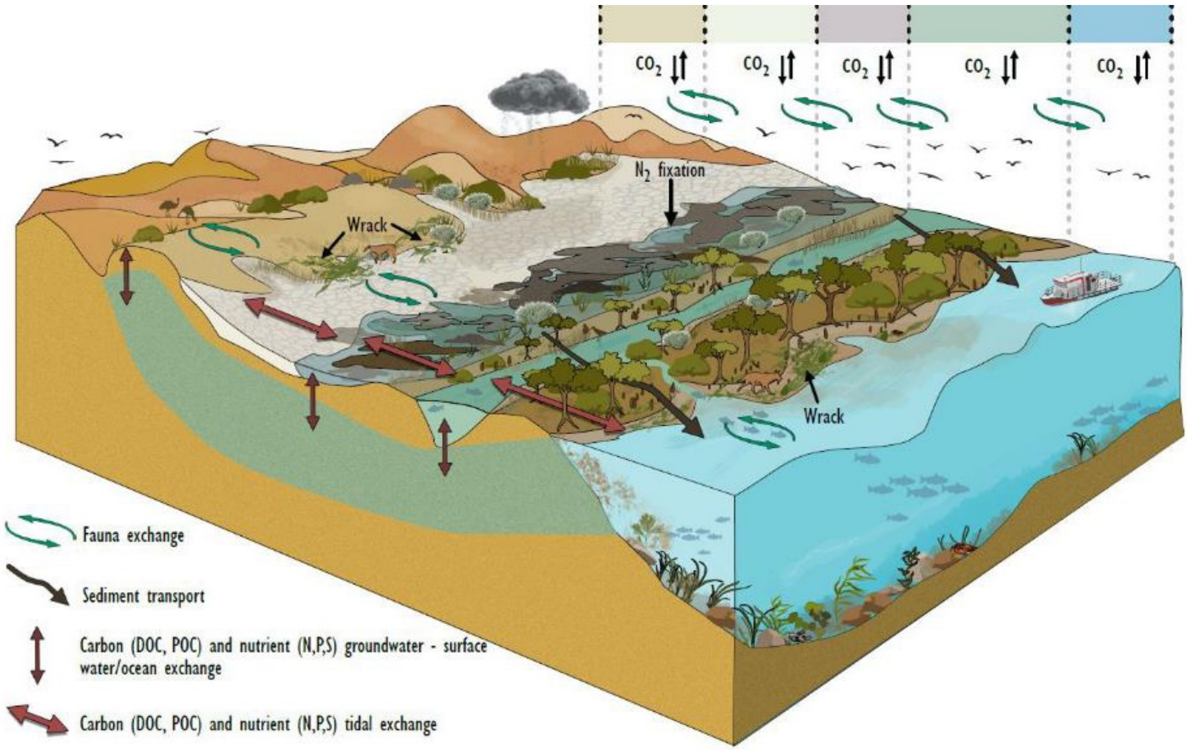
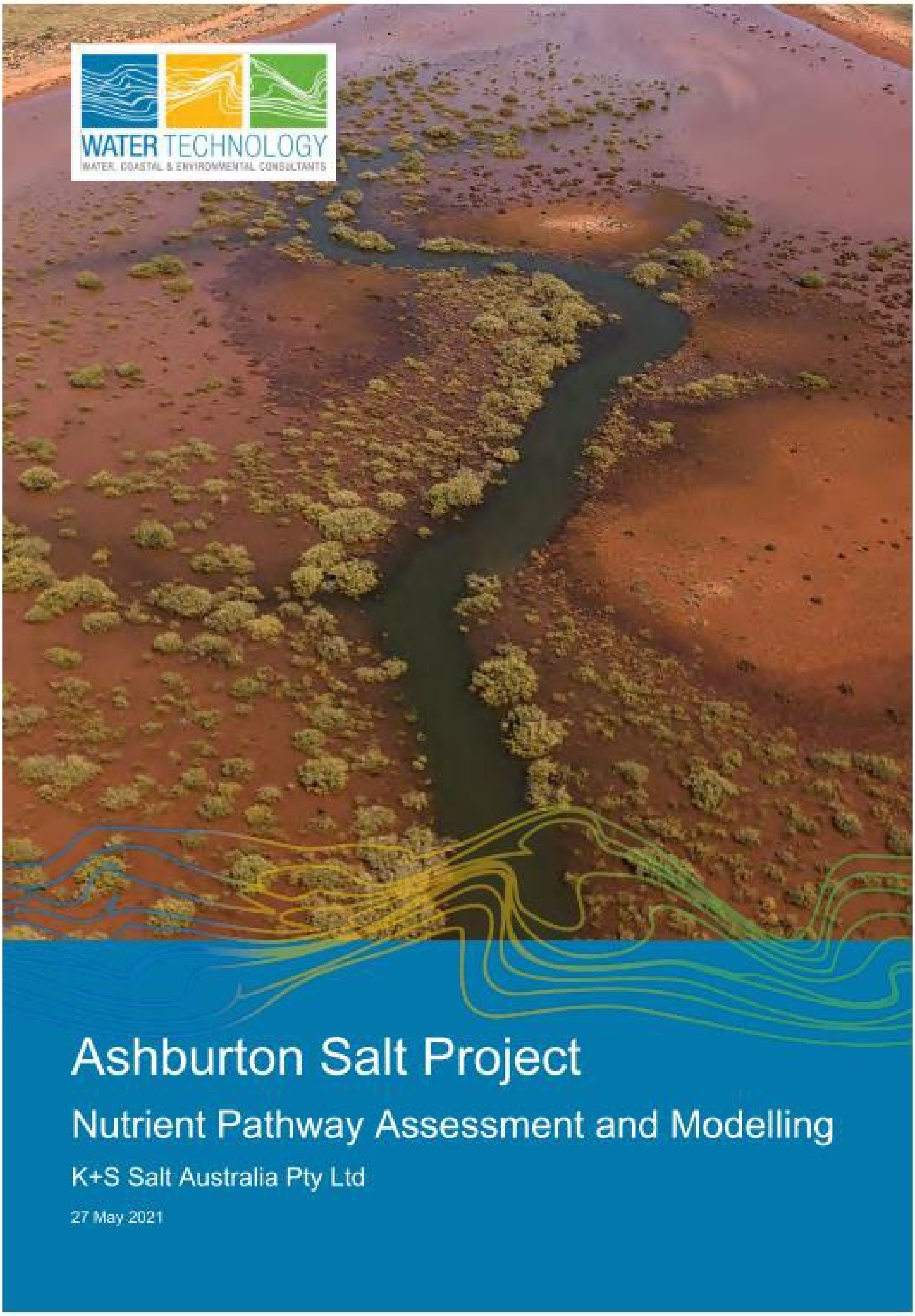


Figure 11: Conceptual model of the potential ecological, biogeochemical and hydrologicla process occurring in the Exmouth Gulf, based on the available literature. Design: OOID Scientific

Appendix 5: Water Technology 2021 Nutrient Pathway Assessment and Modelling Report

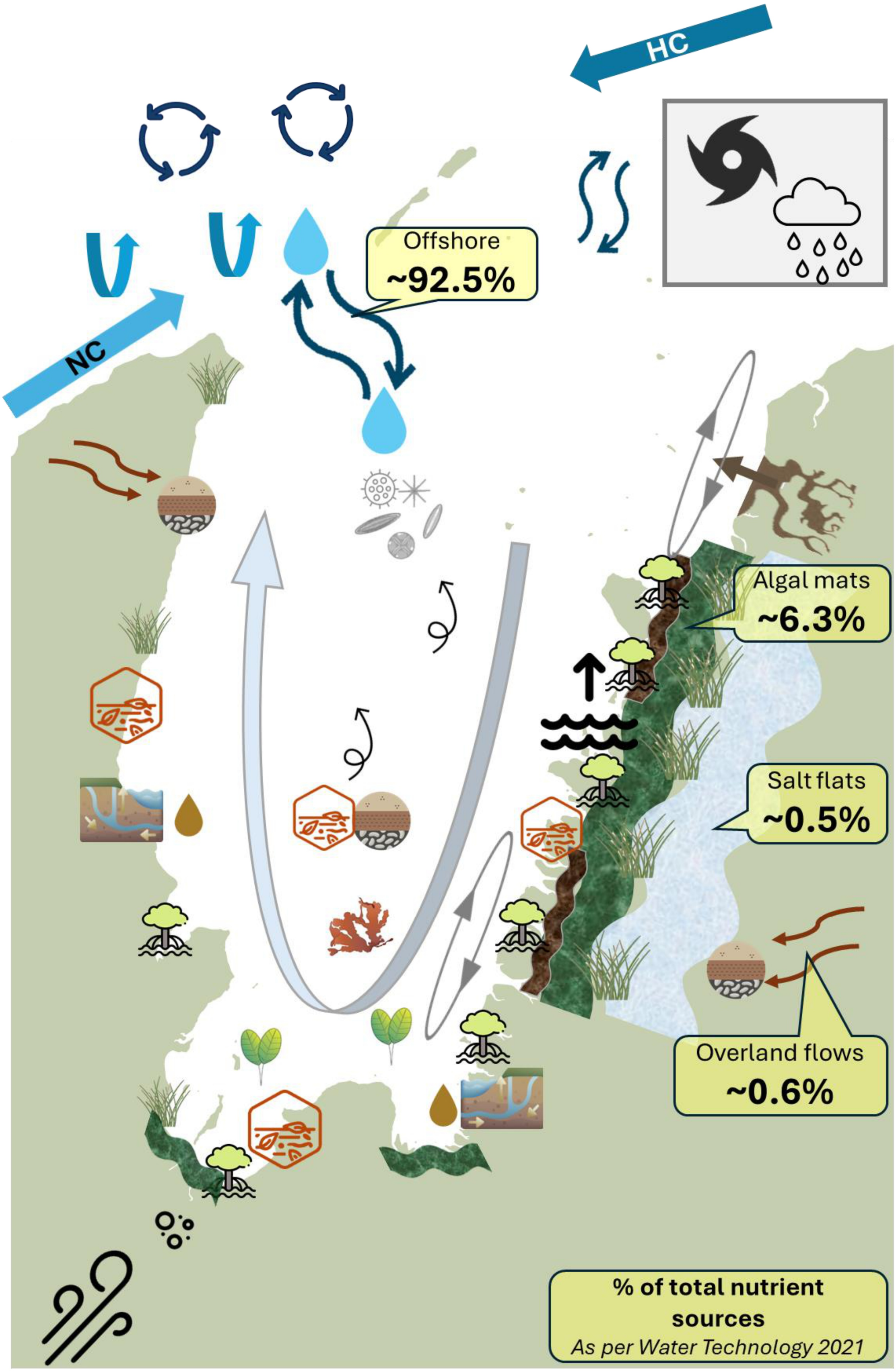


Appendix 6: Table extract from Water Technology 2021 report on % nutrient sources for the Gulf

TABLE 3-4 REGIONAL LAND AND OCEAN NITROGEN CONTRIBUTIONS TO EXMOUTH GULF WATERS

Habitat	N Source or Sink	Primary Nutrient Pathway	Secondary Nutrient Pathway	Area (ha)	Exchange rate (kg/ha/y)	Net TN (tpa)	% of Total to Exmouth Gulf	Source
Mangroves	Sink	Tidal creeks/inundation	Overland Flows	11,780	-3	-34.7	N/A – no net N export to Exmouth Gulf	Adame et al. 2010
Algal Mats	Source and sink	Tidal creeks/ inundation/	Overland Flows	8,080	68	541	6.3	Paling and McComb 1994
Salts Flats	Source	Overland flows	Tidal creeks/ inundation	50,500	0.9	44.7	0.5	Paling and McComb 1994, Project data collection
Hinterland	Source	Overland flows	Wind	560,000	0.12	55.1	0.6	Brunskill et al. 2001
Offshore	Source	Upwelling/Eddies	Tidal forcing	-	-	7,950	92.5	See Section 3.5.3
					Intertidal and terrestrial total	**641**	**7.5**	
					Total	**8,591**	-	

Appendix 7: Draft conceptual model for nutrient sources and pathways in Exmouth Gulf



Note from workshop: General circulation should be anticlockwise based on findings from Camille Grimaldi (UWA/AIMS).

SOURCES

Organic/detrital material	H
Mangroves	H
Saltmarshes/samphire	M
Seagrasses	M
Algae	M
Plankton/microbes	M
Cyanobacterial mats	H
Salt flats	L
Mud flats	L
Sediments	M
Nutrient rich water	H
Groundwater	L
Dust particles/eroded soil **(?)**	L

PATHWAYS

Tidal creek flushing	I S D
Tidal inundation	R D
Overland flows/run-off	I S
Groundwater seepage	R S D
Resuspension of sediments	R
Tidal exchange	R D
Upwelling	I S
Ningaloo Current	I S
Holloway Current **(?)**	I S
Offshore eddies	I S
Winds **(?)**	R D S
Predominate clockwise water circulation	R D S
Coastal trapping of nutrients	R D

AMPLIFIERS FOR PATHWAYS

Cyclones	I S
Storms/flooding	I S

H	High source of nutrients
M	Med source of nutrients
L	Low source of nutrients
R	Regular delivery of source
I	Irregular delivery of source
S	Seasonal influence on delivery
D	Daily influence on delivery

Exmouth Gulf benthic habitat mapping workshop report

Exmouth Gulf benthic habitat mapping workshop report

August 2024

Workshop date:

Wednesday 29 May 2024

Location:

Indian Ocean Marine Research Centre (UWA)

Acronyms and abbreviations

Acronyms	Definition
AIMS	Australian Institute of Marine Science
CATAMI	Collaborative and Automated Tools for Analysis of Marine Imagery
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DBCA	Department of Biodiversity, Conservation and Attractions
DOT	Department of Transport
DPIRD	Department of Primary Industries and Regional Development
DWER	Department of Water and Environmental Regulation
EG	Exmouth Gulf
EIA	Environmental Impact Assessment
ECU	Edith Cowan University
EPA	Environmental Protection Authority
UWA	The University of Western Australia
WABSI	Western Australian Biodiversity Science Institute
WAMSI	Western Australian Marine Science Institution

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Exmouth Gulf Benthic Habitat Mapping Workshop Summary

WAMSI was engaged by the Exmouth Gulf Taskforce to produce a comprehensive, contemporary, high resolution benthic habitat map for Exmouth Gulf. On 29 May 2024, WAMSI facilitated a workshop with 21 researchers and managers from 11 organisations who have historically or currently worked on benthic habitats in Exmouth Gulf.

The purpose of this workshop was to 1) document the existence of benthic habitat data and its availability and 2) decide how best to deliver a comprehensive, high resolution benthic habitat map to the Taskforce.

During the workshop, representatives from DPIRD, DBCA, DoT, Murdoch University, UWA, ECU, CSIRO and AIMS shared the details of past and current benthic habitat data and mapping projects. After the identification of different management objectives and a review of the shared benthic habitat data and maps, workshop participants discussed challenges, considerations and possible approaches in producing the habitat map:

- Challenges
    - It is difficult to produce a single map fit for all purposes
    - When multiple sources with different methodologies, modelling approaches, as well as spatial and temporal considerations are used, how will high confidence in the end-product be retained?
- Considerations
    - How should a high-resolution map be released to the public if it highlights benthic features (e.g. coral bommies) raising concerns about recreational fishing pressure?
    - To better understand data confidence, comprehensive metadata for the final map should be provided from all sources
- Possible approaches
    - Compare and merge DBCA and DPIRD maps as they are the most recent and comprehensive datasets (e.g., 2023-2024)
    - Produce an accompanying map showing modelling and spatial uncertainty
    - Account for potential benthic habitat types in maps using predictive tools
    - Produce a primary map with secondary maps to show detail and confidence
    - Produce a density map, particularly for seagrasses
    - Compile a database of benthic habitat data

The value WAMSI can bring to this project includes coordinating the production of a benthic habitat map across WAMSI Partners and potentially facilitating the collation and storage of benthic habitat data in the WAMSI/WABSI Shared Environmental Analytics Facility (SEAF) or similar.

The next steps following the workshop include delivering a draft workshop report to the Exmouth Gulf Taskforce, producing a consensus map with input from Partners and working towards a shared database of benthic habitat data.

Purpose of the workshop

In 2021, the EPA delivered strategic advice to the Minister for Environment under Section 16(e) of the Environmental Protection Act 1986 on the potential cumulative pressures of the proposed activities and developments on the environmental, social and cultural values of Exmouth Gulf. Following this advice, the Exmouth Gulf Taskforce was established as a Ministerial Advisory Body under s.25 of the EP Act. Under its Terms of Reference, the Taskforce is to provide advice to the Minister for Environment, including knowledge gaps and options to inform terrestrial and marine planning processes.

There is currently no comprehensive, high resolution benthic habitat map available for Exmouth Gulf. This knowledge gap was highlighted in the WAMSI Cumulative Pressures on the Distinctive Values of Exmouth Gulf report (Sutton and Shaw 2021).

The Exmouth Gulf Task Force aims to:

- Improve the understanding of the Gulf ecosystem and habitats
- Improve environmental planning and management of multiple sectors (e.g. tourism, fisheries, conservation, transport)
- Consider the implications of climate change and the need to develop adaptation strategies as part of future conservation, enhancement and management; and
- Inform the environmental impact assessment of development proposals in the Gulf.

As a result, WAMSI has been tasked to undertake a knowledge gaps report including to produce a high resolution intertidal and subtidal benthic habitat map for the whole of Exmouth Gulf, based on existing data. The purpose of this workshop was to bring together researchers and managers who have historically or currently worked on benthic habitats in Exmouth Gulf in order to 1) document the existence of benthic habitat data and its availability and 2) decide how best to deliver a comprehensive, high resolution benthic habitat map to the Exmouth Gulf Taskforce.

Workshop attendees

A total of 21 people attended the Exmouth Gulf Benthic Habitat Mapping Workshop on 29 May 2024. Participants represented 11 organisations: WAMSI, DBCA, DPIRD, DWER, DoT, O2 Marine, UWA, ECU, Murdoch University, AIMS and CSIRO. A list of attendees is provided in Appendix 1.

The agenda for this workshop is provided in Appendix 2 and informs the structure of this workshop report.

Workshop participants were provided with the opportunity to review this workshop report and to make amendments as needed.

Management agency objectives

Four State government departments were in attendance at the Workshop as they all have management objectives and/or current projects relating to Exmouth Gulf. Given the aims of the benthic habitat mapping project outlined above, it was important for everyone at the workshop to understand the management objectives of each of the government departments, which are detailed below.

DBCA objective – State Marine Park Planning

A new state marine park and Class A reserves was proposed for Exmouth Gulf following the Section 16e advice provided by the EPA in 2021. The boundaries of the marine park are yet to be finalised and benthic habitat mapping can assist with the finalisation of those boundaries, as well as zoning within the marine park. While previous benthic habitat mapping is available, there is need for a map with greater confidence. As a result, DBCA commissioned O2 Marine to undertake an extensive mapping exercise this year (2024).

DPIRD objective – Ecosystem Based Fisheries Management and MSC certification

DPIRD have undertaken habitat assessments since 2016 in relation to the Exmouth Gulf for the purposes of Ecosystem Based Fisheries Management and Marine Stewardship Council certification, notably for the Exmouth Gulf Prawn Managed Fishery. The eastern margin of Exmouth Gulf a prawn nursery ground, with an associated fishery management closure. Quantifying seasonal and annual changes in seagrass habitat is important for examining fishery and habitat associations and, as such, DPIRD has maintained benthic habitat assessments in Exmouth Gulf since 2016. This includes mapping, to examine fisheries, ecosystem and habitat associations.

DWER objective – supporting the EPA with EIAs

DWER do not undertake benthic habitat mapping exercises directly and, instead, rely on the fine-scale mapping undertaken by proponents. However, this results in patchy localised maps in Exmouth Gulf, and the importance of these localised patches is not known in the context of the whole Gulf. Having a high resolution map of key benthic habitats in Exmouth Gulf would help DWER to provide robust advice to the EPA for the purposes of environmental impact assessments (EIA). Cumulative EIA and regional planning need to be considered by the EPA, so a consolidated map will help in understanding impact and informing decision makers across different portfolios.

DoT objective – climate change

DoT has received funding from the Federal government to undertake bathymetric lidar mapping exercises to assess inundation and erosion hotspots along sections of the WA coastline. Most of the Exmouth Gulf coastline is not included in this project, but the capacity is there to collect bathymetric lidar for the whole Gulf if funding becomes available. The cost estimate is $1.5m.

Available data for benthic habitat mapping

Workshop participants were provided with a list of existing data sources and benthic maps relating to Exmouth Gulf prior to the workshop (Appendix 3). One aim of the workshop was to expand on this list, particularly to identify data and maps that may not be publicly available.

During the workshop, representatives from DPIRD, DBCA, DoT, Murdoch University, UWA, ECU, CSIRO and AIMS shared the details of past and current benthic habitat data and mapping projects, and these are provided in Table 1. If available, further details on the datasets were included from reports and papers after the workshop.

Some participants shared resources such as maps in the form of PowerPoint presentations, and permitted slides are provided in Appendix 4, along with maps from other studies mentioned throughout the workshop.

Table 1: Details of past and current benthic data and mapping projects within Exmouth Gulf shared by workshop participants.

Name / Organisation	Spatial area	Temporal range	Methodology	Classification categories	Data/mapping confidence	Data storage location and accessibility
DPIRD Scott Evans **See Appendix 4.1**	Exmouth Gulf Prawn Managed Fishery Nursery Area	April 2016 ongoing Summer/ winter 2016 – 2019, 2021, 2023,	• Towed camera with forward and downward facing cameras, only used downward facing in the end due to turbidity • 612 testing and training sites • 10 tows/drops per site • 64 points annotated per frame • Used kriging to produce the best map output • Tested whether additional data could improve the modelled output e.g., acoustic mapping, satellite data, predictive modelling, environment data/loggers (2016 onwards), BRUVS (2022 onwards), and juvenile prawn assessments • FRDC Project - Map and quantify habitats to assess relationships between prawns, seagrass, and macroalgae	• CATAMI Classification Scheme • Identified to lowest possible taxonomy • Combined to four classes for DPIRD purposes but extraction to different classes is possible, as are different predictive map outputs	• Conf est. provided • 95% accuracy using AI for vegetated vs non vegetated benthos, and between seagrass and macroalgae. Above 80% accuracy for seagrass species	DPIRD Map becoming available ~Dec 2024
DPIRD Scott Evans **See Appendix 4.1**	EG minus prawn nursery	April 2024	• Drop cameras • 600 sites • Aligned with nursery ground using machine learning (krigging or inverse distance weighting) • Compared with Lyne et al. 2006 benthic map - good correlation but Lyne et al. used broad categories • Ecosystem Based Fisheries Management and Marine Stewardship Council certification purposes	• CATAMI Classification Scheme • Combined classes TBA • Extraction to different classes is possible	• Confidence est. provided • Site positions accurate to +/- 20cm	DPIRD Map becoming available ~Dec 2024
DPIRD Scott Evans **See Appendix 4.1**	EG minus prawn nursery	August 2018	• Inverse distance weighting map • 127 sites • Compared with Lyne et al. 2006 benthic map - good correlation but Lyne et al. used broad categories	• CATAMI Classification Scheme • Combined to four classes • Further extraction of classes possible e.g., ascidians	• No conf est.	DPIRD

Name / Organisation	Spatial area	Temporal range	Methodology	Classification categories	Data/mapping confidence	Data storage location and accessibility
DBCA Tom Holmes O2 Marine Adam Gartner Max Stacey (consultants) **See Appendix 4.2**	Entire EG + Targeted dugong area = south east EG	July 2023	• Mapping of two areas (approx. 800m x 300m) known as dugong hotspots in south east EG – using sidescan sonar and towed video. • Mapping of broader area in south east EG (targeted dugong area) using towed video (46 transects), sentinel-2 satellite imagery (10 x 10 m grid cell resolution) • Mapping of entire EG using array of pre-existing towed video data (EG wide) + 2023 towed video from dugong area • Predictive modelling approach to mapping uses a series of environmental layers for supervised classification, including bathymetry (satellite derived), bathymetry indices (e.g., slope), deep water proximity (20m depth), seabed shear stress etc. •	• CATAMI Classification Scheme • Broad scale map: six classes • Targeted dugong area: six classes	• Confidence est. provided	DBCA O2 Marine
DBCA Tom Holmes O2 Marine Adam Gartner Max Stacey (consultants) **See Appendix 4.2**	Entire EG	Feb-May 2024	• Towed video from 179 sites across EG – 50-150m in length • Mix of random and targeted sites • Targeted sites chosen based on features observed in satellite derived bathymetry data, and Sentinel 2 images • Predictive modelling approach to mapping which uses a series of environmental layers for supervised classification, including bathymetry (satellite derived), bathymetry indices (e.g., slope), deep water proximity (20m depth), seabed shear stress etc. • Incorporates ground truthing from 2023 O2 Marine / DBCA survey	• CATAMI Classification Scheme • Mapping classes TBC	• Confidence est. will be provided • Aim to provide more confidence than 2023 map with the addition of extra ground truthing points	DBCA O2 Marine Data and shapefiles can be released, incl classified ground truthing points – availability ~ Aug 2024
Murdoch University Halina Kobryn **See Appendix 4.3**	Ningaloo Marine Park (including Bundegi and Muiron Islands) to 20 m depth	Apr/May 2006	• Optical sensors (HyMap), to-date highest spectral and spatial resolution mapping of the Ningaloo Marine Park • Hyperspectral imaging for habitat mapping and high resolution bathymetry extraction • 3.5 pixels, and 225 (21 under water) spectral channels, so can determine different spectra within the one pixel. Data were corrected for atmospheric and water column (see methods in the two publications below)	• 46 different classes used, determined from spectral measurements • Spectral library available at Geoscience Australia	Validation supported by 2500 field location measurements. Depending on the thematic level 80%+ accuracy)	Murdoch University, on demand. Data also lodged with Geoscience Australia, CSIRO and DBCA

Name / Organisation	Spatial area	Temporal range	Methodology	Classification categories	Data/mapping confidence	Data storage location and accessibility
			○ Kobryn et al. (2022) Bathymetry derivatives and habitat data from hyperspectral imagery establish a high-resolution baseline for managing the Ningaloo Reef, Western Australia. Remote Sensing 14, 1827. https://doi.org/10.3390/rs14081827 ○ Kobryn et al. (2013) Ningaloo Reef: shallow marine habitats mapped using a hyperspectral sensor. PLoS ONE 8: e70105			
Murdoch University Halina Kobryn **See Appendix 4.3**	Eastern EG	1998 - 2021	• Examining impact of cyclones and heatwaves on mangroves recovery in Exmouth Gulf • Landsat time series (1998-2016) • Atmospherically corrected satellite remote sensing images from Landsat 5 (TM), Landsat 7 (ETM) and Landsat 8 (OLI) (30 m resolution) • Change analysis performed	Spectral endmember analysis within pixels of cover by mangrove, saltmarsh, bare mud and sand, algal mats and water	Spectral mixture analysis modeling	Murdoch University
UWA Sharyn Hickey **See Appendix 4.4**	South of Learmonth to Karratha, intertidal zone	Imagery: 2013, 2019, 2020, 2021, 2022 Plus additional time points provided by Minderoo	• Focus on intertidal habitats (mangrove, cyanobacteria, salt marshes, tidal flats, bright salt) • High resolution aerial imagery (Google Earth Pro) • Landsat 8 satellite imagery (30m x 30m pixels) • Looked at how pixels changed through time, but limited to the availability of aerial imagery • Next: Will do fine scale modelling using lidar (0.5m), hyperspectral and some field data, focused on Giralia and Urala	• Eight classes	• Spatial uncertainty modelling and accuracy assessment	UWA
UWA Mick O'Leary **See Appendix 4.4**	North-east EG and Western margin	2016 onwards	North-east • Focus on sand islands of the Gulf and reefs that fringe • Satellite derived bathymetry – Sentinel 2 imagery – to 25m depth • 10m resolution for all of gulf. • Shows clumps and of reef structure in NE, fringing reef along western side down to Doole Island (not really a reef anymore) • Some groundwater discharge may be causing the 'build up' of shoals - doesn't know what the ecology is of these shoals			UWA

Name / Organisation	Spatial area	Temporal range	Methodology	Classification categories	Data/mapping confidence	Data storage location and accessibility
			• Imagery shows hard grounds with a mix of macroalgae and coral, and also seagrass habitats • As soon as more funding comes in will do some high resolution bathymetry mapping of 'build ups' and hardgrounds. • Eastern margin is different to west, habitat growing in different ways and in different locations in the Gulf, and this can change seasonally and annually Wester margin • Limestone terrace along western margin from Bundegi south • Spring low tide surveys revealed a fossil reef structure – covered in dead coral - less than 1% of live coral cover • Ecological surveys at three locations and drone surveys • Dating samples as well - coral rubble dated younger than 1950, so possibly an event happened prior to this time			
ECU Shannon Dee **See Appendix 4.4**	North-east EG, including Islands	Sep/Oct 2018	• High resolution topographic and bathymetric lidar • 8-10m depth • Quadrats and transects (20m in length) data • Used to assess topographic complex at Fly, Eva and Y Islands. • A lot of macroalgae communities as well as coral reefs • Fine-scale mapping of coral genera, seagrass cover, macroalgae and rubble • Paula Cartwright has also done patch habitat mapping with towed video for another project (see Appendix 3)			
ECU/Murdoch/ DBCA Nicole Said **See Appendix 4.5**	South-east EG	Dugong sites: 2018-2019 Long term monitoring sites: Every 3mo: Aug 2013 – June 2015,	Dugong sites • Mapped seagrass habitat and dugong distribution • Towed video • 3 x 100 m transects at 26 sites Long term monitoring • measuring species composition and % cover of seagrass, algae and coral • 2 sites (200 m apart) • 3 x 50m photo transects at each site via SCUBA			ECU/ Murdoch/ DBCA

Name / Organisation	Spatial area	Temporal range	Methodology	Classification categories	Data/mapping confidence	Data storage location and accessibility
		Evry 6mo: Nov 2017 – June 2019				
DOT Ralph Talbot-Smith **See Appendix 4.6**	Lidar: Tantabiddi to Exmouth townsite (plus elsewhere) Aerial imagery: Kalbarri to Cape Leveque	Lidar: May/June 2024 Aerial imagery: upcoming	• Federal funding for aping coastal erosion and inundation hotspots, out to 20m depth • File outputs can include: geotiff, Google Pro movies, colour coded pdfs, BAG files • Keeping raw waveform data which can use to determine habitat e.g., can assign habitat to pixels • $1.5mil to do whole EG, or can do by geomorphological coastal compartments • Aug- Sep is the weather window for EG if doing lidar • DoT working up in the area for next three years • Aerial imagery 1-2 m resolution			Data will become available on Coastal Capture WA WA BATHY PORTAL (arcgis.com) – cloud portal
CSIRO Damien Thompson No future work currently planned by CSIRO	Condition reports: around the North West Cape to Learmonth	Condition reports: Mar/Apr 2024	• Updated conditions reports on habitats e.g., coral reefs, • Current data for 35 locations			
CSIRO Dirk Slawinski (provided data for workshop, but not shown) **See Appendix 4.7**	Coral Bay, NW Cape, Bundegi, Exmouth, Learmonth	May, Aug 2016 May, Oct 2017	• Measurements of seawater temperature, water turbidity, sediment deposition rates, and sediment properties, as well as benthic, fish, and juvenile coral community structure • Temperature loggers • Sediment deposition traps • PQs - 17-31 replicate quadrats (0.5x0.5m) at each site • 20 points analysed per PQ in Coral Net	Classified coral and algae to genus where possible		CSIRO Freely available

Name / Organisation	Spatial area	Temporal range	Methodology	Classification categories	Data/mapping confidence	Data storage location and accessibility
CSIRO Dirk Slawinski (provided data for workshop, but not shown) (WAMSI Dredging Node) **See Appendix 4.7**	Bundegi, South-east EG, Muiron Islands, Thevenard Island (E and W), Balla Balla, Rosemary Island	Aug, Nov, Dec – 2013 Fe, May, Aug, Nov – 2014 Feb, Mar Jun - 2015	• 7 locations, 2 sites per location • photoquadrats • Seagrass % cover • Species composition • Shoot counts, leave counts, horizontal and vertical nodes counts, flowering intensity, leaf area, leaf area index, dry epiphyte weight, total biomass, isotopes	Seagrass species		CSIRO Freely available
AIMS Ben Radford Not a large focus area for AIMS since 90s **See Appendix 4.8**	South and eastern EG Western and eastern margins of EG	Sep 1994 Aug/Sep 1995	1994 • 64 sites, grouped into five areas • % cover seagrasses and algae • 5 quadrats per 50m transect • Taxa identified under 100 points on a $1m^2$ string grid • Found some sparse seagrass 1995 • 47 transects • % cover seagrasses and algae • 5-10 quadrats per 50m transect	Seagrass species		AIMS Data available

Delivering a benthic habitat map for the Exmouth Gulf Taskforce

Challenges

The consensus amongst many of the workshop participants was that it would be difficult to produce a single map fit for all purposes. For example, given the different management objectives of DBCA and DPIRD, both are currently developing separate benthic habitat maps for Exmouth Gulf. Similarly, the other sources of benthic habitat data and maps discussed at the workshop were collected and produced to answer specific questions and often for specific locations e.g., dugong distribution and the use of seagrass habitat in the SE corner of the Gulf.

The second main challenge discussed at the workshop was how to retain a high confidence in a map that has been generated from multiple sources with different methodologies, modelling approaches and temporal considerations. For example, DPIRD is working on aligning benthic habitat maps from different DPIRD projects/purposes to better define their confidence intervals. Mick O'Leary (UWA) also mentioned how habitats (e.g., sandy shoals) are changing seasonally, as well as yearly, in the Gulf, so factoring these temporal changes into one map is challenging.

Considerations

While a map resolution has not yet been specified for this project, consideration should be given to the resolution of the map and data released to the public. For example, a high resolution map (e.g., using hyperspectral imagery) would show up locations that may become of high interest to the public (e.g., coral bommies) and could result in high human use and subsequent impacts, for example from recreational fishers. It might be appropriate to consider an internal/planning map and a public facing map.

If the decision is made to produce a benthic habitat map from multiple sources of data, then it is imperative that the sources of data and the final map(s) are accompanied by comprehensive metadata so that users can also assess the confidence of the map(s).

Possible approaches

Two Exmouth Gulf wide benthic habitat maps are currently being produced by DBCA and DPIRD, estimated for completion by Aug and Dec 2024, respectively. It was suggested and widely supported by the workshop participants that following the completion of these maps, a consensus map should be generated. Given the complexities in merging two datasets collected with different methodologies, it was recommended that a piece of work could be undertaken to assess the feasibility of a consensus map, and to generate an accompanying map to the consensus map showing modelling and spatial uncertainty. Such a map will identify areas where confidence is low, which could identify area of changing habitats and areas where further ground truthing may be needed. Sharyn Hickey (UWA) and Ben Radford (AIMS) have experience in generating modelling and spatial uncertainty maps and indicated they could assist with this exercise, particularly if the resources or skills are stretched within the Government agencies.

Given the discussion around seasonal and annual changes in benthic habitats, the suggestion to develop a map showing potential habitat areas (e.g., where ephemeral seagrass *could* occur given the right environmental conditions) was also viewed favourably by many workshop participants. If predictive tools/models are used to generate benthic habitat maps, then potential or probable habitat is already considered to a degree in the outputs.

Another approach was to have an overall primary benthic habitat map that was then supported by secondary maps (e.g., seasonal maps, specific habitat maps) to show more detail and to show in which seasons or habitats there is greater confidence.

A density map was suggested as a potentially useful resource, particularly for seagrasses. This approach would require a measure of density or % cover estimate to be captured in ground-truthing exercises and/or discernible in imagery.

Lastly, given the different types of benthic habitat maps that could be produced and the range of purposes they could be produced for, there was a suggestion to focus on a database rather than a single map output. Having all benthic habitat data consolidated into one database and storage facility, and keeping this continually updated with new data, would allow users to create fit for purpose maps and undertake quantitative analyses.

How can WAMSI add value?

It was generally agreed that WAMSI can add value by:

1) coordinating the production of a benthic habitat map(s) that then becomes a shared State asset. The first step in this process was the facilitation of this workshop so that all participants could be made aware of the data available and the different objectives, and so data sources could be identified
2) facilitating the collation and storage of benthic habitat data in the WAMSI/WABSI Shared Environmental Analytics Facility (SEAF), which would allow users to access different datasets to produce a map output that is fit for purpose

Next steps

The next steps following the workshop include:

1) delivery of a draft workshop report to the Exmouth Gulf Taskforce
2) producing a consensus map with input from Partners
3) working towards a shared database of benthic habitat data

Useful resources mentioned during workshop

CATAMI Classification Scheme: https://catami.org/

CATAMI Poster: https://www.nespmarine.edu.au/document/putting-names-sea-faces-standardising-flora-and-fauna-classification-australian-marine

Appendix 1: Exmouth Gulf Benthic Habitat Map Workshop Invited Participants: 29 May 2024 IOMRC

Name	Affiliation	Attended
Jenny Shaw	WAMSI	In person
Luke Twomey	WAMSI	In person
Alicia Sutton	WAMSI	In person
Tom Holmes	DBCA	Online
Sallyanne Gudge	DBCA	Online
Adam Gartner	O2 Marine	Online
Max Stacey	O2 Marine	Online
Scott Evans	DPIRD	In person
Lynda Bellchambers	DPIRD	In person
Fiona Webster	DWER	In person
Hans Kemps	DWER	In person
Wendy Thompson	DWER – EG Taskforce	Online
Naomi Rakela	DWER – EG Taskforce	Not available
Ralph Talbot Smith	DoT	In person
Sharyn Hickey	UWA	In person
Renae Hovey	UWA	Not available
Gary Kendrick	UWA	In person
Mick O'Leary	UWA	In person
Kath McMahon	ECU	Not available
Shannon Dee	ECU	In person
Nicole Said	ECU	In person
Halina Kobryn	MU	In person
John Keesing	CSIRO	Not available
Ben Radford	AIMS	Online
Dirk Slawinski	CSIRO	Not available
Damien Thomson	CSIRO	In person

Appendix 2: Exmouth Gulf Benthic Habitat Map Workshop Agenda

Wed 29th May 9.30 – 11.30am
Exmouth Gulf Benthic Habitat Map

Parking can be difficult around UWA at the moment, so if it suits you to come earlier, please come at 9am for tea, coffee, fruit and pastries.

Agenda:

1. What are we hoping to achieve: Wendy Thompson (DWER), Luke Twomey (WAMSI)
2. Management agency objectives: DPIRD, DBCA, DWER
3. What data is currently available? **Could you please bring your latest habitat maps for a show and tell?*
   Discussion points:
   - Spatial area
   - Methodology
   - Classification categories
   - Confidence
   - Temporal differences
   - Location of data
   - Accessibility
4. Outcome for DWER (presentation and format)
5. Possibility of shared State Asset?
6. Data holding and responsibility for currency?
7. Is there a preferred methodology for a State Asset?
8. How can WAMSI add value?
9. Future ground truthing

Appendix 3: Existing sources of data to inform benthic habitat mapping in Exmouth Gulf

Source	Year of data	Area covered	Methods	Links	Access
DPIRD FRDC	2023	EG prawn nursery area	• Mixed (unknown)	-	In press
DBCA O2 Marine	2023	South east gulf	• Towed video	-	In press?
Oceanwise	Sep 2023	Northern/ central EG?	• Article mentions surveys	News article	Request permission – Ben Fitzpatrick
Reef Life Survey	2010-2021	Bundegi area (west EG) and Muiron Islands	• Photoquadrats at 15 sites • No map produced	Website	Images freely available
Cartwright 2022 - Metocean drivers of turbidity in the Exmouth Gulf	2021	Eastern region, middle north, and Muiron Islands	• ROV at 27 sites • Descriptions but no map produced	Thesis	Request permission – Paula Cartwright
Ashburton Salt Project: Environmental Review Document May 2023	2019	Supratidal, intertidal and subtidal between Locker Point and Talandji, eastern EG	• in 2019, 47 sites sampled for sediments to confirm presence of algal mats • Mangroves: used existing 2005 and 2016 (Biota) mapping overlaid on high resolution satellite imagery. Groundtruthed using helicopter surveys in 2019 • Algal mats: multispectral imagery captured by Fugro on behalf of K+S Salt Australia in May 2017. Groundtruthed using above sediment cores from 2019 and helicopter surveys • Samphire – field surveys during 2018-2019 and aerial imagery • subtidal habitats: Feb 2019, satellite imagery, aerial imagery, groundtruthed using towed video (73 transects)	Environmental review BCH mapping - AECOM Samphire mapping - BIOTA	Request permission – K&S Salt
Subsea 7 Learmonth Pipeline Fabrication Facility 2018	2018-2020	Heron Point, and a strip through the middle of EG	• Benthic – 2018 towed video (114 transects), aerial imagery • Benthic – 2020 towed video at 12 sites	Benthic survey report – MBS Environmental	MBS 2018 xy data available in appendices BMT 2020 data freely available

Source	Year of data	Area covered	Methods	Links	Access
				Benthic survey report - BMT	on IMSA (xy shapefile)
Gascoyne Gateway Single Jetty Deep Water Port & Renewable Hub	2018-2021 (?)	Exmouth Gulf, and localised near Qualing Pool area	• Used Lyne et al 2006 and DPIRD/MG Kailis 2018 maps • mentions 'Video observations for the region were collected over two seasonal surveys' but no further details provided	Environmental supporting document	Request permission from GG re additional 2021 video observations
DPIRD 2018	2018	All EG except prawn nursery area	• Drop cameras at 127 sites		Request permission – Scott Evans / Lynda Bellchambers
FRDC Project – EGPMF Nursery Ground Mapping	2016	EG prawn nursery area	• 400 ground truthing sites		Scott Evans / Lynda Bellchambers
Wheatstone project: Biota of Subtidal Habitats in Pilbara Mangrove, with Particular Reference to the Ashburton Delta and Hooley Creek	2008-2009	Just outside EG, around Ashburton River, and off Onslow	• ROV and video cameras ~350 transects	Subtidal habitat surveys - URS	Description and location of sites in Appendix, though would need permission from Chevron for shapefiles used in report
Lyne et al 2006 - North West Shelf Joint Environmental Management Study	Various	All EG	• Disparate sources of information on habitats within the study region including published documents, digital and paper maps, imagery, statistical analyses, and expert information	NWSJEMS Final Report	Freely available shapefiles from SeaMap
Yannarie Solar Salt East Coast of Exmouth Gulf 2006	2004-2005	Eastern EG approximately 70 km from the headland of Giralia Bay in the south to the sandy beaches of Tubridgi Point in the north	• Mangroves: 2004 using helicopter, on ground visits, aerial imagery, satellite imagery • Algal mats and salt flats: 2004 sediment sampling, aerial imagery • Subtidal: 2004-2005 surveys, diver and manta tows, drop cameras, satellite	Mangrove mapping - BIOTA Benthic habitats - Oceanica	Request permission – Straits Salt or Biota or Oceanica

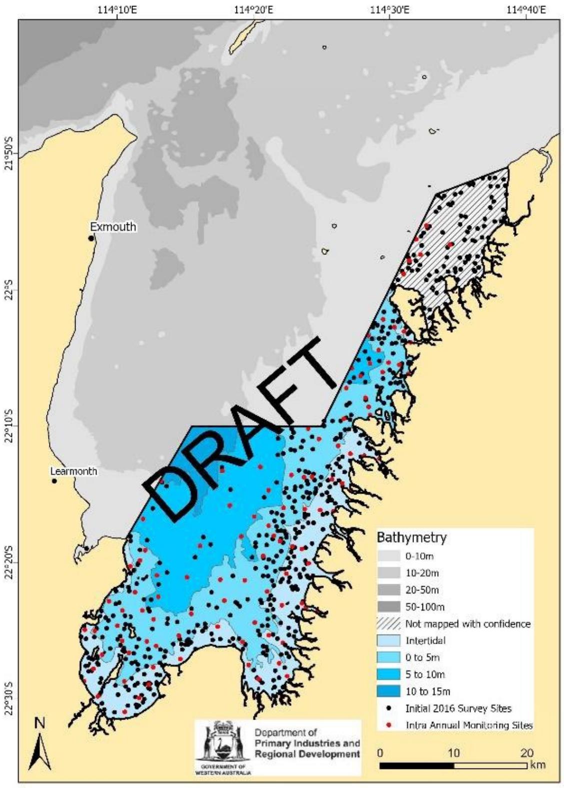
Source	Year of data	Area covered	Methods	Links	Access
		Hope Point for subtidal benthic surveys	imagery and aerial imagery		
GA - Western Australia Coastal Waterways Geomorphic Habitat Mapping, Version 2	2002-2004?	Giralia Bay		Dataset	Shapefiles freely available
Loneragan 2013 macrophytes and tiger prawns Exmouth Gulf	1999-2000	EG margins, mostly south-east	• Diver transects (30m) ~250 sites	Journal article	Request permission – Neil Loneragan
CSIRO seagrass surveys 2000	2000	South-east EG	• Forms part of North West Shelf Joint Environmental Management Study?		
AIMS seagrass surveys	1994-1999?	South-east EG, eastern EG		Journal article Dataset	Looks to be available but no links. Request permission
ACEAS – seagrass P/A	Various	EG	• Course blocks (10x10km) of consolidated seagrass records	Dataset	Shapefile freely available via SeaMap
DPaW - Marine Habitats of Western Australia		Ningaloo Reef Marine Park		Dataset	Shapefile available freely available
ICoAST UWA Mangroves of NW Australia	Mangroves P/A	EG margins		Dataset Associated report	Shapefile freely available via SeaMap
Seamap Australia National Benthic Habitat Layer V2.1 beta 2023	Various	EG margins			Shapefile freely available via SeaMap
Allen Coral Atlas Satellite data	Source imagery 2018-2020	Most EG margins		Website	Shapefile freely available via website

Appendix 4: Resources shared during the Exmouth Gulf Benthic Habitat Map Workshop

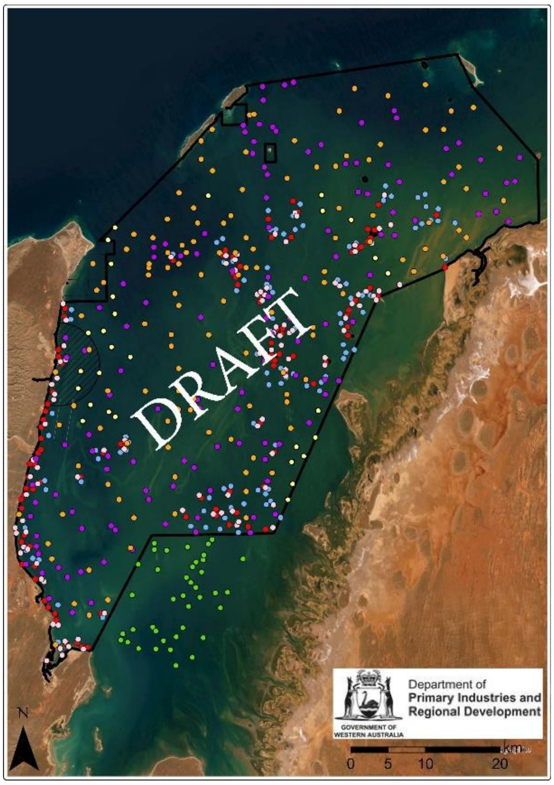
4.1 – DPIRD

Scott Evans from DPIRD presented on habitat mapping programs for Exmouth Gulf and the Exmouth Gulf Prawn Managed Fishery Nursery Grounds from 2016 onwards. Updated habitat maps are currently under review and will become available in the latter half of 2024.

Sampling sites from 2016 onwards



2024 survey sites - expanded 2018 Program



The habitat maps below are from a publicly available 2020 report. The 2024 surveys mentioned above will provide an update to these historical maps and will also include mapping of the nursery grounds.

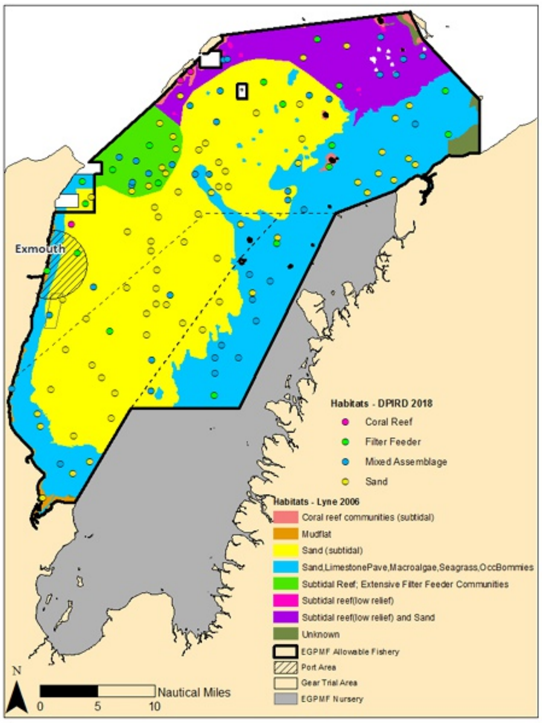


Figure 1.3. Validation surveys, showing benthic validation types, of Lyne et al. (2006) habitat map.

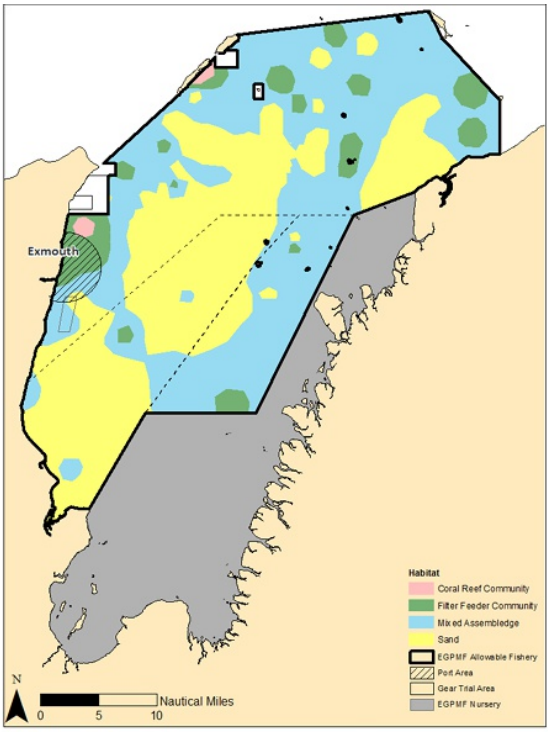


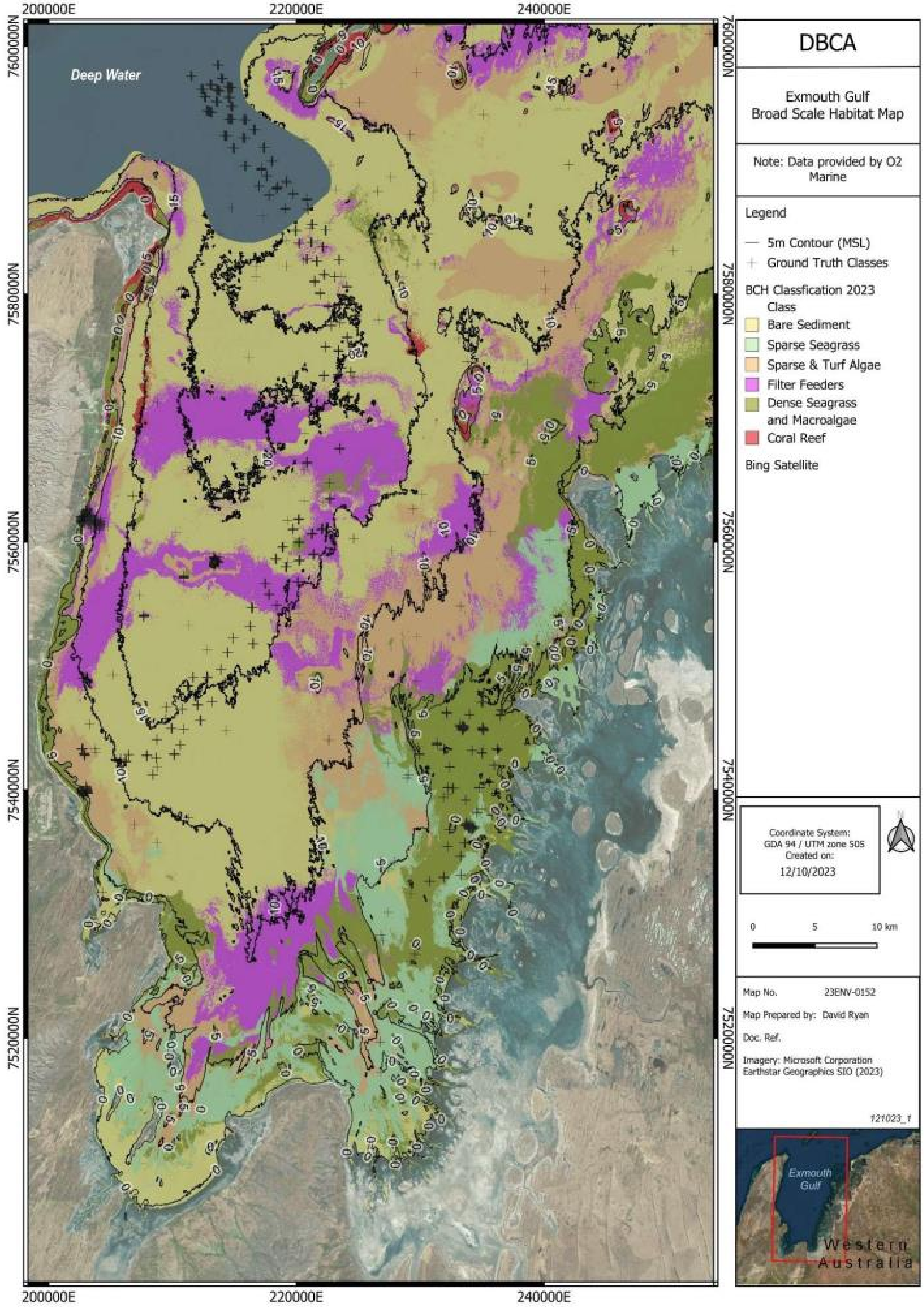
Figure 1.4. EGPMF habitat map developed by DPIRD/MG Kailis in 2018.

DPIRD (2020) Western Australian Marine Stewardship Council Report Series No. 17: Ecological Risk Assessment of the Exmouth Gulf Prawn Managed Fishery. Department of Primary Industries and Regional Development, Western Australia. 61p. https://www.fish.wa.gov.au/Documents/wamsc_reports/wamsc_report_no_17.pdf

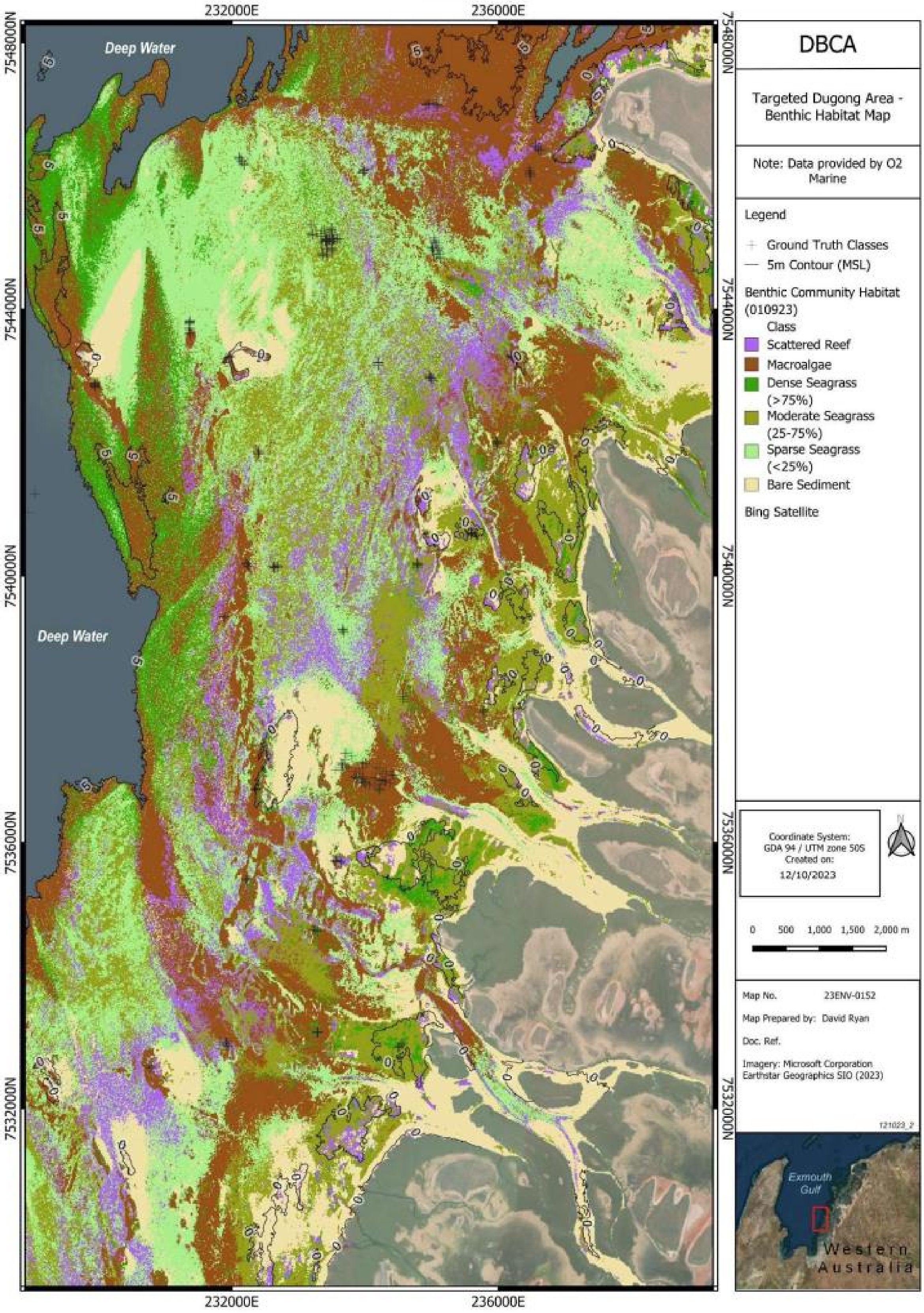
4.2 – DBCA

Tom Holmes from DBCA and Adam Gartner/Max Stacey from O2 Marine presented on 2023 and 2024 benthic habitat maps at the workshop. The 2024 map will become available ~ August 2024.

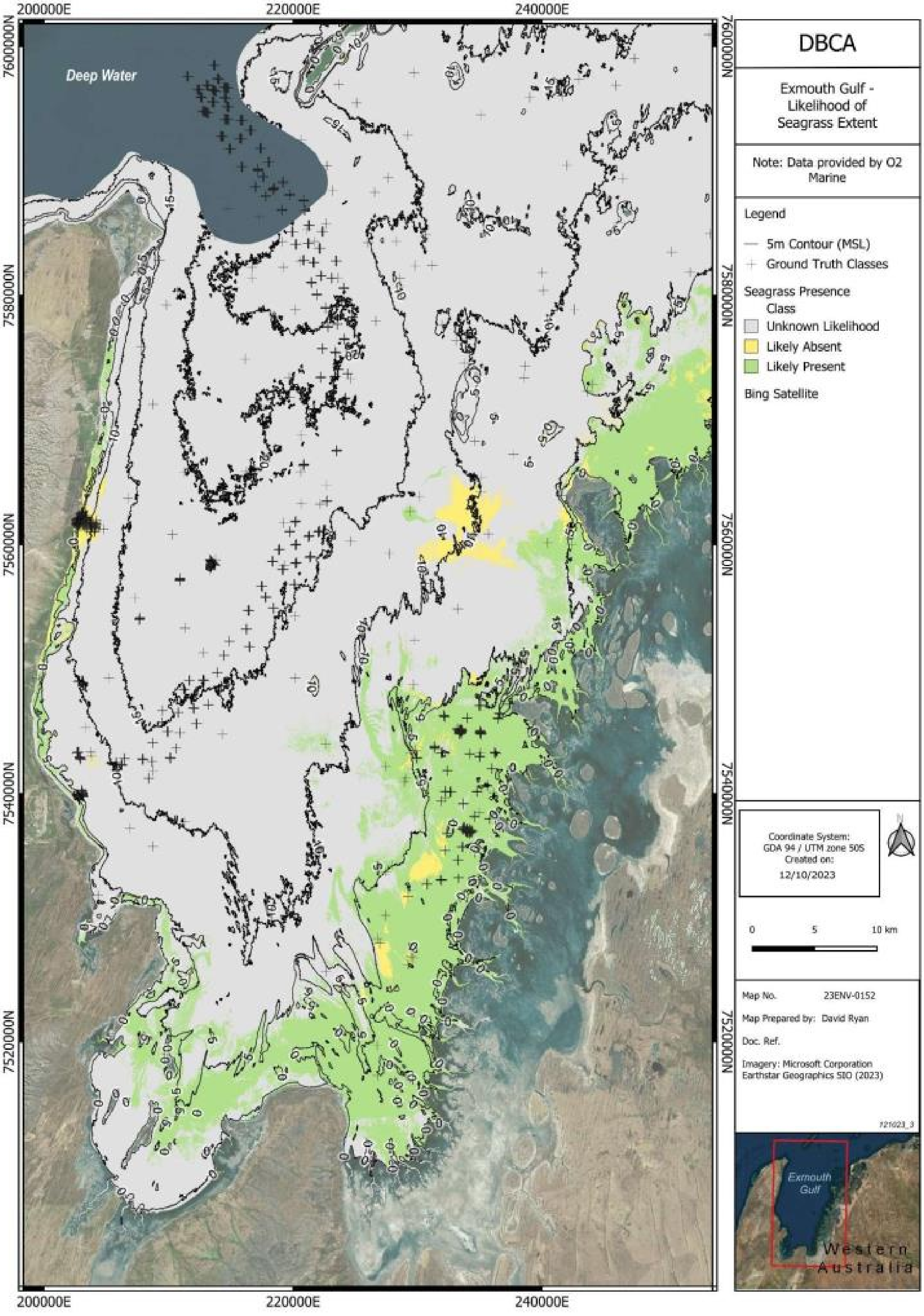
2023 benthic habitat map - entire Exmouth Gulf:



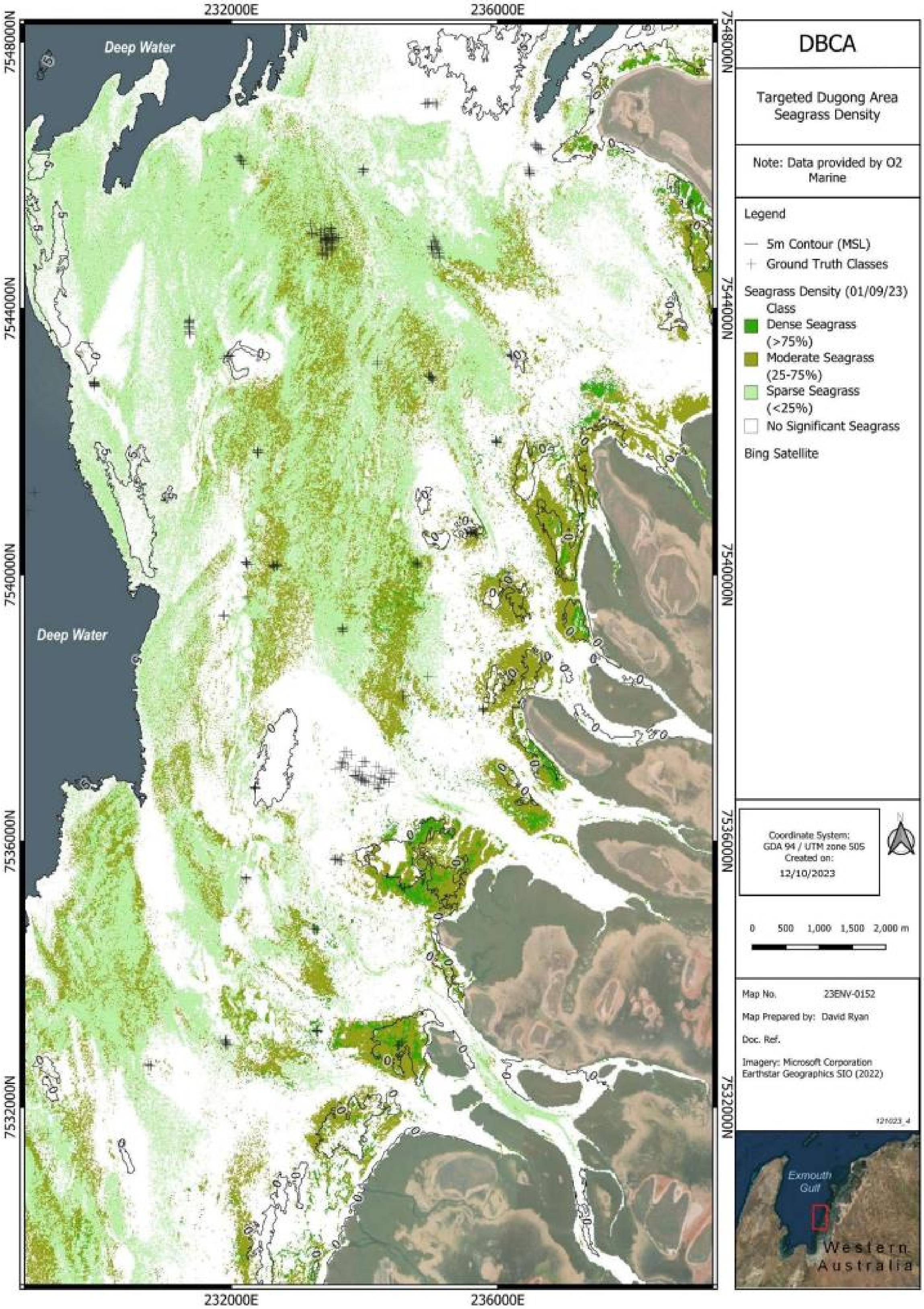
2023 benthic habitat map - Targeted Dugong Area (south east gulf):



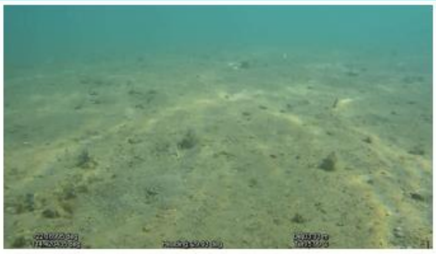
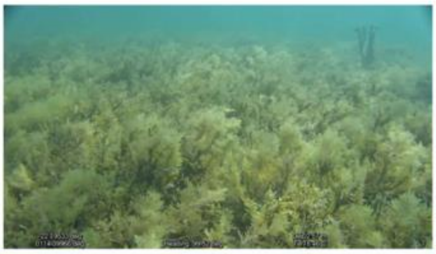
2023 map of likelihood of seagrass present / absence- entire Exmouth Gulf:



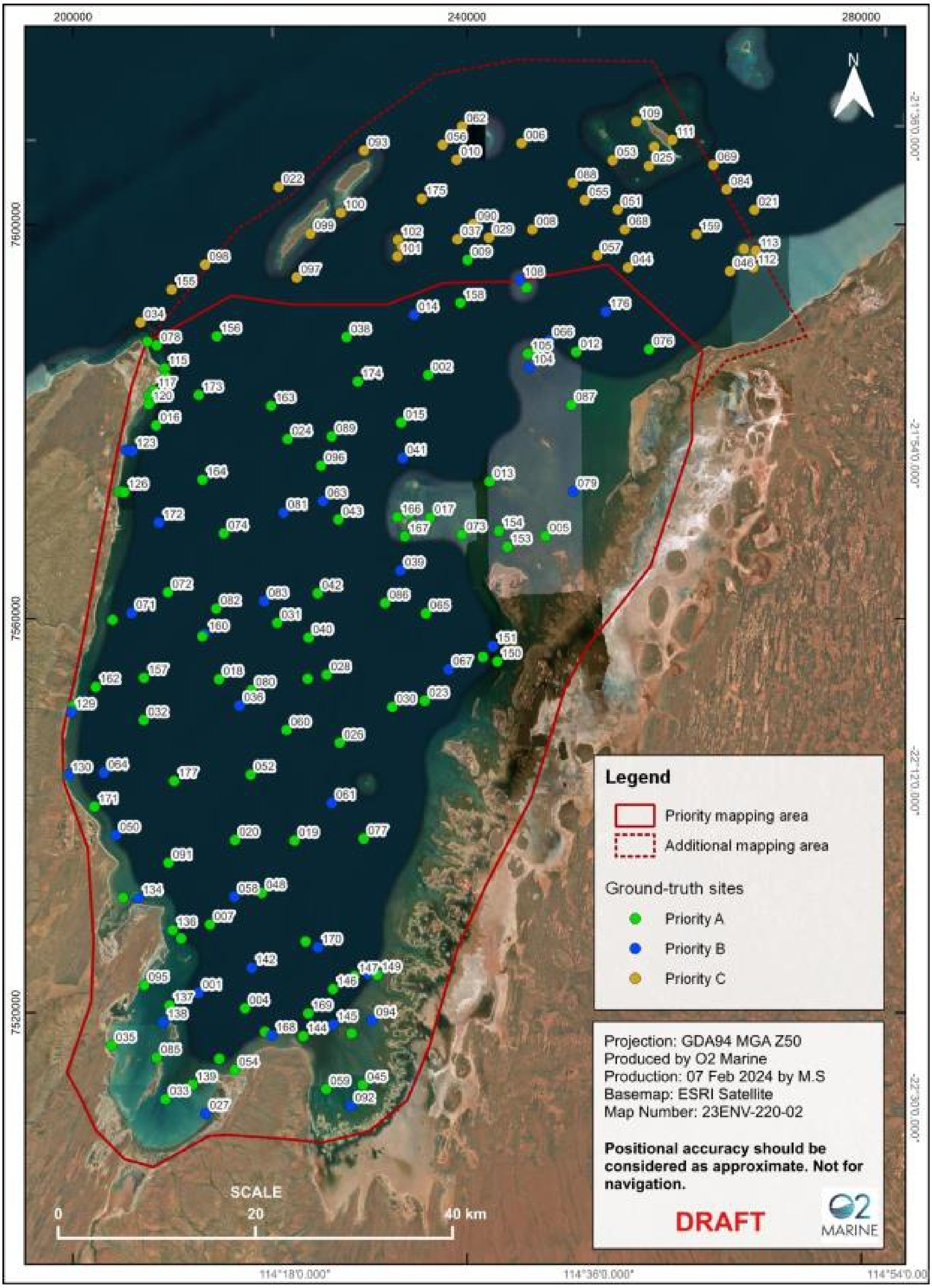
2023 map of seagrass density - Targeted Dugong Area (south east gulf):



Example classification from 2023 benthic map (entire Exmouth Gulf). Images taken from towed video acquired in Targeted Dugong Area:

BCH Classification	Description	Example Image
Bare Sediment	Bare, undifferentiated sediment with no apparent structure or minor ripple features/bioturbation.	
Sparse Seagrass	Sparse (<25%) seagrass on a mostly sand or silty substrate, including potential minor ripple features/bioturbation.	
Moderate Seagrass	Seagrass dominated habitat with moderate (25-75%) cover on predominantly sand or silty substrate. Macroalgae and invertebrates often present. Minor ripple features/bioturbation. Typically adjacent to sparse and/or dense seagrass habitats.	
Dense Seagrass	Continuous, dense (>75%) seagrass cover. Typically mixed with macroalgae, filter feeders, and/or other invertebrates scattered throughout meadow on unconsolidated substrate.	
Macroalgae	Varying cover of macroalgae on low relief substrate, such as sediment or flat rock. Invertebrates often scattered throughout.	
Scattered Reef	Scattered rock over sediment, or on flat reef, generally reef adjacent. Mix of filter-feeders, macroalgae, suspension feeders, and/or hard/soft corals on hard substrate. Evidence of invertebrates present over sediment.	

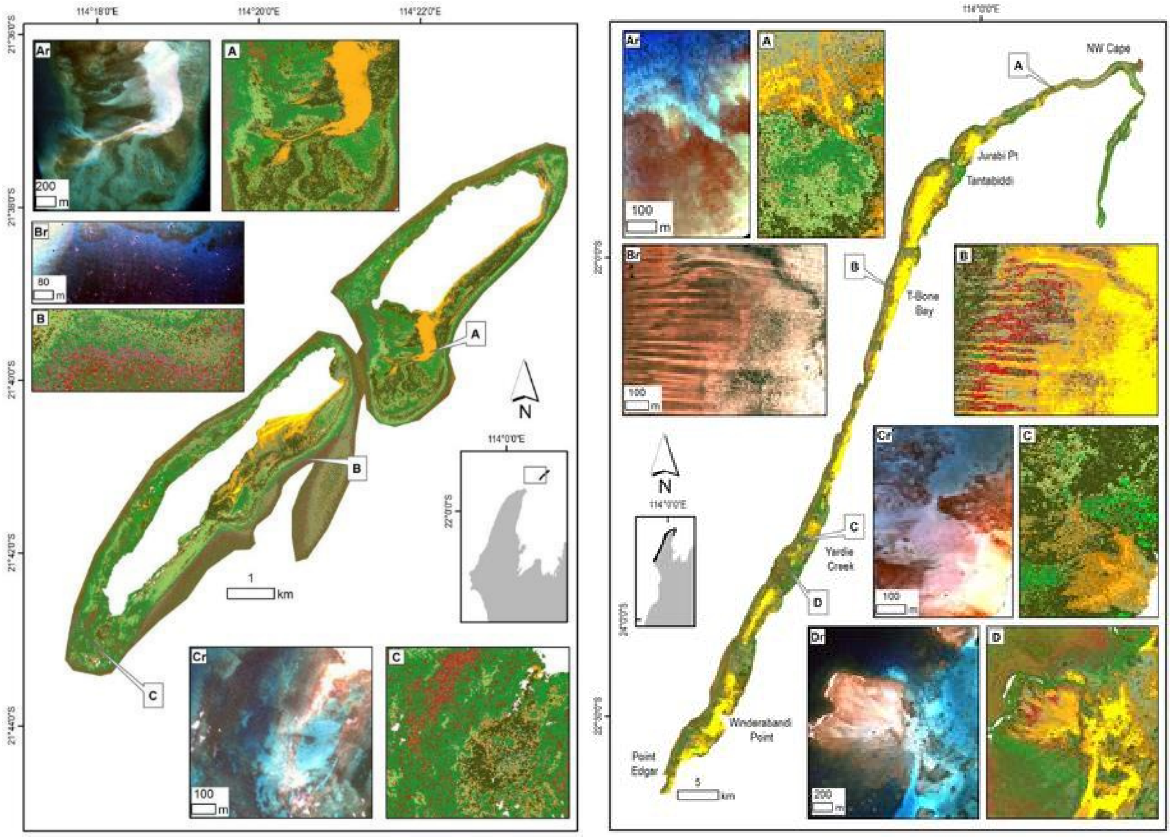
2024 ground-truthing sites map:



4.3 – Murdoch University

Halina Kobryn described the below studies during the workshop.

Kobryn, H. T., Wouters, K., Beckley, L. E., Heege, T. (2013) Ningaloo Reef: Shallow Marine Habitats Mapped Using a Hyperspectral Sensor. PLoS ONE 8(7): e70105. https://doi.org/10.1371/journal.pone.0070105



Kobryn, H. T., Beckley, L. E., and Wouters, K. (2022). Bathymetry derivatives and habitat data from hyperspectral imagery establish a high-resolution baseline for managing the Ningaloo Reef, Western Australia. Remote Sensing 14, 1827. https://doi.org/10.3390/rs14081827.

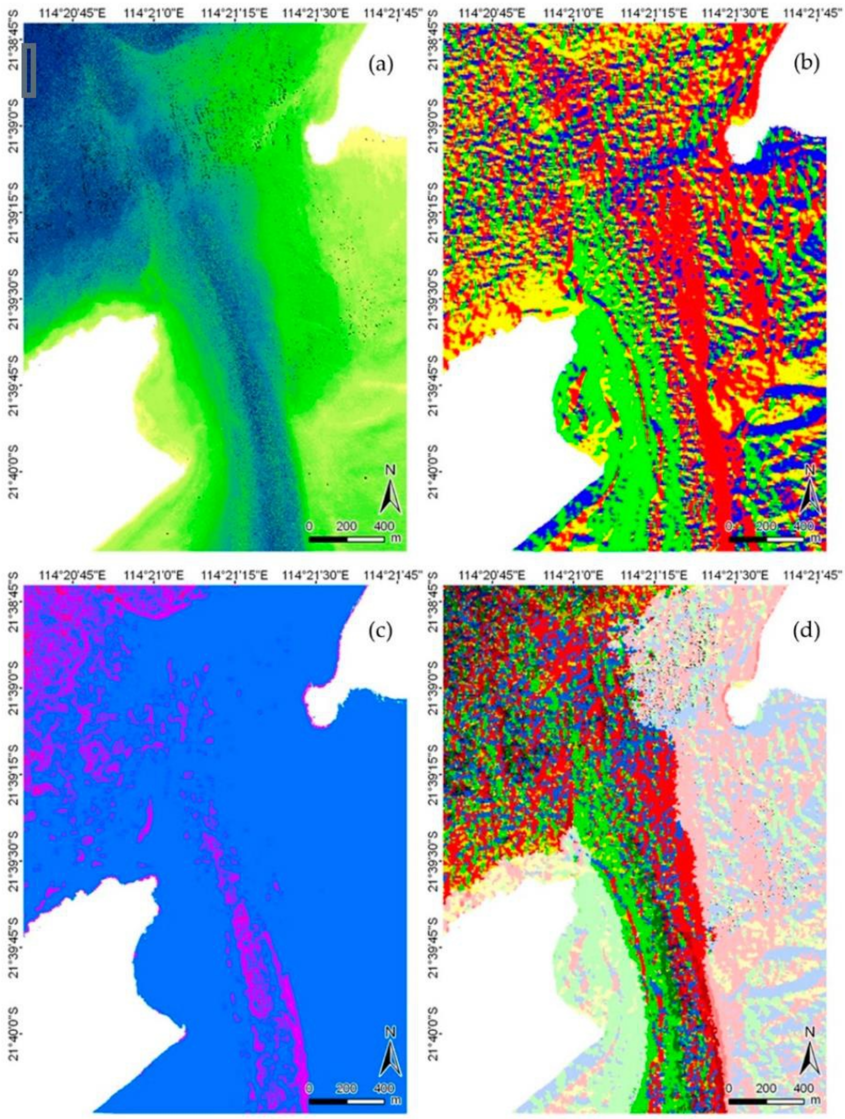


Figure 7. Topographic variables for the focus area at Muiron Islands at the northern extent of the Ningaloo Reef. (**a**) depth, (**b**) aspect, (**c**) slope, and (**d**) topographic classification. Legends in Figure 6 apply.

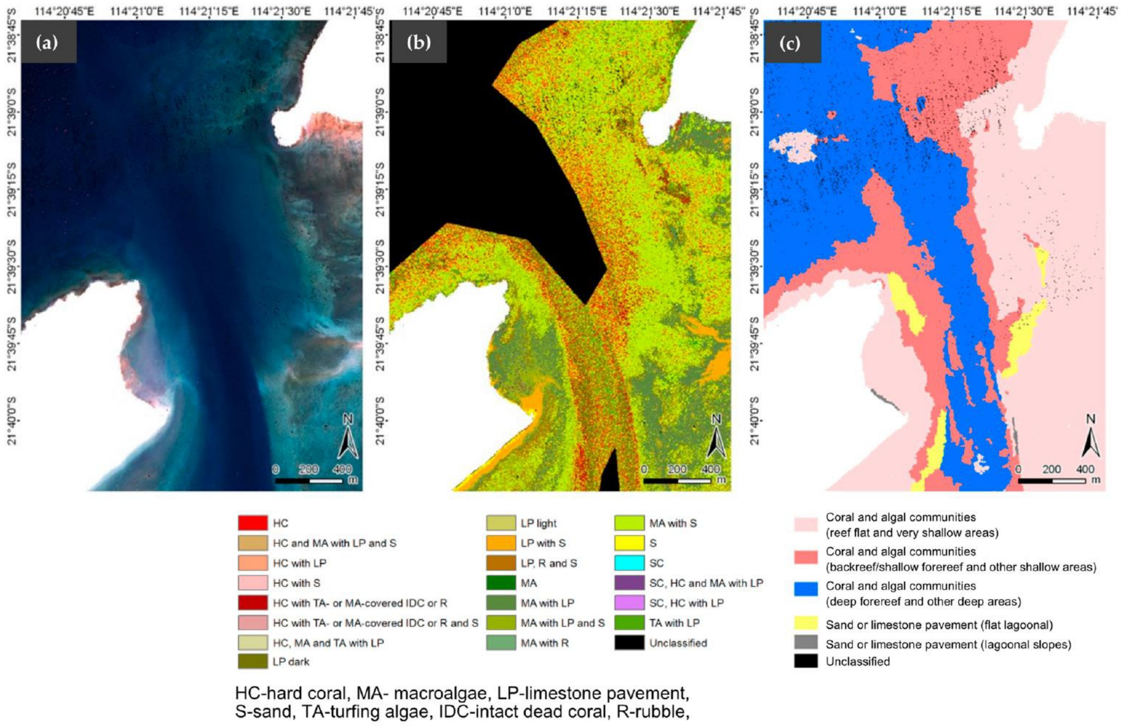


Figure 11. Muiron Islands area (**a**) subsurface reflectance, (**b**) pixel-based benthic habitat map and (**c**) geomorphic classes for the same area.

Stewart-Yates, Zoe (2022). Evaluating impact and recovery of mangroves following extreme climatic events using satellite remote sensing in Exmouth Gulf, north western Australia. Masters Thesis. Murdoch University. 74p.

https://researchportal.murdoch.edu.au/esploro/outputs/graduate/Evaluating-impact-and-recovery-of-mangroves/991005540860607891

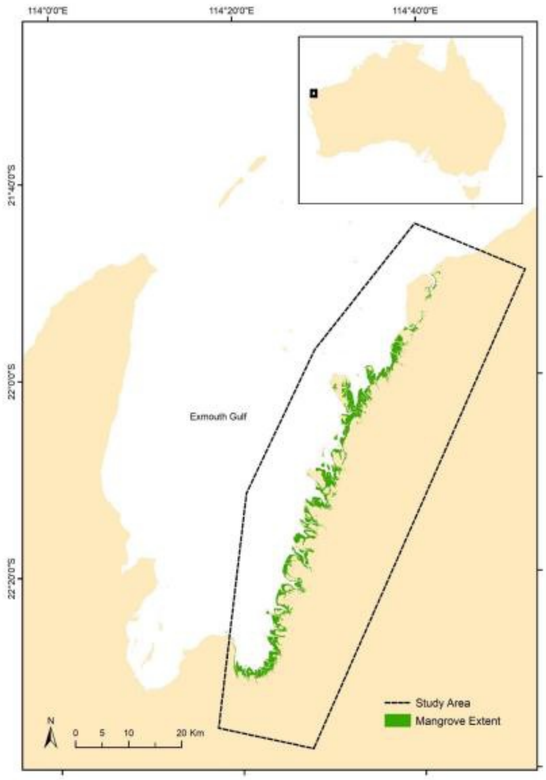


Figure 2.1: Study area of eastern Exmouth Gulf (black dashed line), and the extent of mangroves along this coast in addition to its region of Australia.

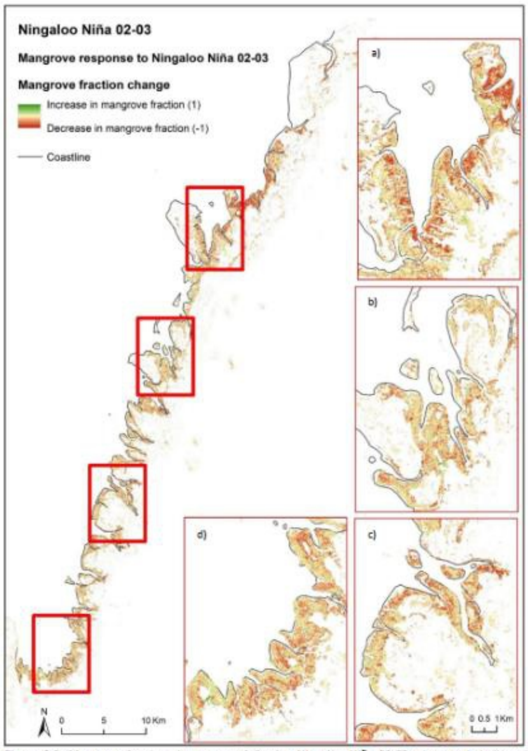
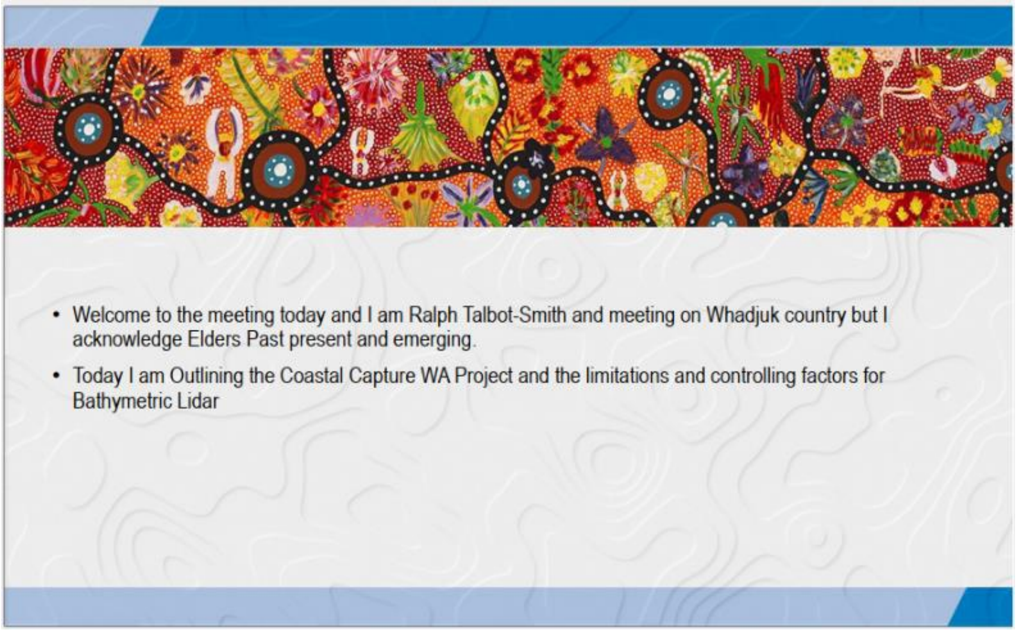
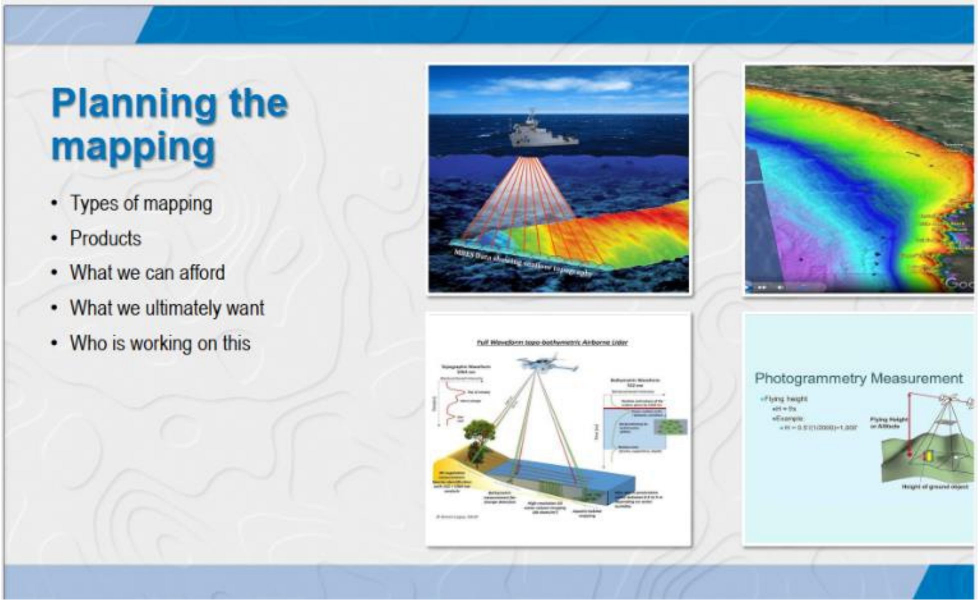


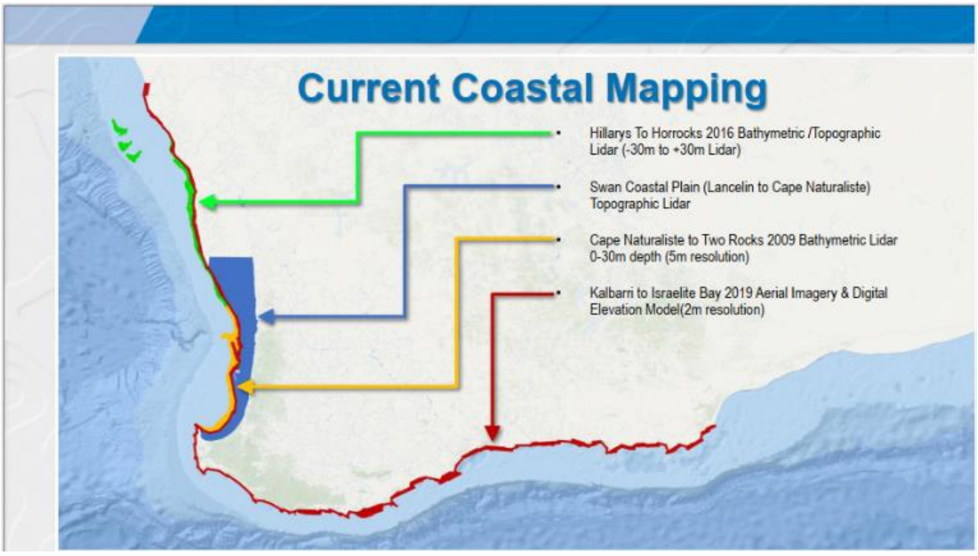
Figure 3.2: Mangrove fraction change map following Ningaloo Niña 02-03 where reds indicated mangrove fraction decreases and greens indicate mangrove fraction increases, including zoom insets of part of the northern (a), upper central (b), lower central (c), and southern localities of the study area. The scale of all insets is the same as in inset (c).

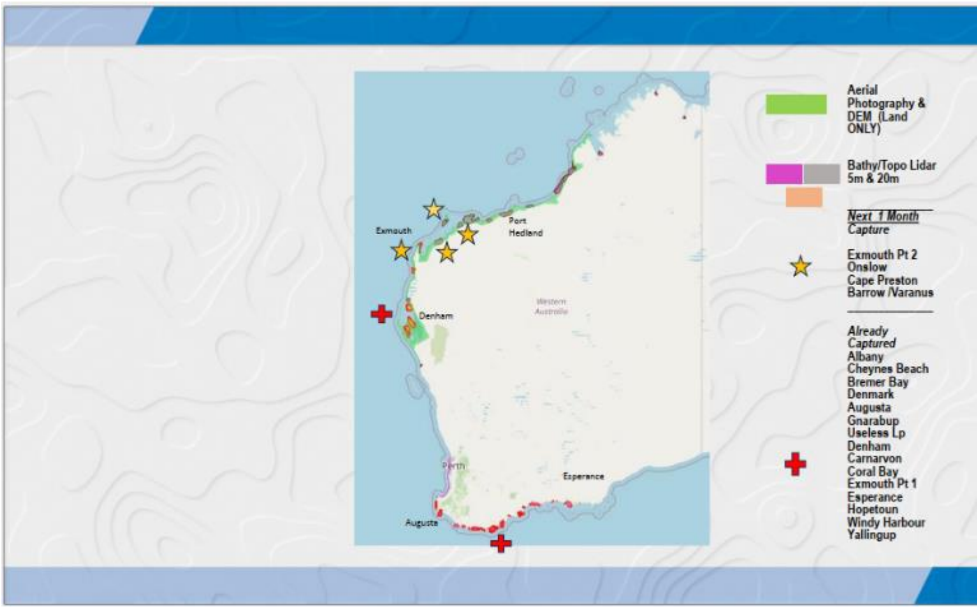
4.4 – DoT

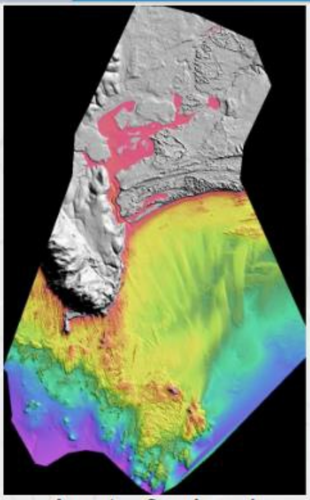
Ralph Talbot-Smith shared a presentation on the mapping activities DoT have been doing up and down the WA coastline, including the costs associated with mapping Exmouth Gulf.



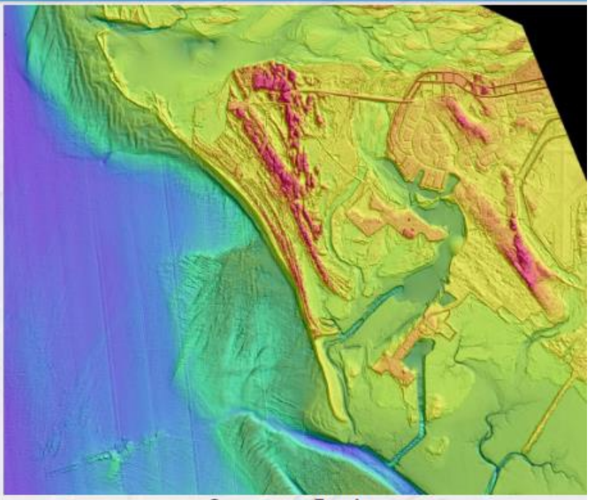

Planning the mapping
Types of mapping
Products
What we can afford
What we ultimately want
Who is working on this
Full Waveform topo-bathymetric Airborne Lidar
Photogrammetry Measurement


Current Coastal Mapping
Hillarys To Horrocks 2016 Bathymetric /Topographic Lidar (-30m to +30m Lidar)
Swan Coastal Plain (Lancelin to Cape Naturaliste) Topographic Lidar
Cape Naturaliste to Two Rocks 2009 Bathymetric Lidar 0-30m depth (5m resolution)
Kalbarri to Israelite Bay 2019 Aerial Imagery & Digital Elevation Model(2m resolution)

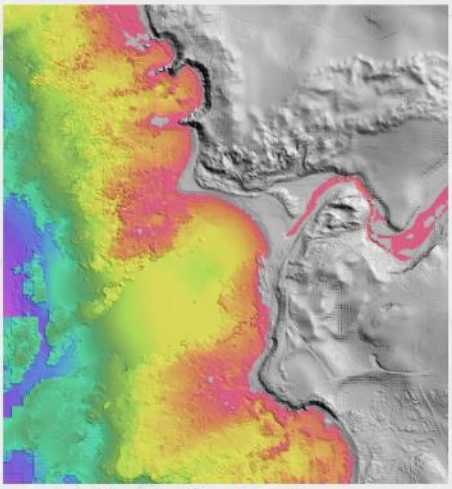

Aerial Photography & DEM (Land ONLY)
Bathy/Topo Lidar 5m & 20m
Next 1 Month Capture
Exmouth Pt 2
Onslow
Cape Preston
Barrow /Varanus
Already Captured
Albany
Cheynes Beach
Bremer Bay
Denmark
Augusta
Gnarabup
Useless Lp
Denham
Carnarvon
Coral Bay
Exmouth Pt 1
Esperance
Hopetoun
Windy Harbour
Yallingup
Exmouth
Port Hedland
Denham
Perth
Esperance
Augusta



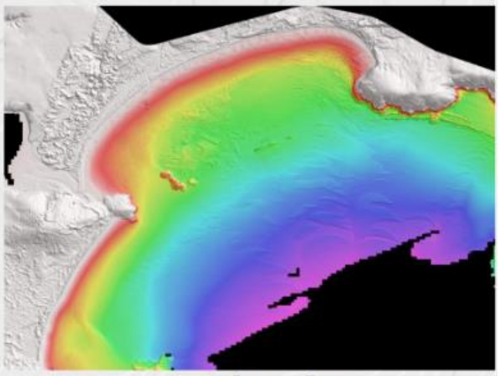
Augusta – Cape Leeuwin



Carnarvon - Fascine



Augusta – Cape Leeuwin



Bremer Bay

Considerations for LIDAR Capture

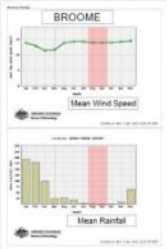
- Aviation conditions
- Whitewater
- Tannin
- River runoff
- Tidal turbidity
- Rough conditions

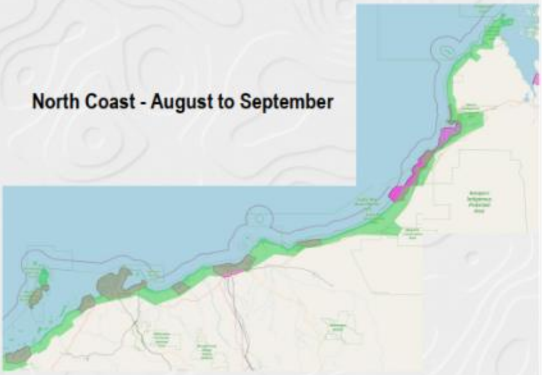
North Coast Seasonal Timings

North Coast - August to September

- Cyclone season
- Tidal turbidity
- Wind chop
- Local knowledge

North Coast - August to September



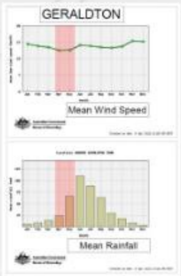


West Coast Seasonal Timings

West Coast - April to May

- Cyclone season extending south
- Winter storms
- Whitewater
- Local knowledge

West Coast
April to May

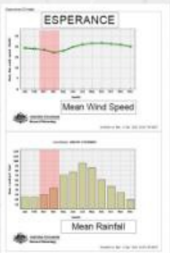


South Coast Seasonal Timings

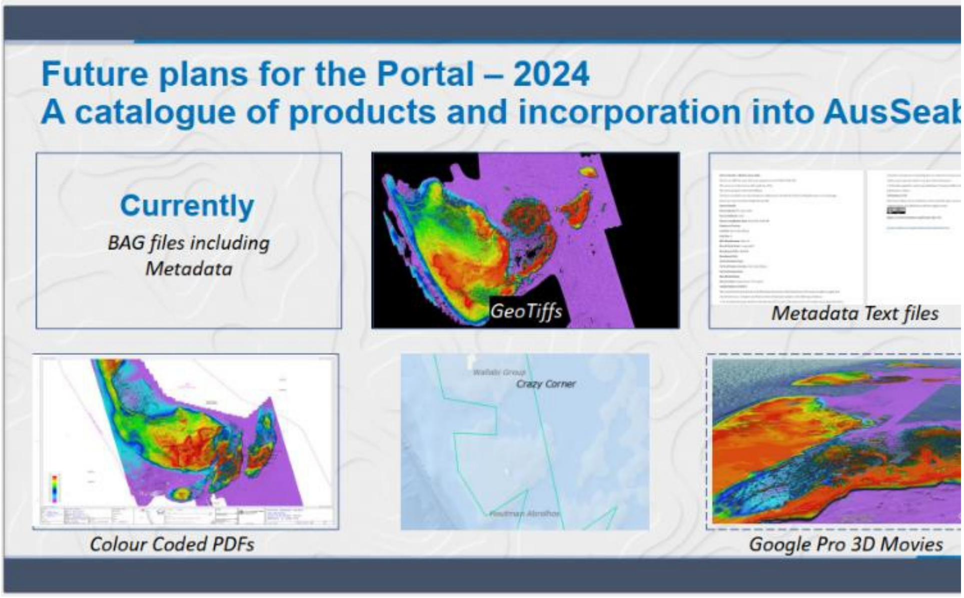
South Coast - March to April

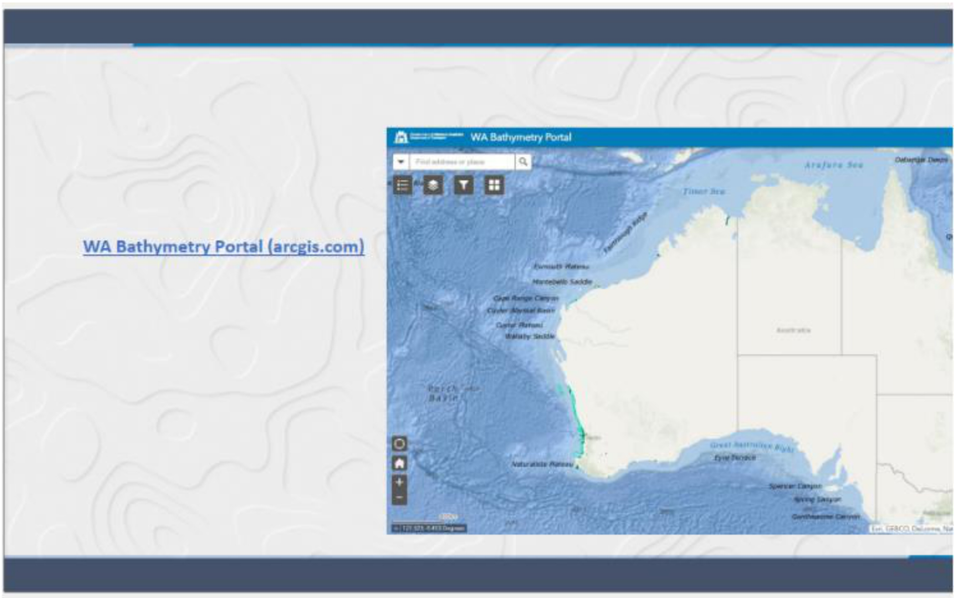
- Rainfall
- River runoff
- Tannin
- Local knowledge

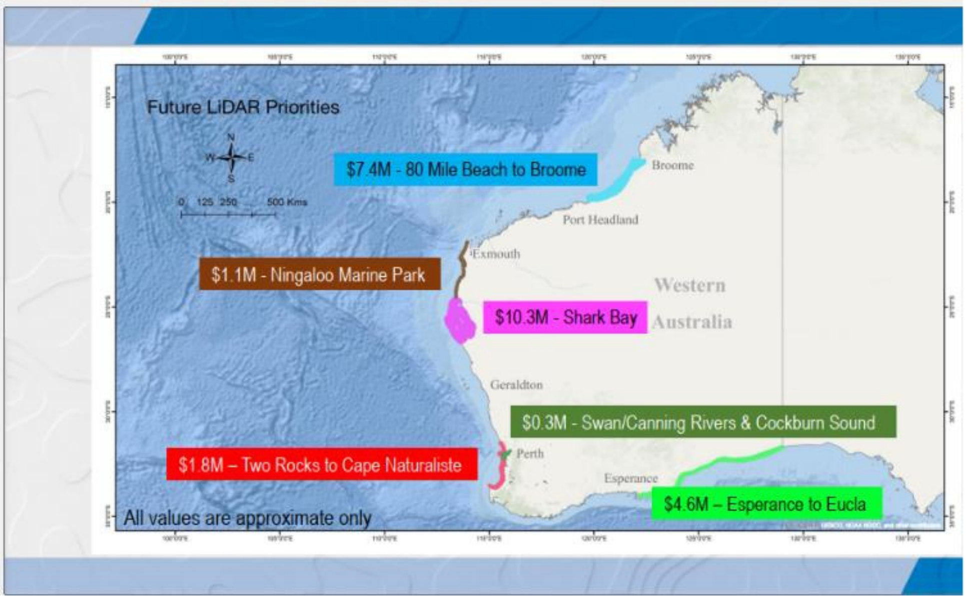
South Coast - March to April




Who will benefit
WA coastal communities
Marine habitat
Climate change inundation
Wave run-up forecasting
Marine parks
Underwater culture (Aboriginal/European)
Nautical charting


Future plans for the Portal – 2024
A catalogue of products and incorporation into AusSeab
Currently
BAG files including Metadata
GeoTiffs
Metadata Text files
Colour Coded PDFs
Crazy Corner
Google Pro 3D Movies


WA Bathymetry Portal (arcgis.com)
WA Bathymetry Portal



Summary

- Cost
- Open Data
- Coastal Hotspots and Watchspots
- Priority 1 areas of the state
- 3 years program
- Websites
  - Charts https://www.transport.wa.gov.au/imarine/nautical-charts.asp
  - CoastCams https://www.transport.wa.gov.au/imarine/coast-cams.asp
  - Coastal Data https://www.transport.wa.gov.au/imarine/coastal-data-and-charts.asp
  - AusSeabed https://www.ausseabed.gov.au
  - HIPP https://www.hydro.gov.au/NHP/hipp.htm

Supporting organisations and Project Collaborators wit
Dept. of Fire & Emergency Services
Southern Ports
Midwest Ports
Pilbara Ports
Dept. Planning Lands & Heritage
Dept. Primary Industries & Regional Development
Dept. Biodiversity , Conservation & Attraction
Dept. Water & Environmental Regulation
Landgate
Water Corporation
West Australian Local Government Association
PAWSEY
Geoscience Australia
Western Australian Museum

4.5 – UWA

Sharyn Hickey outlined the below study during the workshop.

Hickey, S., Stone, A., & Lovelock, C. (2023) The Cyanobacterial Mats of the Exmouth Gulf, Western Australia: Mapping Report. Report prepared for the Minderoo Foundation by The University of Western Australia and The University of Queensland. 56p.

https://research-repository.uwa.edu.au/en/publications/the-cyanobacterial-mats-of-the-exmouth-gulf-western-australia-map

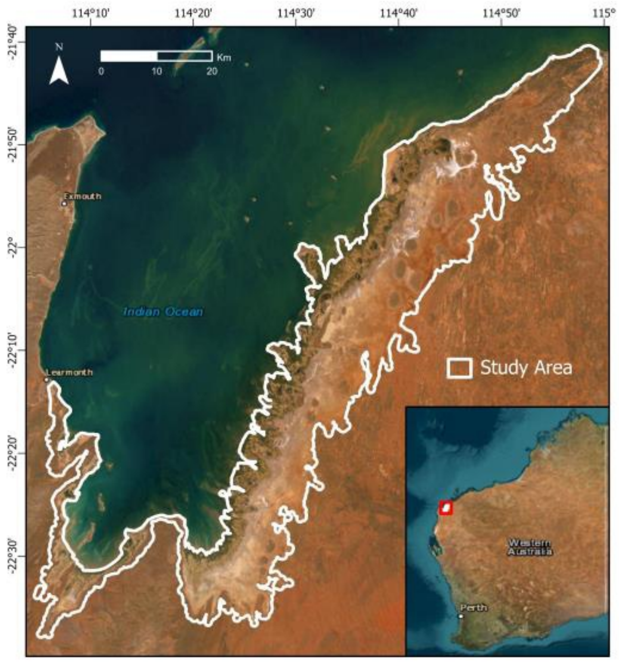


Figure 4: Study extent (white outline) for mapping of cyanobacterial mats and associated intertidal habitats of the Exmouth Gulf.

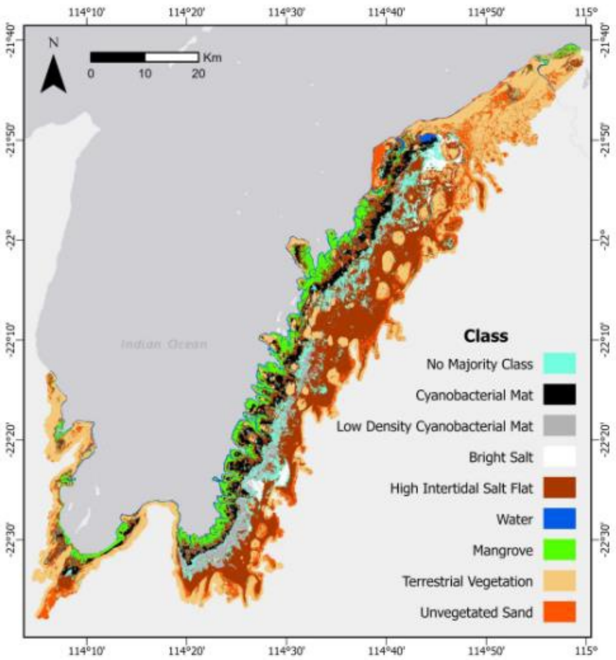
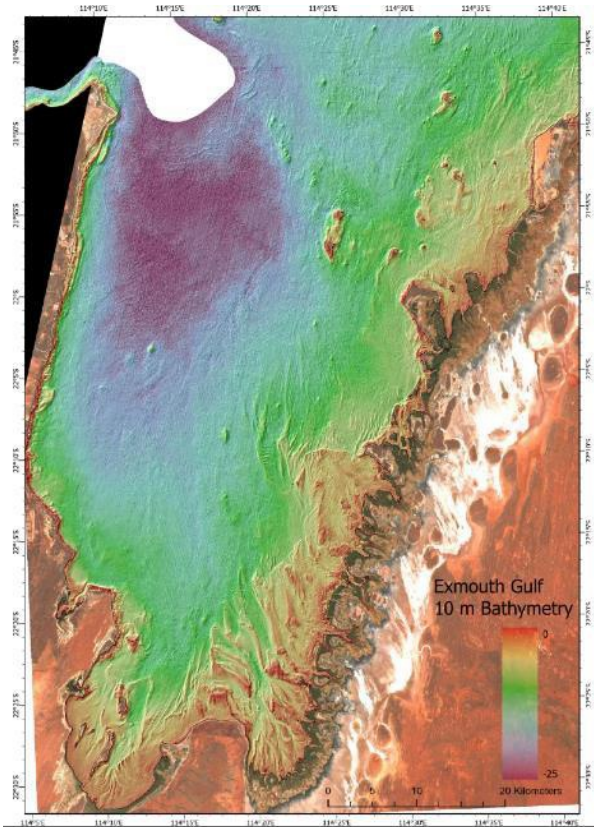
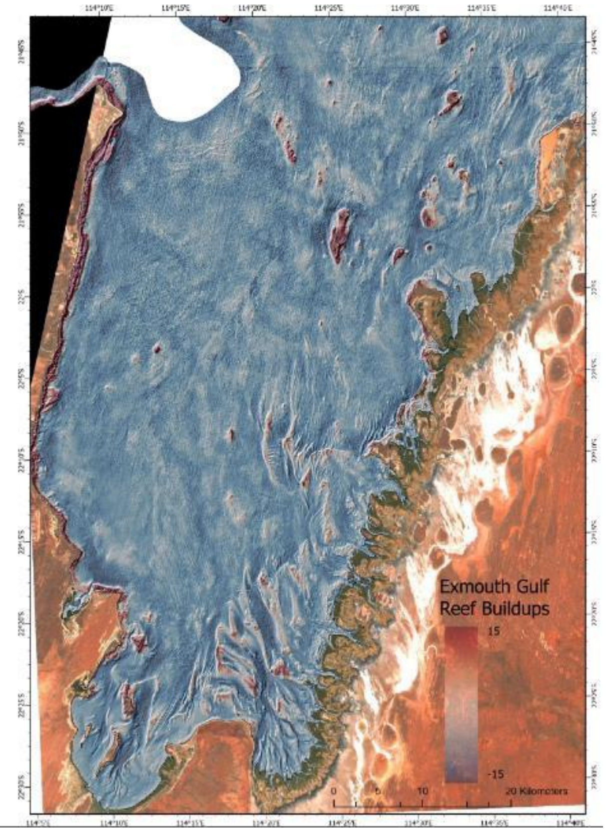
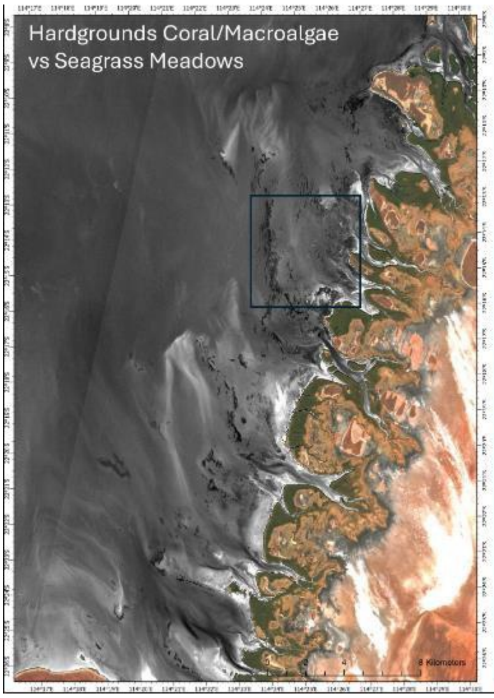


Figure 14: Linear Additive habitat model generated from the majority habitat class assignment for each pixel from the 5 time-point models.

Mick O’Leary and Shannon Dee presented the below maps during the workshop.

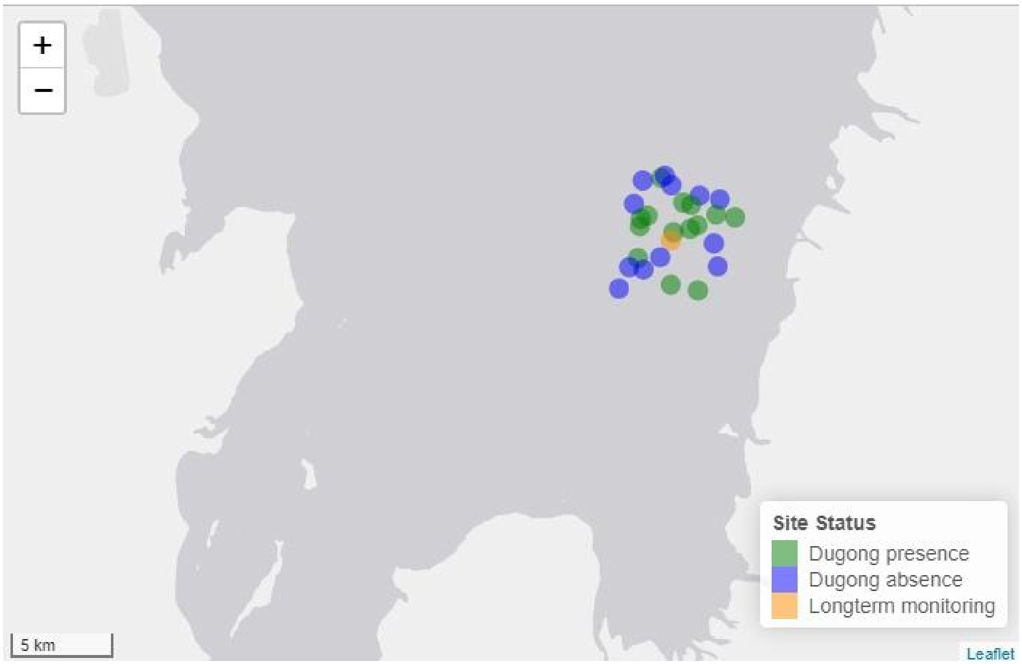

Exmouth Gulf
10 m Bathymetry
0
-25
0
5
10
20 Kilometers


Exmouth Gulf
Reef Buildups
15
-15
0
5
10
20 Kilometers


Hardgrounds Coral/Macroalgae
vs Seagrass Meadows

4.6 – ECU

Nicole Said described the below study during the workshop.



Linked to project: Conserving critical seagrass habitat for dugong: an integrated assessment across the Pilbara

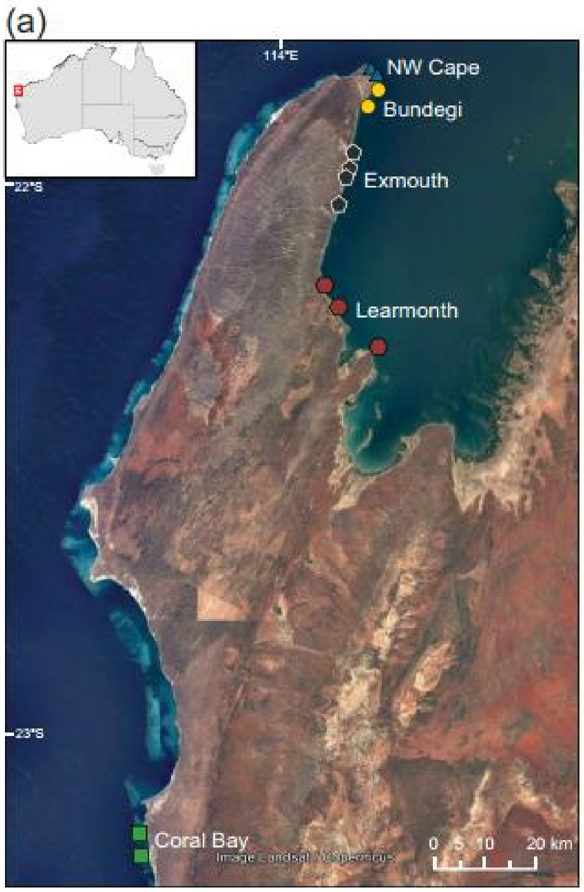
https://www.ecu.edu.au/schools/science/research/school-centres/centre-for-marine-ecosystems-research/research-themes/habitat-connectivity-and-trophic-interactions/related-content/lists/habitat-connectivity-and-trophic-interaction/conserving-critical-seagrass-habitat-for-dugong-an-integrated-assessment-across-the-pilbara

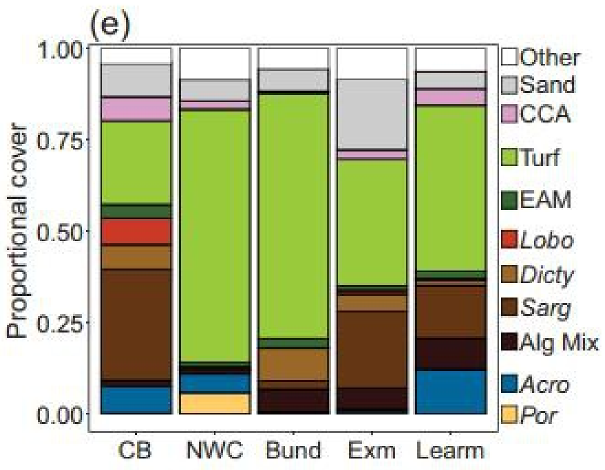
4.7 – CSIRO

Dirk Slawinski provided information on the below CSIRO projects prior to the workshop, but these studies were not shown to participants during the workshop.

Doropoulos, C, Gómez-Lemos, L. A., Salee, K., McLaughlin, M. J., Tebben, J., Van Koningsveld, M., Feng, M., Babcock, R.C. (2022) Limitations to coral recovery along an environmental stress gradient. Ecological Applications 32: e2558.

https://esajournals.onlinelibrary.wiley.com/doi/full/10.1002/eap.2558





Vanderklift, M., Bearham, D., Haywood, M., Lozano-Montes, H., McCallum, R., Mc Laughlin, J., McMahon, K., Mortimer, N., Lavery, P. (2017) Natural dynamics: understanding natural dynamics of seagrasses of the north west of Western Australia. Report of Theme 5 - Project 5.3 prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 55 pp.

https://wamsi.org.au/project/5-3-seagrass-natural-dynamics/

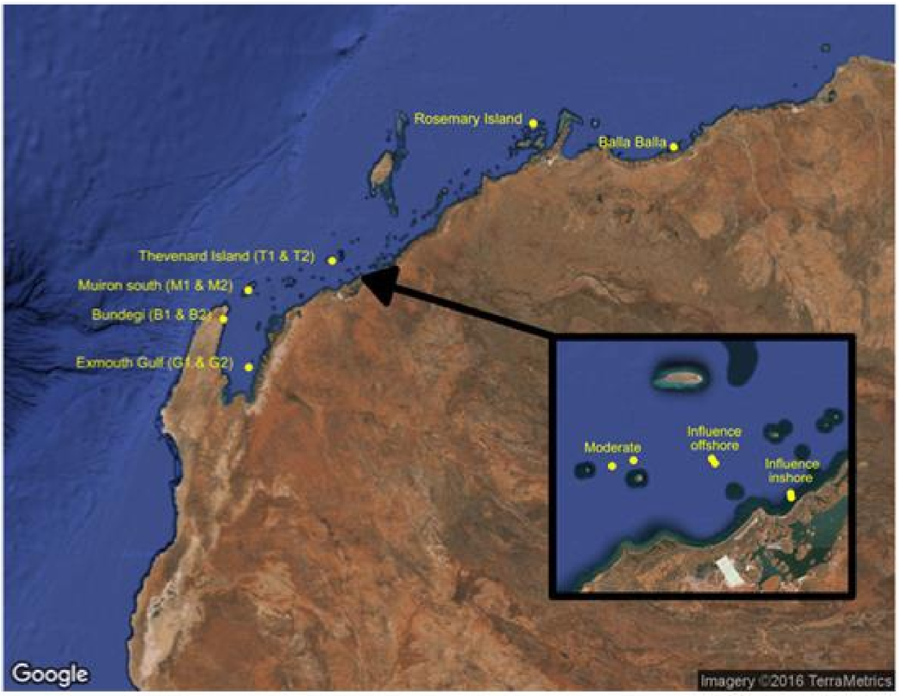


Figure 1. Locations surveyed during the study. Sites surveyed as part of Wheatstone LNG Project monitoring program are shown in the inset. Two sites were sampled in each location, each separated by about 200 m except at Wheatstone where the distance among sites was variable.

4.8 – AIMS

Ben Radford described two AIMS studies on seagrass in Exmouth Gulf, corresponding to the consolidated map (i.e. for both studies) shown below.

- McCook, L. J., Klumpp, D. W., McKinnon, A. D. (1995) Seagrass communities in Exmouth Gulf, Western Australia: a preliminary survey. Journal of the Royal Society of Western Australia 78: 81-87.
- Schaffelke, B., Klumpp, D.W. (1996) Biomass and productivity of a tropical seagrass community in North-West Australia (Exmouth Gulf). pp. 13-20. In: Kuo J, Walker DI and Kirkman H (eds) Seagrass biology: scientific discussion from an international workshop: Rottnest Island, Western Australia, 25-29 January 1996. Faculty of Science, University of Western Australia. 276 p.

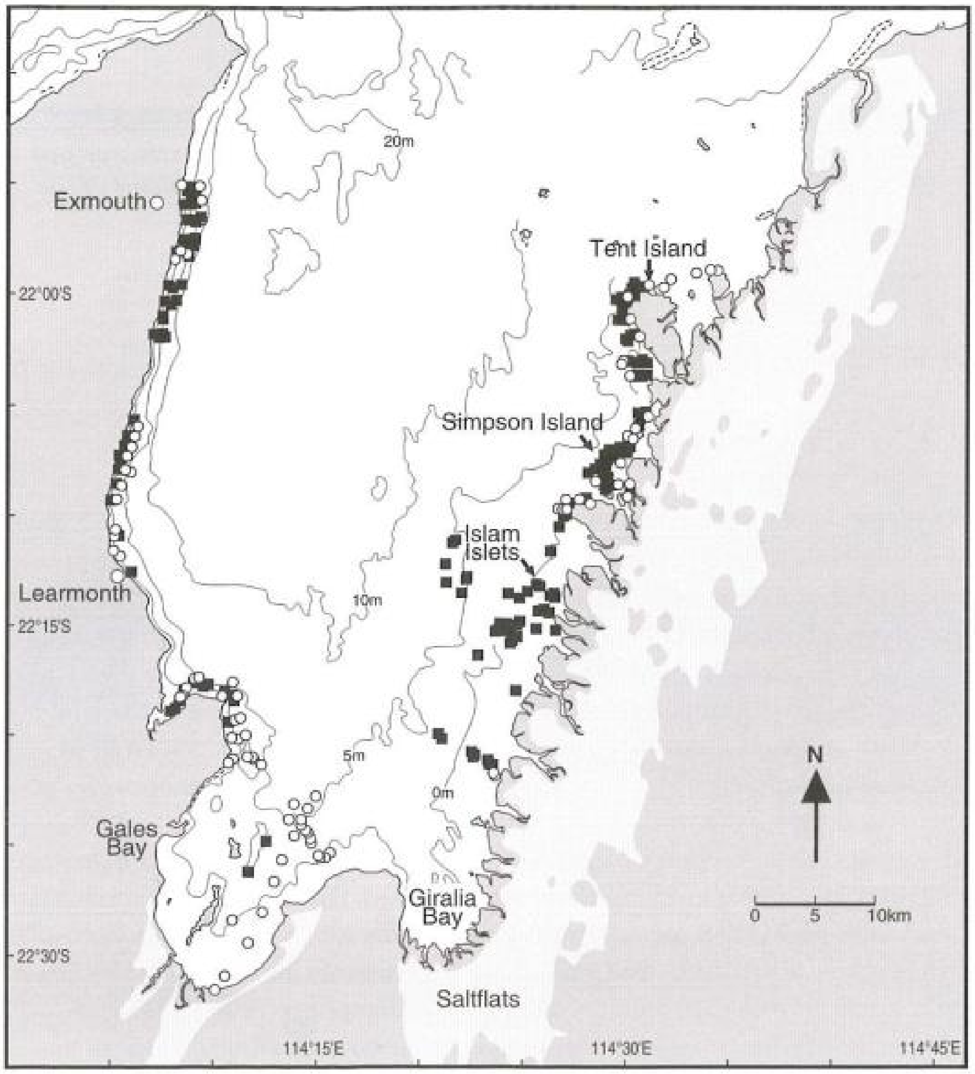


Figure 1. Map of Exmouth Gulf showing locations of sites in the visual survey according to the GPS (Global Positioning System) positions taken. Black squares: sites with macrophytes present; white circles: sites with bare substratum.

Taken from report: AIMS Western Australian Research Activities 1994-1996.

Occurrence of marine megafauna along the western margin of Exmouth Gulf, Western Australia, July – October 2023

Occurrence of marine megafauna along the western margin of Exmouth Gulf, Western Australia, July – October 2023

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[1] *Irvine Marine Fauna Research, Perth, Western Australia 6076*
[2] *Institute for Marine and Antarctic Studies, University of Tasmania, Tasmania, 7001*

Irvine Marine Fauna Research

UNIVERSITY of TASMANIA | IMAS INSTITUTE FOR MARINE & ANTARCTIC STUDIES

Date presented: Jan 2024

Author Contributions: The work in this report, including the experimental design, was conceived by Lyn Irvine (LI). LI and Jennah Tucker (JT) performed the surveys; Wayne Irvine produced the maps; LI analysed the data; LI and JT provided the draft report.

1. Executive Summary

Exmouth Gulf is recognised as an area of high ecological importance and cultural value. It supports numerous conservation significant megafauna species and is also a focus of industrial interest, with several development proposals currently under consideration that may affect its ecological values. Internationally, Exmouth Gulf is recognised as an Important Marine Mammal Area (IMMA) by the Marine Mammal Protected Areas Task Force (MMPATF); at a national level it is recognised by the department of Climate Change, Energy, the Environment and Water (DCCEEW) as a Biologically Important Area (BIA) for several megafauna species including humpback and southern right whales, dugongs, green, hawksbill, flatback and loggerhead turtles; all of which are protected under state and commonwealth laws.

To inform management decisions, an aerial survey program was conducted along the western coast of Exmouth Gulf, the area that hosts the highest concentration of human activity and coastal development. The aerial surveys aimed to determine the relative abundance and distribution of marine megafauna in the area and to identify spatial overlap between megafauna habitats and human activities. These findings are important for understanding the potential ecological impacts of current anthropogenic pressures and for supporting evidence-based management decisions for future developments.

Ten aerial surveys, running down the western margin of Exmouth Gulf, were conducted between 28 July and 5 October 2023. The key findings were the following:

- Humpback whales were the most frequently sighted megafauna species, with a total of 483 humpback whales, including 88 calves observed. These whales were distributed along the entire western margin of Exmouth Gulf, except for the shallow waters of Gales Bay. Most groups (72.9%) were engaged in milling or resting behaviours. Calves were present in 28.4% of groups, with the highest number (25 calves in 72 groups) being observed in mid-September.
- A total of 59 dugongs, including 9 calves, were recorded across the western Gulf. The highest densities were observed between Pebble Beach and Badjirrajirra Creek and in Gales Bay. Mother-calf pairs were found in these high-density areas as well as near the southern boundary of the Ningaloo Marine Park.
- A total of 126 dolphins, including 15 calves, were recorded across the western Gulf, distributed along its entire western margin. The highest densities were recorded south of the Bay of Rest and in Gales Bay.
- A total of 128 manta rays were recorded across the western Gulf, distributed between Bundegi boat ramp and south Pebble Beach. The highest densities were observed between the southern end of the Ningaloo Marine Park and Golf Club Beach, with peak numbers occurring in late August / early September and late September.
- A total of 37 other rays (in addition to manta rays) were observed across the western Gulf, distributed mainly in Gales Bay.
- A total of 12 sharks were observed in the northern and southern sectors of the western Gulf, with the highest density recorded in Gales Bay.
- A total of 291 turtles were observed across the western Gulf, distributed along its entire western margin. The highest densities were recorded between the Navy Pier and Golf Club Beach as well as in Gales Bay.
- A total of 15 sea snakes were observed across the western Gulf, distributed sparsely along its western margin.
- A total of 363 vessels, 341 recreational and 22 commercial vessels, were observed along the western margin of the Gulf. The highest densities were recorded between the Navy Pier and Pebble Beach, coinciding with areas of high human population density and convenient vessel launch locations. The highest numbers of vessels (70) were recorded during the school holiday period, September 23 – October 8, 2023.
- Areas of high vessel activity overlapped with areas of high wildlife density for humpback whales, manta rays and turtles. These overlap zones represent areas of elevated risk for vessel strikes and potential impacts of vessel noise on these species.

The waters along the western margin of Exmouth Gulf are important habitat for numerous marine megafauna species. This area also experiences significant levels of anthropogenic activity, including boating, due to its proximity to residential areas and the availability of boat launching facilities. This spatial overlap between marine megafauna habitat and boating activity increases the potential for human-wildlife interactions such as vessel strikes, habitat disturbance and noise disturbance. Marine mammals and marine reptiles are particularly vulnerable to vessel strikes due to their physiological need to surface for breathing. Similarly, manta rays are at risk as they frequently feed at, or near, the water's surface. Additionally, the resting and milling behaviours exhibited by the majority of humpback whales further increase their susceptibility to disturbance or injury from vessel activity.

To mitigate the risk of vessel strikes on marine megafauna and minimise the negative behavioural and physiological impacts of vessel noise, management strategies such as vessel speed restrictions or designated vessel-use zones are recommended. Additionally, current levels of anthropogenic activity should be incorporated into cumulative impact assessments for any proposed future developments.

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2. Introduction

2.1. Background

Exmouth Gulf (the Gulf), located on the northwest coast of Western Australia, is an area of high ecological importance, supporting a diverse array of conservation-significant species (Sutton and Shaw, 2021). Its sheltered waters provide critical feeding, nursing, and calving habitats for numerous marine mammal species, including humpback whales (*Megaptera novaeangliae*), dugongs (*Dugong dugon*), Indo-Pacific bottlenose dolphins (*Tursiops aduncus*), and Australian humpback dolphins (*Sousa sahulensis*). These species are protected under the Western Australian *Biodiversity Conservation Act 2016* and the Commonwealth *Environment Protection and Biodiversity Act 1999* (*EPBC Act*). Additionally, the Gulf hosts marine turtles such as green (*Chelonia mydas*), hawksbill (*Eretmochelys imbricata*), flatback (*Natator depressus*) and loggerhead turtles (*Caretta caretta*), each listed as Vulnerable under state and commonwealth legislation.

Internationally, the Gulf is recognised as an Important Marine Mammal Area (IMMA) by the Marine Mammal Protected Areas Task Force (MMPATF) due to its significance as a feeding and nursing / calving habitat for Australian humpback dolphins, dugongs and Indo-Pacific bottlenose dolphins as well as its role as a nursery for humpback whales (IUCN-MMPATF, 2022). Nationally, it is identified as a Biologically Important Area (BIA) for several species such as humpback and southern right whales (*Eubalaena australis*), dugongs, and multiple turtle species. Additionally, the Gulf is under assessment as a BIA for both Australian humpback and Indo-Pacific bottlenose dolphins, further highlighting its conservation value.

The western margin of the Gulf, adjacent to the Ningaloo Coast World Heritage Area, is particularly unique and diverse (Fitzpatrick et al., 2019), and hosts multiple megafauna species such as humpback whales, manta rays (*Mobula alfredi*), and sea turtles (e.g. Irvine and Salgado Kent, 2019, Armstrong et al., 2020). Between July and October, Exmouth Gulf becomes particularly important, as humpback whales migrate to the area for biologically important activities including mating, resting and nursing (Jenner and Jenner, 2005, Irvine and Salgado Kent, 2019).

However, the Gulf also experiences significant human activity, including recreational boating, commercial fishing, and tourism, which pose risks to wildlife, such as vessel strikes, noise pollution, and habitat disturbance. Recognising the overlap between ecological values and human impacts, a survey was conducted from July to October 2023 to determine the occurrence patterns of marine megafauna and their spatial overlap with boat activity along the Gulf's western margin. This study aimed to document spatial and temporal patterns of key species, identify potential human-wildlife conflicts, and provide data to inform management decisions. The findings will contribute to ongoing conservation planning efforts to balance the Gulf's ecological integrity with sustainable human use.

2.2 Previous studies

Numerous studies have investigated the distribution and abundance of marine fauna in the Gulf, spanning various spatial scales (**Table 2-1**). These range from localised studies focusing on small areas within the Gulf (e.g. Cleguer et al., 2021) to surveys encompassing the entire Gulf (e.g. Irvine and Salgado Kent, 2019) and broader scale regional studies extending beyond its boundaries (e.g. Raudino et al., 2023). While some studies have documented a wide range of megafauna (e.g. Jenner and Jenner, 2005, Irvine and Salgado Kent, 2019), most have focused on specific species or taxonomic groups, such as dugongs or delphinids, tailored to particular research objectives (e.g. Hunt et al., 2017).

Recent conservation initiatives by the State Government have prioritised protecting the eastern and southern sections of the Gulf. However, the western margin experiences high levels of human activity due to its proximity to infrastructure, such as boat ramps, and is considered a high-risk area for potential human-wildlife interactions. While targeted studies have been conducted along sections of the western Gulf (e.g. Fitzpatrick et al., 2019, Sprogis and Waddell, 2022, Sprogis and Parra, 2023) to investigate its importance to marine wildlife, these have been spatially limited and have not quantified boating activity in the area.

In 2023 a broader survey program was undertaken to investigate the distribution and abundance of marine megafauna along the entire western margin of Exmouth Gulf during the late July to early October period. This program also incorporated an analysis of vessel activity to identify areas of overlap between human use and wildlife habitats. Conducted as a complementary effort to on-going aerial surveys in the adjacent Ningaloo Marine Park, this program provides valuable insights into human-wildlife interactions in the area.

Table 2-1. Studies investigating the distribution and abundance of marine megafauna in Exmouth Gulf.

Year	Title
(Ingelbrecht et al., 2024)	Evidence of long-distance movement of green sawfish (*Pristis zijsron*) in Western Australia.
(Lear et al., 2024)	The secret lives of wedgefish: first insights into fine-scale behaviour and movement ecology of a globally imperilled ray.
(Sprogis et al., 2024)	Spatiotemporal distribution of humpback whales off north-west Australia quantifying the Exmouth Gulf nursery area.
(Lear et al., 2023)	Growth and morphology of Critically Endangered green sawfish *Pristis zijsron* in globally important nursery habitats.
(Raudino et al., 2023)	Aerial abundance estimates for two sympatric dolphin species at a regional scale using distance sampling and density surface modeling.
(Sprogis and Parra, 2023)	Coastal dolphins and marine megafauna in Exmouth Gulf, Western Australia: informing conservation management actions in an area under increasing human pressure.
(Tucker, 2023)	Extending aerial surveys beyond target marine mammal species: an application of strip transect methodology to humpback whale and dugong abundance estimation in Exmouth Gulf, Western Australia.
(Hanf et al., 2022)	Dolphin Distribution and Habitat Suitability in North Western Australia: Applications and Implications of a Broad-Scale, Non-targeted Dataset.
(Raudino et al., 2022)	Species identification of morphologically similar tropical dolphins and estimating group size using aerial imagery in coastal waters.
(Sprogis and Waddell, 2022)	Marine mammal distribution on the western coast of Exmouth Gulf, Western Australia.
(Cleguer et al., 2021)	A Novel Method for Using Small Unoccupied Aerial Vehicles to Survey Wildlife Species and Model Their Density Distribution.
(Armstrong et al., 2020)	Satellite Tagging and Photographic Identification Reveal Connectivity Between Two UNESCO World Heritage Areas for Reef Manta Rays.
(Haughey et al., 2020)	Photographic Capture-Recapture Analysis Reveals a Large Population of Indo-Pacific Bottlenose Dolphins (*Tursiops aduncus*) With Low Site Fidelity off the North West Cape, Western Australia.
(Hunt et al., 2020)	Identifying priority habitat for conservation and management of Australian humpback dolphins within a marine protected area.
(Irvine and Salgado Kent, 2019)	The distribution and relative abundance of marine mega-fauna, with a focus on humpback whales (*Megaptera novaeangliae*) in Exmouth Gulf, Western Australia, 2018.
(Bayliss et al., 2018)	Dugong (*Dugong dugon*) population and habitat survey of Shark Bay Marine Park, Ningaloo Reef Marine Park and Exmouth Gulf.
(Hunt et al., 2017)	Demographic characteristics of Australian humpback dolphins reveal important habitat toward the southwestern limit of their range.
(Sobtzick et al., 2015)	Chevron Wheatstone Project Dugong Research Program: Phase 2, 2014 Final Report.
(Sobtzick et al., 2014)	Chevron Wheatstone Project Dugong Research Program: Phase 2, 2013 Final Report.
(Hodgson et al., 2013)	Chevron Wheatstone Project Dugong Research Program: Phase 1 Final Report.
(Brown et al., 2012)	The North West Cape, Western Australia: A Potential Hotspot for Indo-Pacific Humpback Dolphins *Sousa chinensis*?
(Hodgson, 2007)	The distribution, abundance and conservation of dugongs and other marine megafauna in Shark Bay Marine Park, Ningaloo Reef Marine Park and Exmouth Gulf.
(Jenner and Jenner, 2005)	Distribution and abundance of humpback whales and other mega-fauna in Exmouth Gulf, Western Australia, during 2004/2005.
(Gales et al., 2004)	Change in abundance of dugongs in Shark Bay, Ningaloo and Exmouth Gulf, Western Australia: evidence for large-scale migration.
(Preen et al., 1997)	Distribution and Abundance of Dugongs, Turtles, Dolphins and other Megafauna in Shark Bay, Ningaloo Reef and Exmouth Gulf, Western Australia.

3. Materials and Methods

3.1. Study area

Exmouth Gulf (the Gulf) is a northward-facing embayment situated on the eastern side of North West Cape between latitudes 21°45’ and 22°33’ (Figure 1). Covering an area of approximately 4000 km^2, the Gulf is characterised by relatively turbid waters (Cartwright et al., 2021) and shallow depths, with a mean depth of less than 20 metres. The waters are shielded from open-ocean swells by the protective barrier formed by the North West Cape and the islands at the Gulf's entrance (Fitzpatrick et al., 2019).

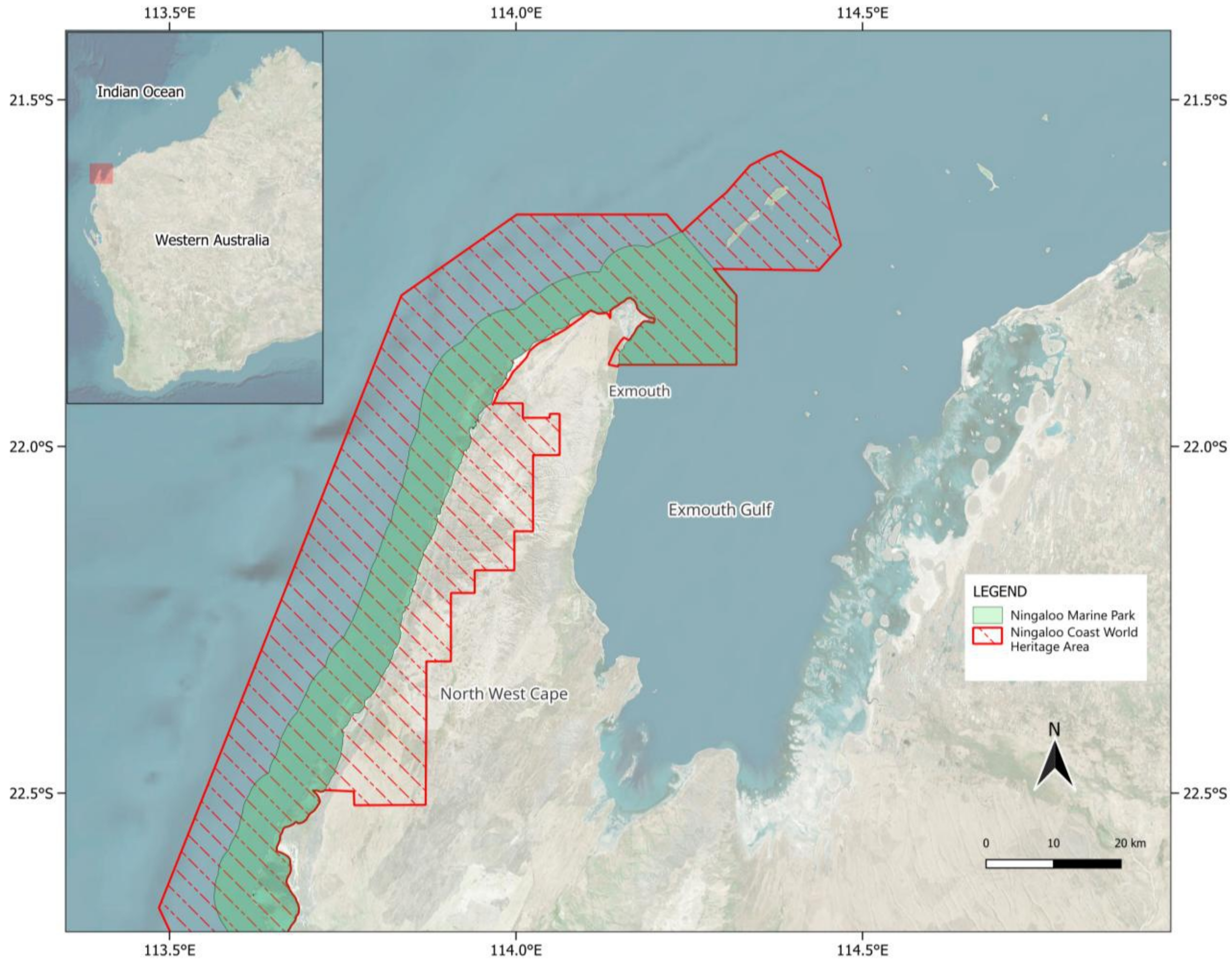

Figure 3-1. Location of the study area of Exmouth Gulf, along the north-west coast of Western Australia.

3.2 Survey Design

The aerial surveys were designed to encompass the western margin of the Gulf. The survey design consisted of six straight line transects, that roughly followed the western coastline between Point Murat and Gales Bay (**Figure 3-2**). Surveys were conducted between 28 July and 5 October 2023, approximately every eight days when weather conditions were favourable.

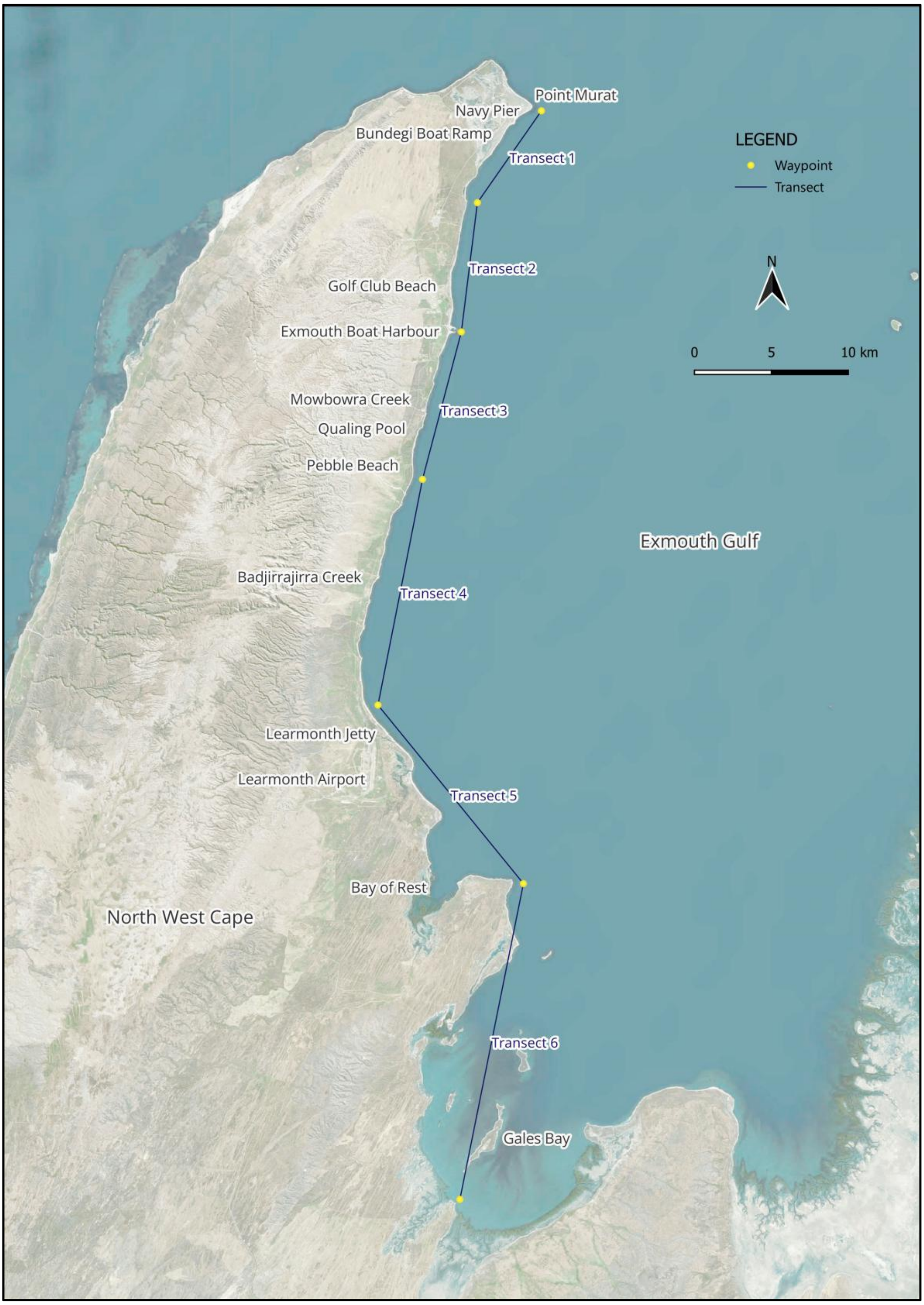

Figure 3-2. Map of the survey design for megafauna along the western margin of Exmouth Gulf.

3.3 Data Collection

The surveys were conducted using a single engine, high wing aircraft (Cessna 172), flying at an altitude of 152m (500 ft) and a speed of 176 km hr^{-1} (95 knots). Survey personnel consisted of a pilot and two observers linked via an intercom system that could be isolated from the pilot when necessary. Observations were recorded on a time-coded digital sound recorder synchronised to a hand-held GPS that provided coordinates every second during the flight. All devices (including a digital camera) were calibrated to ±1 sec accuracy prior to each flight. Angle of drift of the aircraft from the flight path (Lerczak and Hobbs, 1998) was recorded by the pilot. All observations were collected in passing mode, where observations were recorded without deviating from the transect line.

For marine mammals (whales, dolphins and dugongs), observers recorded the location of each pod sighted, in relation to the aircraft by recording the vertical angle down from the horizon (using *Suunto* PM-5/360PB clinometers), and the horizontal angle (using a compass board) from the aircraft's travel direction to the whale. The position of each group of marine mammals was calculated post survey following Salgado-Kent *et al.* (2012). In addition to location, observers recorded group size, group composition, behaviour, and direction of travel. Group composition was described in terms of the number of adults and calves present. Here, a calf was defined as an individual within close proximity to another whale and visually estimated to be less than 2/3rds of the length of the accompanying animal (Clapham, 1999). Behaviour was categorised as travelling, milling, resting or undetermined.

For marine reptiles (turtles and sea snakes) and elasmobranchs (sharks and rays) locations were recorded when the animals were abeam of the aircraft; for mapping purposes vertical angles were assumed to be 50 degrees (at 500ft this is a distance of 128m from the transect line). This is a variation of strip sampling and was conducted in this manner as there were too many individual animals to record vertical angles at the travel speed of the aircraft. It is assumed that small animals such as these can only be seen out to a distance of 200 m - the maximum distance at which complete detection of dugongs is assumed (Pollock et al., 2006).

At the beginning of each transect, the following environmental conditions were recorded: sea state (Beaufort scale) (Appendix A: **Table 8-1**), wind speed (knots), wind direction, cloud cover (oktas), visibility, turbidity (Appendix A: **Table 8-2**) and glare intensity and coverage on each side of the aircraft. These conditions were updated during the transect whenever they changed. Surveys were planned for weather conditions of Beaufort sea state ≤3 as the high windspeed and extensive white caps in higher Beaufort conditions (sea state ≥4) typically restrict sightings to surface active species and individuals (e.g. humpback whales breaching or tail slapping).

3.4 Data Analysis

The position (latitude and longitude) of each group of whales was calculated post survey using the R function 'destPoint' in the package *geosphere* in R v4.4.1 (R Development Core Team, 2017). 'destPoint' requires radial distances from the position at the track line in which the observation was made. Distances were calculated by: RD = $h * tan(\theta)$, where RD is the radial distance, h is the height of the observer from the surface of the ocean, and θ is the vertical angle up to the group from directly below the aircraft (calculated by subtracting the declination angle from the horizon from 90°) (Lerczak and Hobbs, 1998). The measured angles from the aircraft to the group were corrected for the course: $AW = AC + MHA$, where *AW* is the true angle to the whale, *AC* is the aircraft's course, *MHA* the measured horizontal angle (as defined and described in Lerczak and Hobbs, 1998 and applied in Salgado Kent et al. 2012).

The positions of all sightings were plotted in QGIS version 3.38.3. Kernel density plots were produced, using the kernel density estimation tool, to visually show the magnitude of relative abundance per unit area surveyed, using the kernel function to fit a smooth surface to observation points. A Geodesic method was used with an output cell size of 50 m and radius of 1000 m. The analyses here do not include absolute estimates that adjust for imperfect detection, using distance sampling techniques.

4. RESULTS

A total of 10 surveys were conducted between 28 July and 5 October 2023 (Table 1). The majority of surveys were completed in a Beaufort Sea State ≤3, other than transect 4 in survey 4 which was completed in a Beaufort Sea State of 4 (as the wind speed increased, contrary to the forecast, in this section of the survey). The results from this section of the survey will be under-estimates of the smaller megafauna, as they are difficult to see amongst the white caps generated in force 4 seas. Additionally, some small sections of transect 4 were dry in surveys 2 and 3 as the surveys coincided with low tide. These surveys were designed to complement on-going studies in the Ningaloo Marine Park and were scheduled around those pre-existing efforts.

Table 4-1. Aerial surveys completed in Exmouth Gulf between 28 July and 5 October 2023.

Date	Survey Number	Transects completed	Beaufort sea state	Comments
28/07/23	1	1 - 6	1 - 3	
31/07/23	2	1 - 6	0 - 3	T4 dry at times on port side
08/08/23	3	1 - 6	1 - 2	T4 dry at start on both sides
14/08/23	4	1 - 6	3 - 4	
22/08/23	5	1 - 6	1 - 3	
31/08/23	6	1 - 6	1	
09/09/23	7	1 - 6	1 - 3	
16/09/23	8	1 - 6	1 - 2	
26/09/23	9	1 - 6	1 - 2	
05/10/23	10	1 - 6	1 - 2	

4.1. Humpback whales

4.1.1. Relative abundance and distribution

A total of 483 individuals in 310 groups were sighted in Exmouth Gulf during the ten surveys conducted between 28 July and 5 October 2023 (Table 2). This consisted of between 3 and 105 humpback whales in 3 and 72 groups respectively, sighted each survey. Humpback whale numbers were low in late July / early August and increased steadily throughout August and early September until peak numbers were observed in mid-September (16 Sep 2023). Following the peak, numbers gradually decreased throughout late September and early October when the surveys finished (**Table 4-2**).

Humpback whale calves were sighted in eight of the ten surveys, with a total of 88 calves being observed throughout the survey period. Calves were first sighted on the second survey (31 July 2023) and were in low numbers until late August (31 August 2023) when their numbers started to increase. The total number of calves peaked in mid-late September before decreasing in late September and into October when the surveys finished (**Table 4-2**).

Calves were present in an average of 28.4% of all groups sighted. The percentage of humpback whale groups containing a calf was low during July and August and increased during September and into October when the surveys finished (**Table 4-2**).

Table 4-2. Numbers of humpback whales sighted each survey.

Date	Survey Number	Humpback groups	No. whales	No. calves
28/07/2023	1	3	3	0
31/07/2023	2	14	28	4
08/08/2023	3	19	28	0
14/08/2023	4	24	40	3
22/08/2023	5	14	21	1
31/08/2023	6	48	75	10
09/09/2023	7	53	72	12
16/09/2023	8	72	105	25
26/09/2023	9	39	71	20
05/10/2023	10	24	40	13
Total	10	310	483	88

The majority of humpback whale groups (72.9%) were milling or resting; 24.8% were travelling; and 2.3% had an undefined behaviour (**Table 4-3**).

Table 4-3. Behaviour of humpback whale groups in Exmouth Gulf.

Date	Survey Number	Humpback groups	Groups travelling	Groups milling	Groups resting	Groups undefined
28/07/2023	1	3	2	1	0	0
31/07/2023	2	14	0	6	8	0
08/08/2023	3	19	1	3	15	0
14/08/2023	4	24	5	9	8	2
22/08/2023	5	14	5	3	6	0
31/08/2023	6	48	17	5	23	3
09/09/2023	7	53	8	11	33	1
16/09/2023	8	72	21	11	39	1
26/09/2023	9	39	7	6	26	0
05/10/2023	10	24	11	1	12	0
Total	10	310	77	56	170	7

Humpback whales were distributed along the entire western edge of the Gulf, except for the shallow waters of Gales Bay at the southern end of the Gulf. Both calf and non-calf groups were found in these areas (**Figure 4-1**). The highest densities of humpback whales were found off the Navy Pier, the southern end of the Ningaloo Marine Park to Golf Club Beach, Mowbowra Creek to Qualing Pool, Pebble Beach, Badjirrajirra Creek and Learmonth Jetty to the Bay of Rest (**Figure 4-1**).

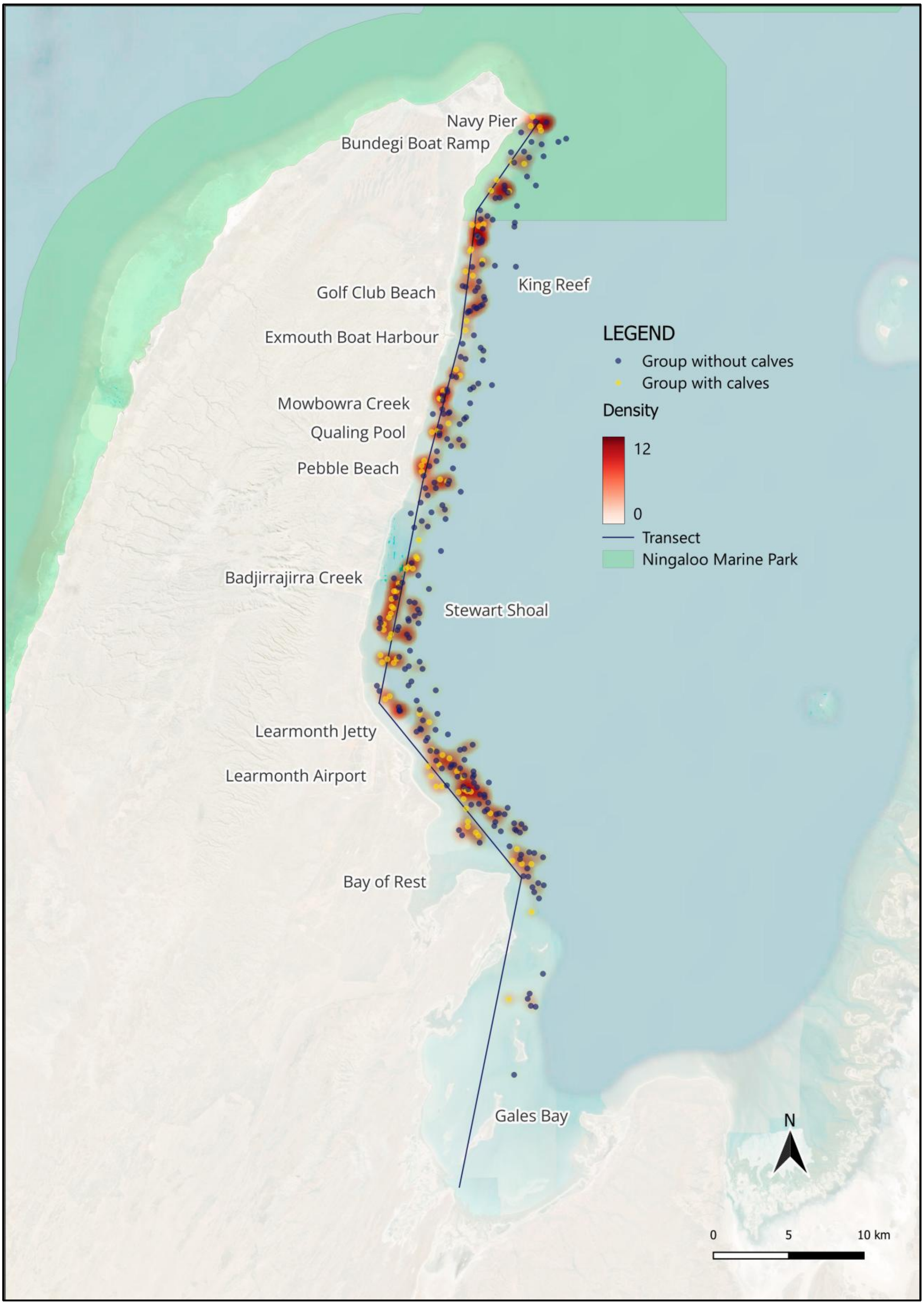

Figure 4-1. Distribution of humpback whales along the western margin of Exmouth Gulf during aerial surveys. Transects are marked in black lines.

4.2. Dugongs

4.2.1. Relative abundance and distribution

A total of 59 dugongs, including nine calves, in 47 groups were sighted in Exmouth Gulf during the during the ten surveys conducted between 28 July and 05 October 2023 (**Table 4-4**). This consisted of between 1 and 17 dugongs in 1 and 12 groups, respectively, observed each survey (**Table 4-4**).

Dugong numbers oscillated between July and September with highest numbers occurring in late August and late September (**Table 4-4**). Dugong calves were sighted on four of the ten surveys, with the nine calves constituting 15.3% of all individuals sighted during the surveys. The highest number of calves (n=4) were seen on 28 August 2023. The number of dugong calves could have been underestimated as they are difficult to sight due to their small size and the surveys were not carried out in closing mode (i.e. leaving transect to circle a group of interest) to confirm group size and composition.

The majority of dugong groups (46.8%) were travelling; 38.3% were milling or resting; and 14.9% had an undefined behaviour (**Table 4-4**).

Table 4-4. The number of dugongs sighted each survey along with the behaviour of each group.

Date	Survey Number	Dugong groups	No. dugongs	No. calves	Groups travelling	Groups milling	Groups resting	Groups undefined
28/07/2023	1	0	0	0	0	0	0	0
31/07/2023	2	5	5	0	2	0	1	2
08/08/2023	3	6	7	1	3	0	1	2
14/08/2023	4	1	1	0	0	0	0	1
22/08/2023	5	12	17	4	4	4	4	0
31/08/2023	6	7	9	2	5	0	2	0
09/09/2023	7	4	4	0	3	1	0	0
16/09/2023	8	5	6	0	2	3	0	0
26/09/2023	9	7	10	2	3	2	0	2
05/10/2023	10	0	0	0	0	0	0	0
Total	10	47	59	9	22	10	8	7

Dugongs were distributed along most of the western edge of the Gulf, other than the Bay of Rest (**Figure 4-2**). The highest densities of dugongs were found between Pebble Beach and Badjirrajirra Creek and in Gales Bay (**Figure 4-2**). Calf groups were found in these two high density areas plus the southern border of the Ningaloo Marine Park (**Figure 4-2**).

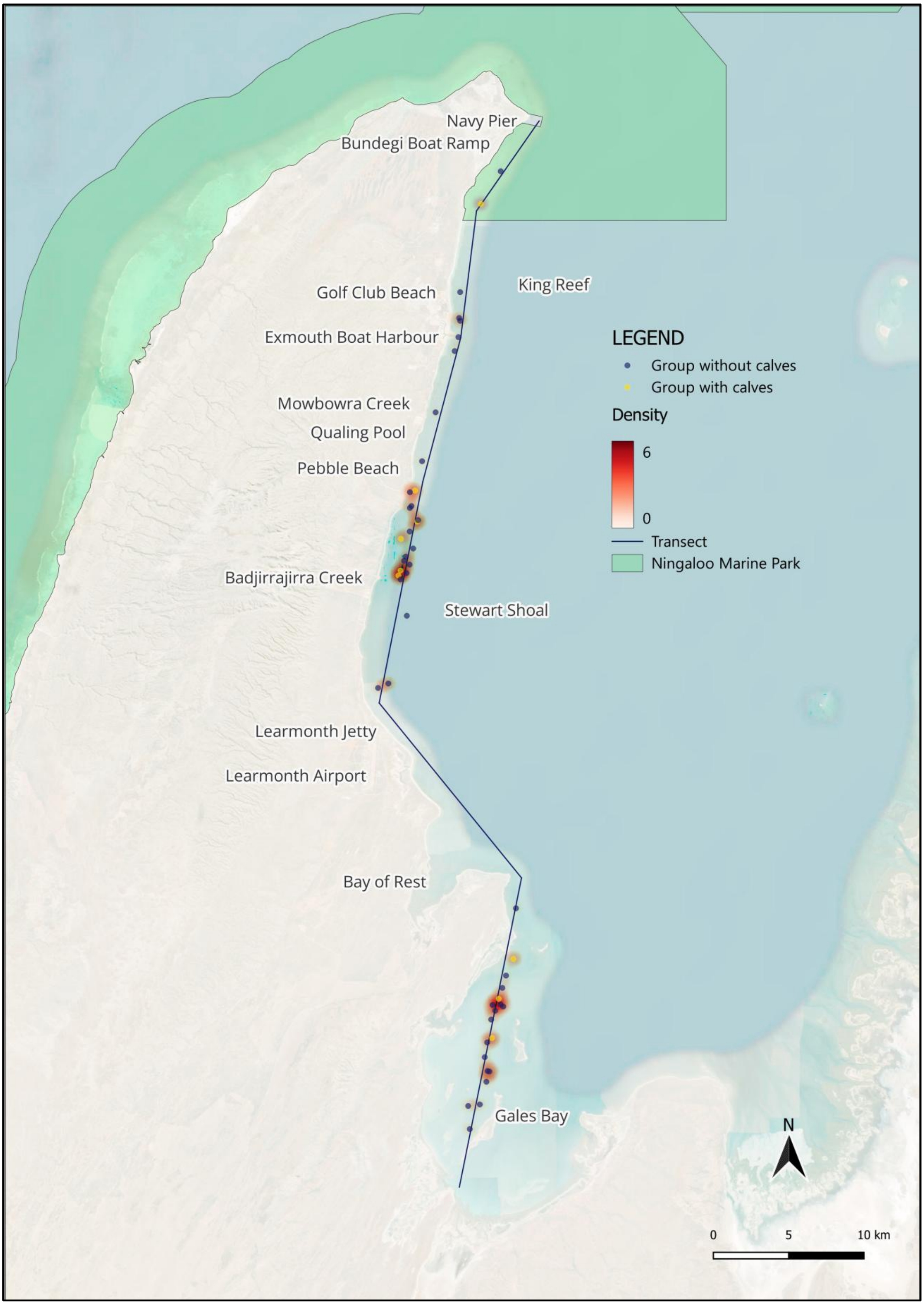

Figure 4-2. Distribution of dugongs along the western margin of Exmouth Gulf during aerial surveys. Transects are marked in black lines.

4.3. Dolphins

4.3.1. Relative abundance and distribution

A total of 126 dolphins (including 15 calves) in 42 pods were sighted in Exmouth Gulf during the ten surveys conducted between 28 July and 5 October 2023 (**Table 4-5**). This consisted of between 3 and 35 dolphins in 1 and 9 pods, respectively, observed each survey (**Table 4-5**). Both Indo-Pacific bottlenose and Australian humpback dolphins were observed during the surveys, however not reported in detail here as the surveys were not conducted in closing mode (i.e. leaving transect to circle a group of interest) to enable identification of all pods to species level.

Dolphin numbers oscillated between July and October with high numbers in late July/early August and mid-September (**Table 4-5**). Dolphin calves were sighted on four out of the ten surveys and constituted 11.9% of the dolphins sighted during the survey period (**Table 4-5**). The number of dolphin calves could have been underestimated as they are difficult to sight due to their small size and the surveys were not carried out in closing mode.

The majority of dolphin groups (52.4%) were milling or resting; 45.2% were travelling; and 2.4% had an undefined behaviour (**Table 4-5**).

Table 4-5. Numbers of dolphins sighted each survey along with the behaviour of each group.

Date	Survey Number	Dolphin pods	No. dolphins	No. calves	Groups travelling	Groups milling	Groups resting	Groups undefined
28/07/2023	1	2	8	0	2	0	0	0
31/07/2023	2	9	35	0	2	7	0	0
08/08/2023	3	3	14	1	1	2	0	0
14/08/2023	4	3	6	0	1	2	0	0
22/08/2023	5	2	4	0	1	0	1	0
31/08/2023	6	7	10	0	5	2	0	0
09/09/2023	7	4	16	4	2	2	0	0
16/09/2023	8	9	25	9	2	6	0	1
26/09/2023	9	2	3	1	2	0	0	0
05/10/2023	10	1	5	0	1	0	0	0
Total	10	42	126	15	19	21	1	1

Dolphins had a broad distribution along most of the western edge of the Gulf (**Figure 4-3**). Calf groups were found off Bundegi Boat Ramp, south of Pebble Beach, Learmonth Jetty, south of the Bay of Rest and in Gales Bay (**Figure 4-3**). The highest densities of dolphins were found south of the Bay of Rest and in Gales Bay (**Figure 4-3**).

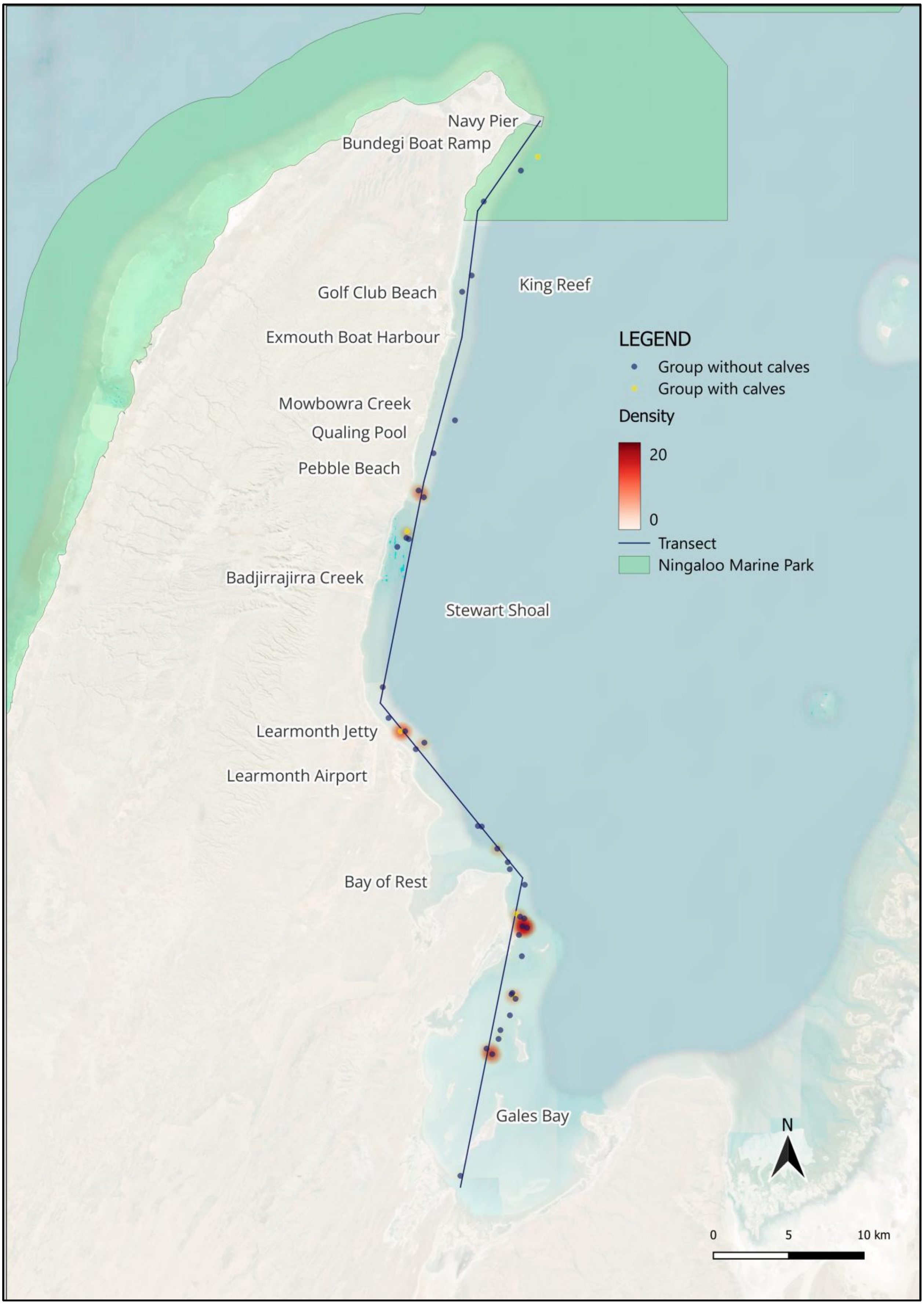

Figure 4-3. Distribution of dolphins along the western margin of Exmouth Gulf during aerial surveys. Transects are marked in black lines.

4.4. Turtles

4.4.1. Relative abundance and distribution

A total of 291 turtles were sighted in Exmouth Gulf during the ten surveys conducted between 28 July and 05 October 2023 (**Table 4-6**). This ranged between 10 and 70 turtles in each survey (**Table 4-6**), with highest numbers being observed in late August to early October (**Table 4-6**). Turtles observed during the surveys could not be identified to species level. However, based on findings from previous vessel-based surveys, the majority of the turtles sighted are likely green turtles, with hawksbill turtles predominantly occurring in the shallow mangrove areas (Jenner and Jenner, 2005); loggerhead turtles (*Caretta caretta*) may have also been present (Sprogis and Waddell, 2022).

Turtles were distributed along the entire west coast of Exmouth Gulf, with the highest densities in an area between the Navy Pier and Bundegi Boat Ramp, the southern boundary of the Ningaloo Marine Park, Golf Club Beach, Mowbowra Creek, and in Gales Bay (**Figure 4-4**).

Table 4-6. Numbers of marine reptiles (turtles and sea snakes) sighted each survey.

Date	Survey Number	Turtles	Sea snakes
28/07/2023	1	11	1
31/07/2023	2	18	0
08/08/2023	3	10	0
14/08/2023	4	12	0
22/08/2023	5	48	2
31/08/2023	6	41	4
09/09/2023	7	19	0
16/09/2023	8	70	1
26/09/2023	9	39	4
05/10/2023	10	23	3
Total	10	291	15

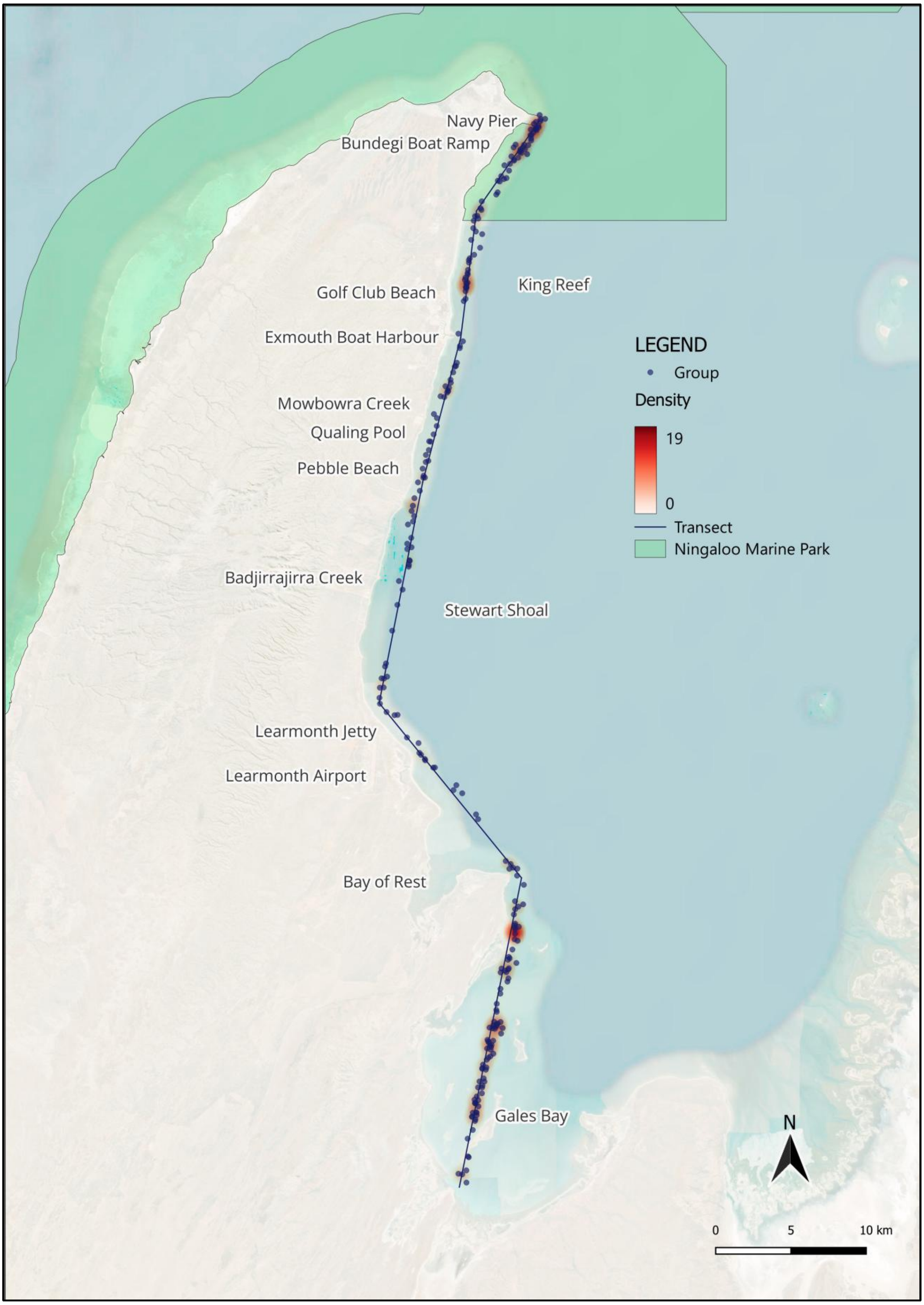

Figure 4-4. Distribution of turtles along the western margin of Exmouth Gulf during aerial surveys. Transects are marked in black lines.

4.5. Sea snakes

4.5.1. Relative abundance and distribution

A total of 15 sea snakes were sighted in Exmouth Gulf during the ten surveys conducted between 28 July and 5 October 2023 (**Table 4-6**). This ranged between 0 and 4 sea snakes in each survey (**Table 4-6**). Sea snakes were distributed sparsely along the west coast of Exmouth Gulf, with the highest densities south-west of Stewart Shoal and in north-west Gales Bay (**Figure 4-5**).

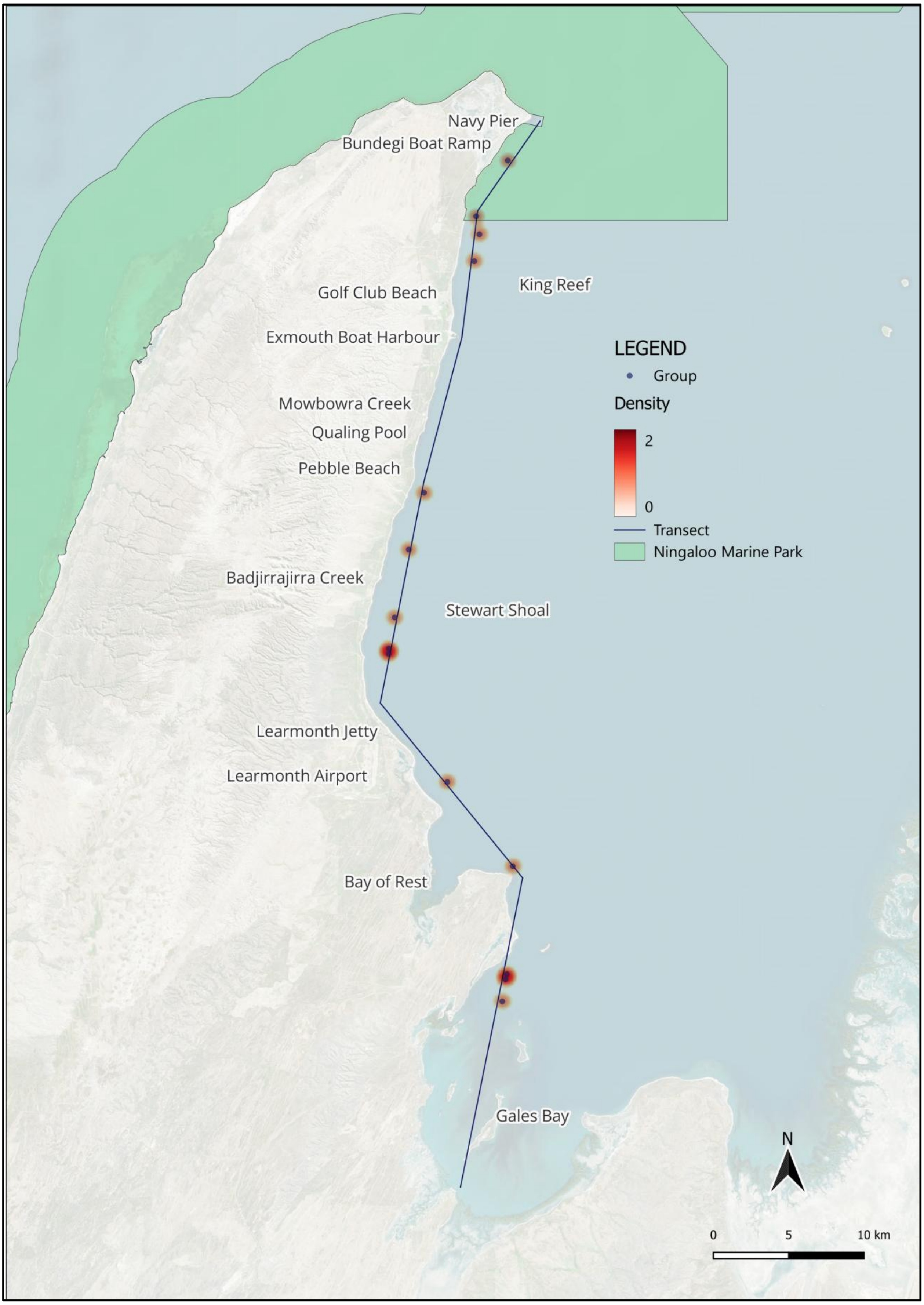

Figure 4-5. Distribution of sea snakes along the western margin of Exmouth Gulf during aerial surveys. Transects are marked in black lines.

4.6. Manta rays and other rays

4.6.1. Relative abundance and distribution

A total of 128 manta rays were sighted in Exmouth Gulf during the ten surveys conducted between 28 July and 5 October 2023 (**Table 4-7**). This ranged between 0 and 41 manta rays in each survey, with the highest numbers being observed between late August and late September (**Table 4-7**). Manta rays were identified by their distinctive shape and white cephalic lobes; however, it is possible that some were assessed as eagle rays in the highly turbid waters in the southern Gulf, and thus not documented.

Manta rays were distributed along the west coast of Exmouth Gulf between Bundegi boat ramp and south Pebble Beach (**Figure 4-6**). The highest densities were between the southern boundary of the Ningaloo Marine Park and Golf Club Beach. High densities were also found between Golf Club Beach and Exmouth Boat Harbour, Mowbowra Creek and Pebble Beach.

Table 4-7. Numbers of elasmobranchs (manta rays, other rays and sharks) sighted on each survey.

Date	Survey Number	Mantas	Other rays	Sharks
28/07/2023	1	3	1	0
31/07/2023	2	0	1	1
08/08/2023	3	4	2	0
14/08/2023	4	1	7	1
22/08/2023	5	8	2	0
31/08/2023	6	32	3	0
09/09/2023	7	41	4	1
16/09/2023	8	3	0	5
26/09/2023	9	31	10	2
05/10/2023	10	5	7	2
Total	10	128	37	12

A total of 37 'other' rays were sighted in Exmouth Gulf during the ten surveys conducted between 28 July and 05 October 2023 (**Table 4-7**). This ranged between 0 and 10 rays in each survey (**Table 4-7**). Rays, other than mantas, were found mainly in Gales Bay (**Figure 4-7**).

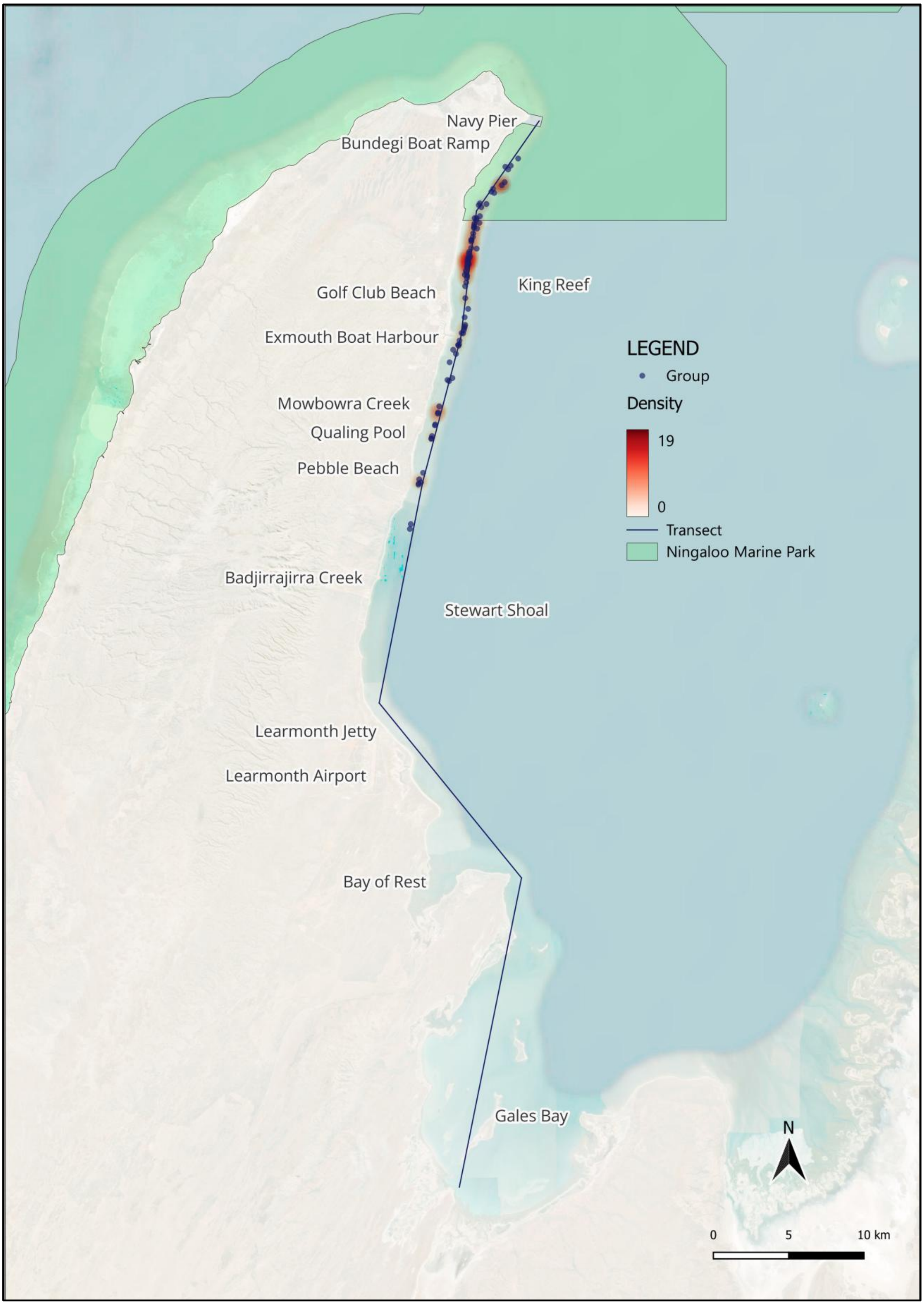

Figure 4-6. Distribution of manta rays along the western margin of Exmouth Gulf during aerial surveys. Transects are marked in black lines.

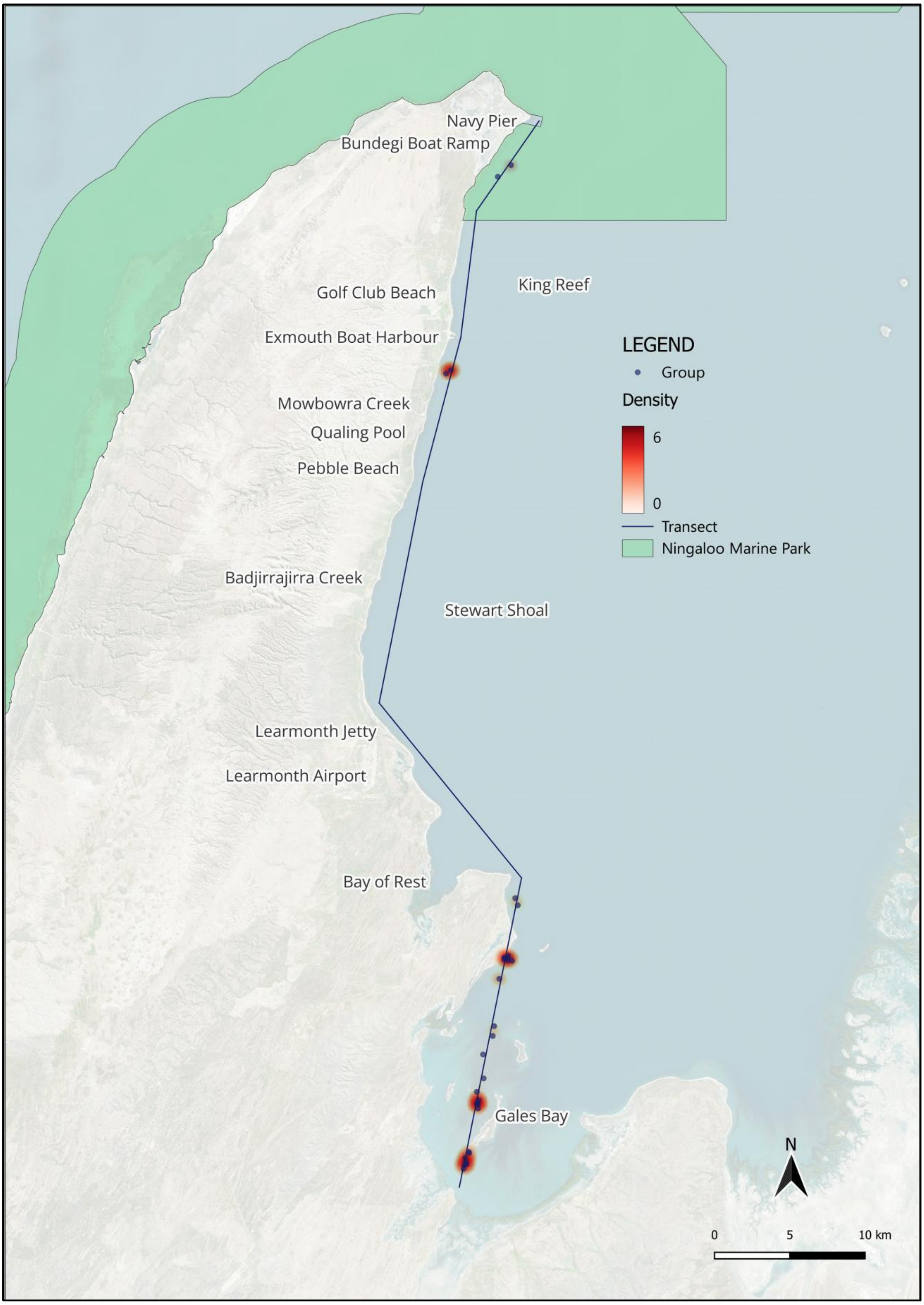

Figure 4-7. Distribution of rays, other than mantas, along the west coast of Exmouth Gulf during aerial surveys. Transects are marked in black lines.

4.7. Sharks

4.7.1. Relative abundance and distribution

A total of 12 sharks were sighted in Exmouth Gulf during the ten surveys conducted between 28 July and 05 October 2023 (**Table 4-7**). This ranged between 0 and 5 sharks in each survey (**Table 4-7**). Sharks were distributed sparsely along the western margin of Exmouth Gulf with the highest density in Gales Bay (**Figure 4-8**).

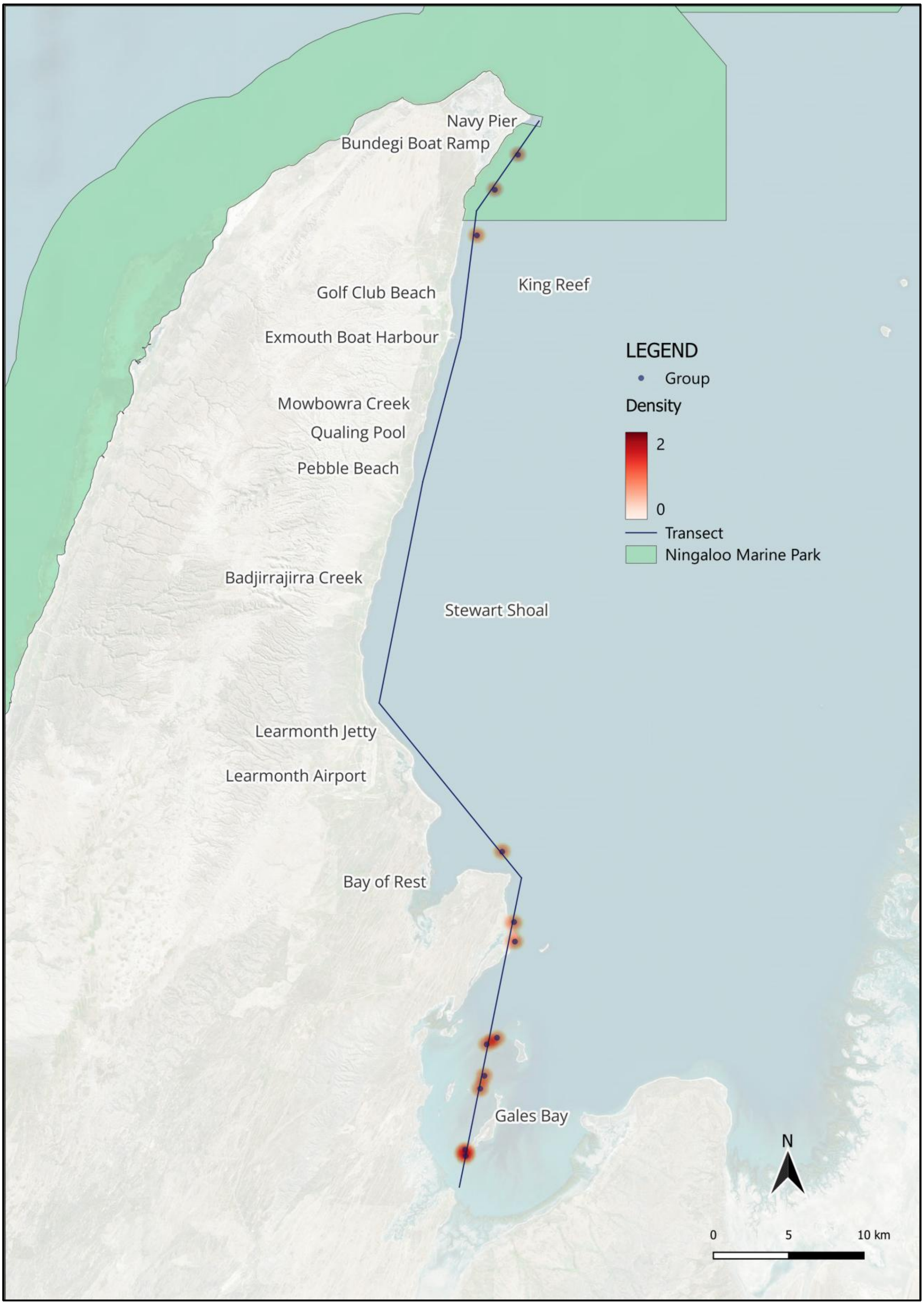

Figure 4-8. Distribution of sharks along the western margin of Exmouth Gulf during aerial surveys. Transects are marked in black lines.

4.8. Vessels

4.8.1. Relative abundance and distribution

A total of 363 vessels (341 recreational and 22 commercial vessels) were sighted in the Gulf during the ten surveys conducted between 28 July and 5 October 2023 (**Table 4-8**). This ranged between 6 vessels (5 recreational and 1 commercial) and 70 (65 recreational and 5 commercial) vessels, in each survey (**Table 4-8**). Vessel activity was relatively low until mid-August, after which it began to increase, peaking in late September and early October during the Western Australian school holidays.

Vessels were distributed along most of the western margin of Exmouth Gulf with high density activity between the Navy Pier and Pebble Beach. The highest density area was around Exmouth Boat Harbour with other high-density areas recorded between the Navy Pier and Bundegi Boat Ramp, near the southern boundary of the Ningaloo Marine Park and Golf Club Beach. The area between Mowbowra Creek and Pebble beach also experienced relative high densities of vessel activity (**Figure 4-9**). These high-density areas are near the main residential areas of Exmouth and centred at locations where vessels can be launched, either from boat ramps or beaches.

Table 4-8. Numbers of vessels sighted on each survey.

Date	Survey Number	Recreational vessels	Commercial vessels
28/07/2023	1	5	1
31/07/2023	2	29	1
08/08/2023	3	15	3
14/08/2023	4	13	2
22/08/2023	5	41	3
31/08/2023	6	41	1
09/09/2023	7	30	3
16/09/2023	8	35	0
26/09/2023	9	65	5
05/10/2023	10	67	3
Total	10	341	22

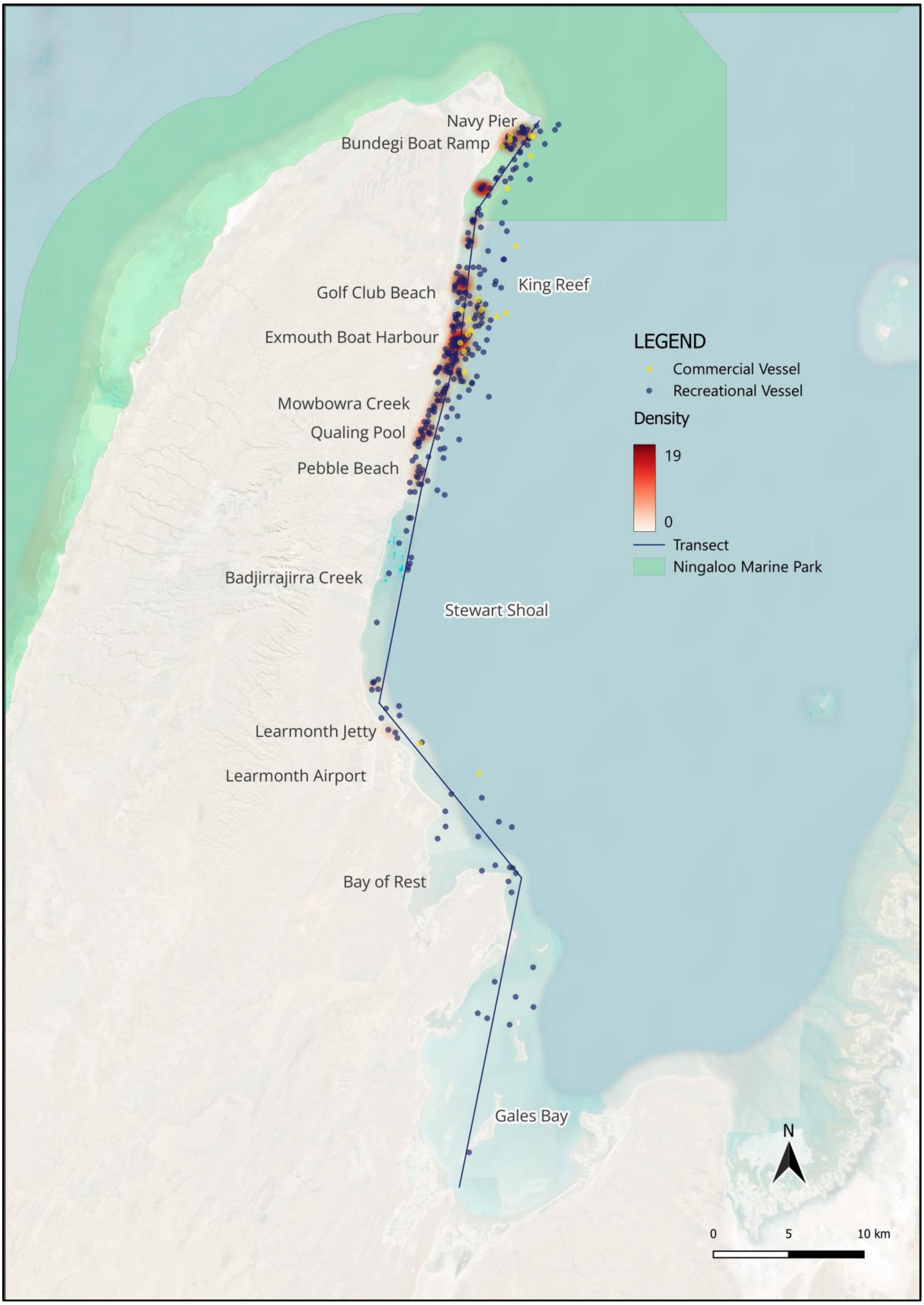

Figure 4-9. Distribution of vessels (recreational and commercial) along the western margin of Exmouth Gulf during aerial surveys. Transects are marked in black lines.

4.9. Overlap between vessels and marine fauna habitat

Observations of marine megafauna and vessels for each survey are presented in Appendix B (**Figure 8-1- Figure 8-10**). These figures show high numbers of wildlife and vessel from survey 5 (22 August) to survey 10 (5 October). More specifically, the pattern of boating activity - low until mid-August followed by a marked increase - is similar to the occurrence patterns of humpback whales, manta rays and turtles (**Figure 4-10**).

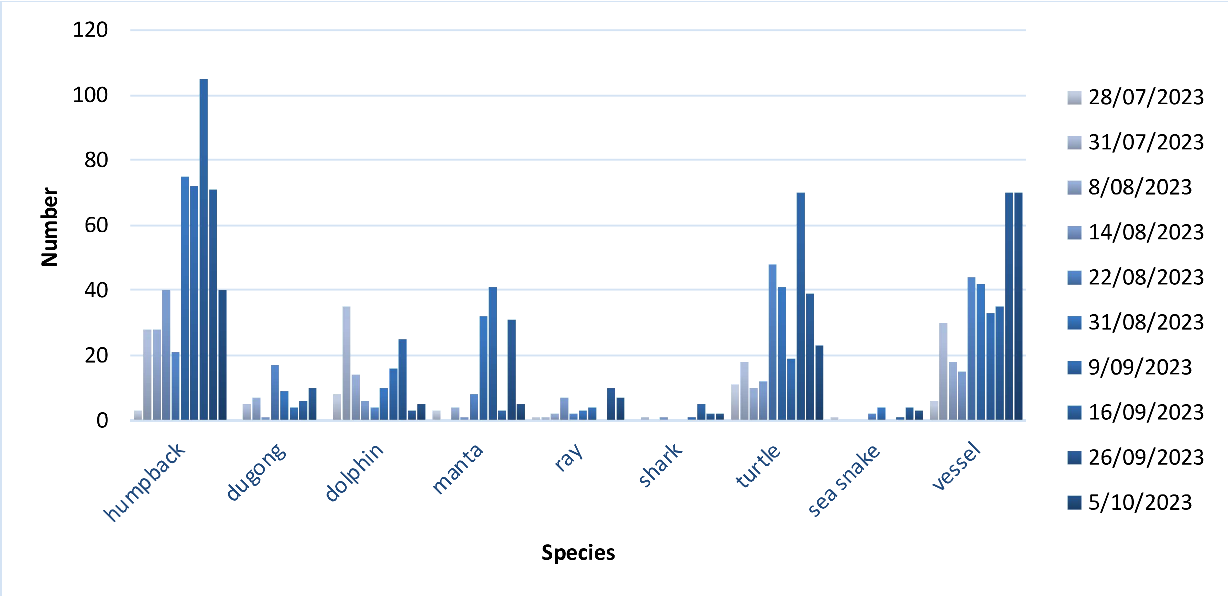

Figure 4-10 Occurrence patterns of wildlife and vessels along the western margin of Exmouth Gulf during aerial surveys.

Areas of high-density vessel activity between the Navy Pier and Pebble Beach also overlapped with high density habitats for these species (**Figure 4-11**). For humpback whales, this overlap was concentrated along much of the coastal area between the Navy Pier and Pebble Beach, including groups with calves. For turtles, significant overlap was observed just north of Golf Club Beach and the area between the Navy Peir and Bundegi Boat Ramp. For manta rays, the greatest overlap with vessel activity occurred just north of Golf Club Beach, extending northward almost to Bundegi Boat Ramp.

It is important to note that while **Figure 4-11** presents fixed positions for both vessels and wildlife, both are in fact dynamic. Vessels were likely launched and travelled from boat ramps or adjacent beaches, and marine wildlife are mobile, inferring that the areas of overlap are more extensive than shown in the figures.

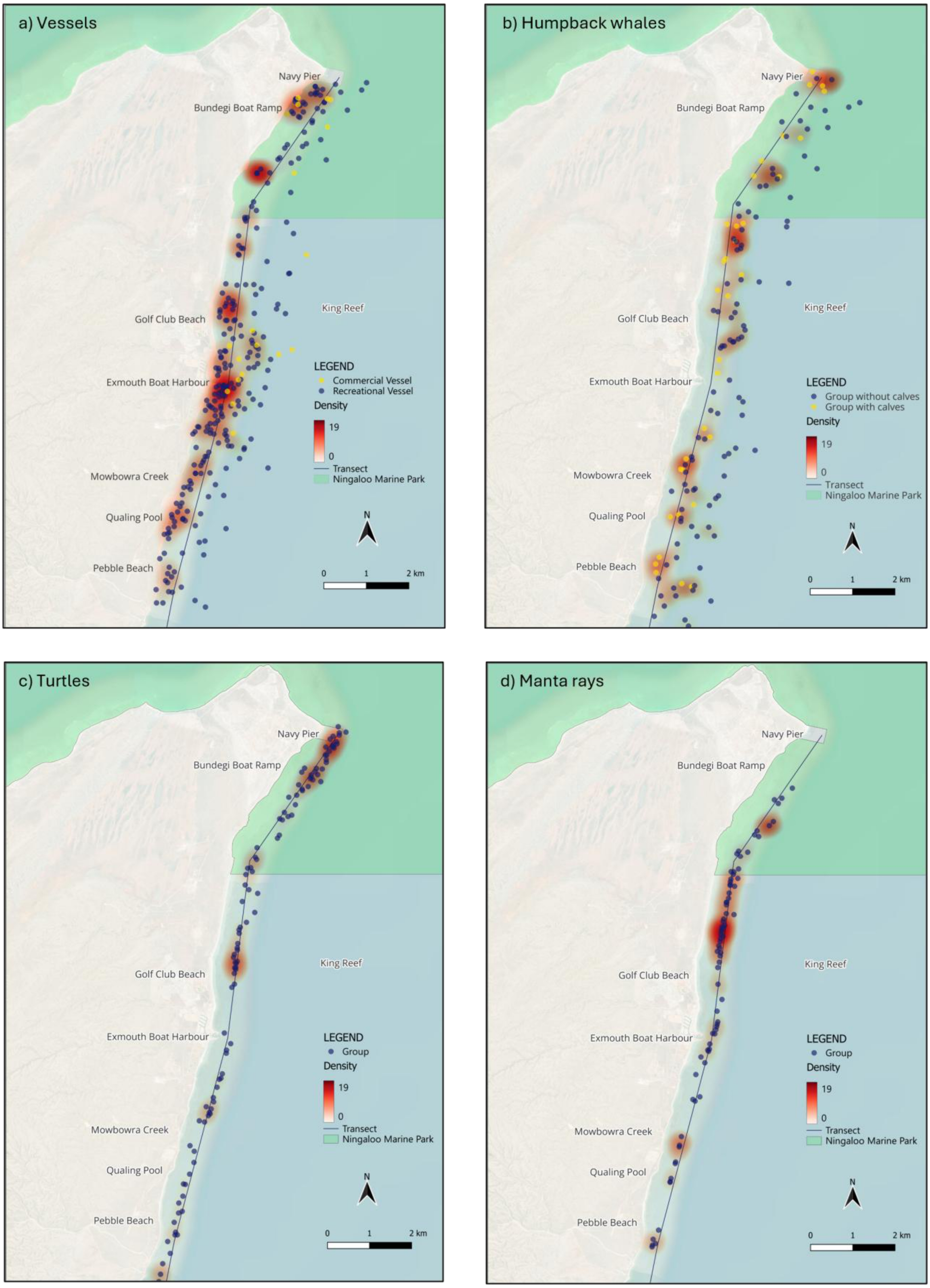

Figure 4-11 a) Areas of high-density vessel activity between the Navy Pier and Pebble Beach, alongside areas of high-density occurrences of b) humpback whales, c) turtles and d) manta rays.

5. Discussion

To inform effective management of Exmouth Gulf, comprehensive data on marine fauna occurrence and human activity is required. This study's aerial surveys provided information on the distribution and relative abundance of marine megafauna along the Gulf's western margin during winter, alongside data on vessel activity, revealing spatial overlaps with wildlife habitats. These findings offer valuable insights into current levels of anthropogenic pressure on marine megafauna in high-activity areas and provide a scientific foundation for conservation strategies and sustainable coastal development planning.

Exmouth Gulf supports a rich diversity of marine megafauna, including marine mammals, marine reptiles and elasmobranchs (Jenner and Jenner, 2005, Irvine and Salgado Kent, 2019). Its ecological importance is recognised at both international and national levels. At an international level, the Gulf has been designated as an Important Marine Mammal Area (IMMA) by the Marine Mammal Protected Areas Task Force (MMPATF). Its sheltered waters are an important feeding and nursing / calving habitat for Australian humpback dolphins, dugongs and Indo-Pacific bottlenose dolphins as well as an important nursery for humpback whales (IUCN-MMPATF, 2022). At a national level, the Gulf is recognised as a BIA by DCCEEW for several megafauna species including humpback and southern right whales, dugongs, and turtles including flatback, green, hawksbill and loggerhead turtles. Additionally, it is currently under assessment as a BIA for Australian humpback and Indo-Pacific bottlenose dolphins.

The western margin of Exmouth Gulf is particularly vulnerable to anthropogenic impacts due to its proximity to human populations and coastal infrastructure. This area experiences the highest levels of coastal development and human activity. Aerial surveys demonstrate the ecological importance of this area as habitat for marine mammals, marine reptiles and elasmobranchs, with high numbers of humpback whales, turtles and manta rays all being documented. Furthermore, observations of calves among the humpback whale, dolphin and dugong groups illustrate that the Gulf is an important nursery area for marine mammals.

Some megafauna species in the Gulf are migratory species, as reflected in the seasonal patterns of humpback whales, turtles and manta rays. Numbers of these species were relatively low in early August 2023 and increased substantially between late August and September 2023. This increase in wildlife numbers coincided with increased vessel activity, leading to significant overlap between human activities and wildlife habitat. The highest number of vessels were recorded during the Western Australian school holidays, a period when humpback whales, turtles and manta ray numbers were also high. Many recreational vessels were engaged in unlicenced wildlife interactions, with snorkelers frequently observed swimming with manta rays.

Spatiotemporally, the greatest overlap between anthropogenic activity and wildlife habitats occurred between Exmouth Boat Harbour and the Navy Pier during the school holidays. This period saw increased vessel traffic and human activity, placing additional pressure on the widlife using this popular coastal area.

Further detail on each species is discussed below:

5.1. Marine mammals

Humpback whales

Humpback whales were the most frequently observed marine mammal in Exmouth Gulf, with 483 individuals recorded along the western margin between late July and early October. These long-distance migratory whales are seasonally present in the Gulf, arriving in late July and early August, with numbers peaking in mid-September, before declining in late September / early October. This seasonal timing is earlier than previous surveys (2004/05 and 2018), which reported peak abundance occurring between mid-September and early October (Jenner and Jenner, 2005, Irvine and Salgado Kent, 2019).

Although abundance estimates were not possible in this study, previous studies in the Gulf indicate a more than fourfold increase in peak numbers from 174 whales in 2005 (Jenner and Jenner, 2005) to 754 whales in 2018 (Irvine and Salgado Kent, 2019), consistent with an annual growth rate exceeding 10% for the Western Australian humpback whale population (Salgado Kent et al., 2012). The high numbers of sightings in September and October 2023 coincided with the Western Australian school holidays, a period of heightened tourist activity and peak boating levels. During vessel-based research, instances of recreational boaters attempting to swim with humpback whales were observed. This highlights the growing popularity of in-water interactions with marine megafauna, including humpback whales. The risks associated with unlicenced in-water interactions should be considered in management strategies to ensure the safety of both humans and whales.

The composition of humpback whale groups varied over the breeding season. Juveniles and adults predominated in July and August, while mother-calf pairs were most common from late August onwards. This reflects the established migration pattern where juveniles lead, followed by males and non-pregnant females, and mothers with calves at the rear (Chittleborough, 1965, Dawbin, 1997). This behaviour aligns with the need for the mothers to spend longer in the Antarctic feeding grounds to build energy reserves before birthing and nursing in non-productive tropical waters (Irvine et al., 2017).

The Gulf is a recognised resting and nursing area for the Breeding Stock D (BSD) humpback whales that migrate along the Western Australian coast (Chittleborough, 1953, Jenner et al., 2001, Irvine and Salgado Kent, 2019). In this study, calves were observed in 28.4% of all groups, though their numbers are likely under-estimated due to their small size and protective behaviour of their mothers. Most calves were sighted during September and October, consistent with post-neonate calves (Irvine et al., 2018) resting during their southern migration (Jenner et al., 2001). A small number of calves were also sighted between late July and late August. These are likely small neonate calves entering the Gulf during their northern migration. This behaviour, first documented in 2018 (Irvine et al., 2018, Irvine and Salgado Kent, 2019), appears to be increasing in frequency (e.g. Sprogis and Parra, 2023). Neonate calves are particularly vulnerable to disturbance from anthropogenic activities due to their small size and limited swimming and diving capabilities (Thomas and Taber, 1984), highlighting this as a potential conservation concern.

Humpback whales, including a high percentage of calves, were distributed in high densities along the western edge of the Gulf, excluding the shallow waters of Gales Bay. Most groups (72.9%) exhibited milling or resting surface behaviours, increasing their vulnerability to vessel strike, particularly in areas of overlapping high whale and vessel densities. This is discussed further in section 5.4.1.

Dugong

A total of 59 dugongs, including nine calves were observed along the western margin of the Gulf. Dugongs were widely distributed along the shallow waters of this region, with the highest densities recorded between Pebble Beach and Badjirrajirra Creek, as well as in Gales Bay. Mother-calf pairs were observed in these high-density areas.

Previous studies have highlighted Exmouth Gulf as important dugong habitat (Preen et al., 1997, Gales et al., 2004, Bayliss et al., 2018, Irvine and Salgado Kent, 2019), supporting an estimated population of at least 2,500 individuals (Bayliss et al., 2018). While most dugongs have been recorded in the eastern and southern Gulf, the presence of calves in the western Gulf highlights its importance as a breeding area for the species. Dugongs are vulnerable to vessel strike due to their tendency to inhabit shallow waters, where they are more likely to encounter boats. This is discussed further in section 5.4.1.

Dolphins

A total of 126 dolphins, including 15 calves were observed along the western margin of Exmouth Gulf. These dolphins were broadly distributed in the shallow waters of this region, with the highest densities recorded south of the Bay of Rest, and in Gales Bay. Although species identification was not possible for all groups sighted, both Indo-pacific bottlenose and Australian humpback dolphins were confirmed, consistent with findings from previous studies in the area (Hunt et al., 2017, Hunt et al., 2020, Haughey et al., 2020, Sprogis and Parra, 2023).

The presence of dolphins throughout the survey period supports earlier research suggesting that these species are resident in the Gulf during winter and spring (Sprogis and Waddell, 2022). Notably, recent studies have identified the waters around North West Cape, including the Gulf, as important habitat for the Australian humpback dolphin, with density estimates (1 individual / km^2) being the highest recorded for this species (Hunt et al., 2017).

Coastal dolphins, such as those recorded in the Gulf, are considered particularly vulnerable to anthropogenic impacts due to their small, isolated populations, high site fidelity, slow life histories, and the increasing pressures from coastal development (Parra and Cagnazzi, 2016). Vessel noise can interfere with dolphin echolocation which is used for foraging, navigation and communication. In some cases, vessel noise has been known to displace dolphins from their habitat (Fitzpatrick et al., 2019). This is discussed further in section 5.4.2.

5.2 Marine reptiles

Turtles

A total of 291 turtles were sighted along the western Gulf with the highest numbers occurring from late August to late September. Although species identification was not possible during the aerial surveys, the turtles in the Gulf were likely predominantly green turtles with this area known to support a very high density of turtles compared to other locations around Australia (Preen et al., 1997). Based on previous vessel based surveys, hawksbill turtles (Jenner and Jenner, 2005) and loggerhead turtles may have also been present (Sprogis and Waddell, 2022). All three species are known to forage in Exmouth Gulf (Fitzpatrick et al., 2019). Notably, the Gulf is recognised as a BIA for each of these turtle species.

High densities of turtles were sighted between the Navy Pier and Gold Club beach, an area that also experiences high levels of boat traffic. This overlap raises concerns about vessel strike and is discussed further in section 5.4.1.

Sea snakes

A total of 15 sea snakes were sighted along the western margin of the Gulf with the highest densities south of Stewart Shoal and northern Gales Bay. Very little is known about sea snakes in the Gulf; this has been identified as a knowledge gap (Sutton and Shaw, 2021) and is currently an area of active research.

5.3 Elasmobranchs

Manta rays

High numbers of manta rays were observed along the western Gulf, with 128 individuals recorded between July and October, and peak numbers occurring from late August to late September. This seasonal pattern aligns with previously reported high concentrations of manta rays feeding in the Gulf and around the Muiron Islands during winter, coinciding with the peak prawn spawning period (Armstrong et al., 2020). Armstrong et al. (2020) also documented distinct seasonal patterns in manta ray abundance along Ningaloo Reef, with peak numbers occurring at Coral Bay in autumn, Ningaloo Reef in winter and the Gulf in spring.

The late September peak in manta ray sightings coincided with the Western Australian school holidays, a period that also experiences the highest recorded boating activity in the area. Many observed manta rays were accompanied by snorkelers and recreational vessels, reflecting the growing popularity of manta ray tourism. In Coral Bay (Ningaloo Marine Park), licenced operators offering in-water interactions with manta rays increased from one in the 1990's to five by 2016 (Venables et al., 2016). However, a preliminary assessment of such interactions revealed short-term behavioural responses in approximately one third of cases, raising concerns about the potential long-term impacts on manta ray populations. While the biological significance of these changes remains unclear, Venables et al. (2016) recommended applying precautionary principles to managing tourism activities.

Unlicenced interactions with manta rays in the Gulf have also increased substantially, particularly since the COVID-19 pandemic, likely driven by heightened exposure to these activities through social media (personal observation). This unregulated growth underscores the need for effective management to mitigate potential risks to both manta rays and the sustainability of human interactions.

High concentrations of manta rays were observed between Bundegi Boat Ramp and south Pebble Beach, an area that experienced high levels of boat traffic. This spatial overlap raises concerns about vessel strikes, as manta rays spend considerable time feeding near the water's surface, making them particularly vulnerable to collisions (McGregor et al., 2019). This is discussed further in section 5.4.1.

5.4 Overlap between vessels marine fauna habitat

The area between the Navy Pier and Pebble Beach experiences substantial overlap between high boating activity and dense wildlife populations, resulting in an increased risk of impacts such as vessel strike and vessel noise. This risk is particularly pronounced during the school holiday period (Sat Sept 23 - Sun Oct 8, 2023) when boating activity peaks. Further details on vessel strikes and vessel noise are provided below.

5.4.1 Vessel strike

Vessel strikes pose a significant threat to marine megafauna, particularly where high densities of vessels and wildlife overlap (Smith et al., 2020). While much of the research has focused on collisions involving large vessels and large whales, increasing evidence reveals that smaller marine species are also at significant risk, particularly those in coastal areas with high densities of smaller vessels (Schoeman et al., 2020, Mayaud et al., 2024). The risk of vessel strike rises with increased vessel speeds, with higher velocities linked to a greater probability of lethal injury (Vanderlaan and Taggart, 2007).

Globally, approximately 18% of reported whale-vessel collisions occur in Australian waters, predominantly involving humpback and southern right whales (Peel et al., 2018). Among humpback whales, mother-calf pairs are particularly vulnerable as they spend a substantial percentage of their time at or near the water's surface, where the likelihood of collision is elevated (Bejder et al., 2019, Smith et al., 2020). This is significant for the western margin of the Gulf, where nearly 30% of observed humpback whale groups contained a calf.

Data on vessel strikes involving smaller species, such as dolphins, dugongs and turtles, are comparatively sparse and likely under-reported (Schoeman et al., 2020). However, a recent global review has shown that these species are also frequent casualties of boat collisions (Schoeman et al., 2020). For instance, vessel strikes have been suggested as the most serious threat to Florida manatees, close relatives of dugongs, and 10.6% of individuals examined in the New York State Marine Mammal and Sea Turtle Stranding Program, showed evidence of propellor wounds. In the case of manta rays, evidence from Coral Bay suggests a considerable risk of vessel strikes, with injuries consistent with vessel strikes observed regionally (McGregor et al., 2019). Notably, the rapid wound-healing capabilities of manta rays may result in underestimation of the true incidence of such events (McGregor et al., 2019).

These findings highlight the need for more comprehensive data collection and targeted management strategies to better understand and mitigate vessel strike risks for the diverse range of marine megafauna inhabiting the Gulf.

5.4.2 Vessel noise

Marine mammals rely on underwater sound for essential activities such as communication, navigation, foraging and predator avoidance. However, noise from vessels – ranging from large commercial ships to smaller recreational boats – can interfere with these processes by overlapping with the sound frequencies used by marine mammals. This acoustic interference can lead to behavioural disturbances, acoustic masking, temporary or permanent hearing loss (Temporary Threshold Shift 'TTS' or Permanent Threshold Shift 'PTS' respectively), stress and habitat displacement (Allen and Read, 2000, Bejder et al., 2006, Rolland et al., 2012, Erbe et al., 2019).

In the Gulf, studies on noise impacts have primarily focused on humpback whales. High noise levels have been shown to cause behavioural changes in mother-calf pairs, including reduced resting time for mothers, increased respiration rates, and faster swim speeds (Sprogis et al., 2020). These behavioural changes can adversely affect calf development, as energy typically allocated for suckling and thus calf growth may instead be re-allocated to other energy demanding activities (Bejder et al., 2019).

Humpback whale mothers and calves in the Gulf maintain close contact and communicate with each other through low-level vocalisations. Vessel noise can increase the risk of mother-calf separation and potentially reduce suckling rates, negatively impacting calf growth and overall fitness (Videsen et al., 2017). Furthermore, acoustic masking from vessel noise may also disrupt mating behaviours, as adult males rely on songs to attract mates (Bejder et al., 2019).

These findings highlight the need to consider vessel noise in management strategies for important marine mammal habitats such as the Gulf.

5.5 Recommendations for Exmouth Gulf

To mitigate the impacts of vessel strikes and noise on marine megafauna in Exmouth Gulf, the following actions are recommended:

Data Collection and Risk Assessment

- Develop a comprehensive vessel strike database for marine megafauna recorded in the Gulf, including whales, dolphins, dugongs, turtles, sea snakes, rays and sharks.
- Establish species-specific necropsy protocols to reliably identify collision-related injury, particularly blunt force trauma.
- Identify high-risk areas for vessel-wildlife collisions by integrating data on vessel traffic and wildlife distribution.

Collison Prevention

- Avoid introducing new activities or developments that increase vessel traffic in the Gulf.
- Re-route vessels away from high density wildlife habitats and create 'no-go' zones in important areas or during sensitive times of the year.
- Introduce vessel speed restrictions in important habitats.

- Launch educational campaigns to create awareness among vessel operators about collision risks, the consequences for marine fauna and human safety, and strategies for minimising impacts. Include information about high density wildlife areas and avoidance techniques.

Noise Mitigation

- Encourage the adoption of quieter vessel technologies and operational practices, including speed restrictions, especially in areas of high wildlife density.
- Establish temporal and spatial restrictions on vessel activities in important habitats during biologically sensitive periods, such as calving and nursing seasons.

6. Conclusion

The western Gulf is an important area for a wide array of marine megafauna, including conservation-significant marine mammals, marine turtles and elasmobranchs. However, its proximity to Exmouth township and associated infrastructure such as boat ramps results in high levels of boating activity. This spatial overlap creates a significant risk of impacts, including vessel strikes and noise disturbance. These risks must be carefully considered in management strategies, with current levels of human activity integrated into cumulative impact assessments for future development proposals.

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8. APPENDICES

8.1. Appendix A: Scales for environmental conditions

Table 8-1. The Beaufort scale (sea state).

Force	Description	Sea state	Wind speed (knots)
0	Calm	Mirror calm	<1
1	Light air	Ripples, no crests	1-3
2	Light breeze	Small wavelets, crests glassy	4-6
3	Gentle breeze	Large wavelets, scattered whitecaps	7-10
4	Moderate breeze	Small waves 0.5-1.25m high, numerous whitecaps	11-16
5	Fresh breeze	Moderate waves 1.25-2.5m high, many whitecaps	17-21
6	Strong breeze	Large waves 2.5-4m high, whitecaps everywhere	22-27

Table 8-2. Turbidity scale.

Turbidity	Water quality	Water Depth	Visibility of sea floor
1	Clear	Shallow	Clearly visible
2	Variable	Variable	Visible but unclear
3	Clear	>5m	Not visible
4	Turbid	Variable	Not visible

8.2. Appendix B: Observations marine megafauna and vessels for each survey

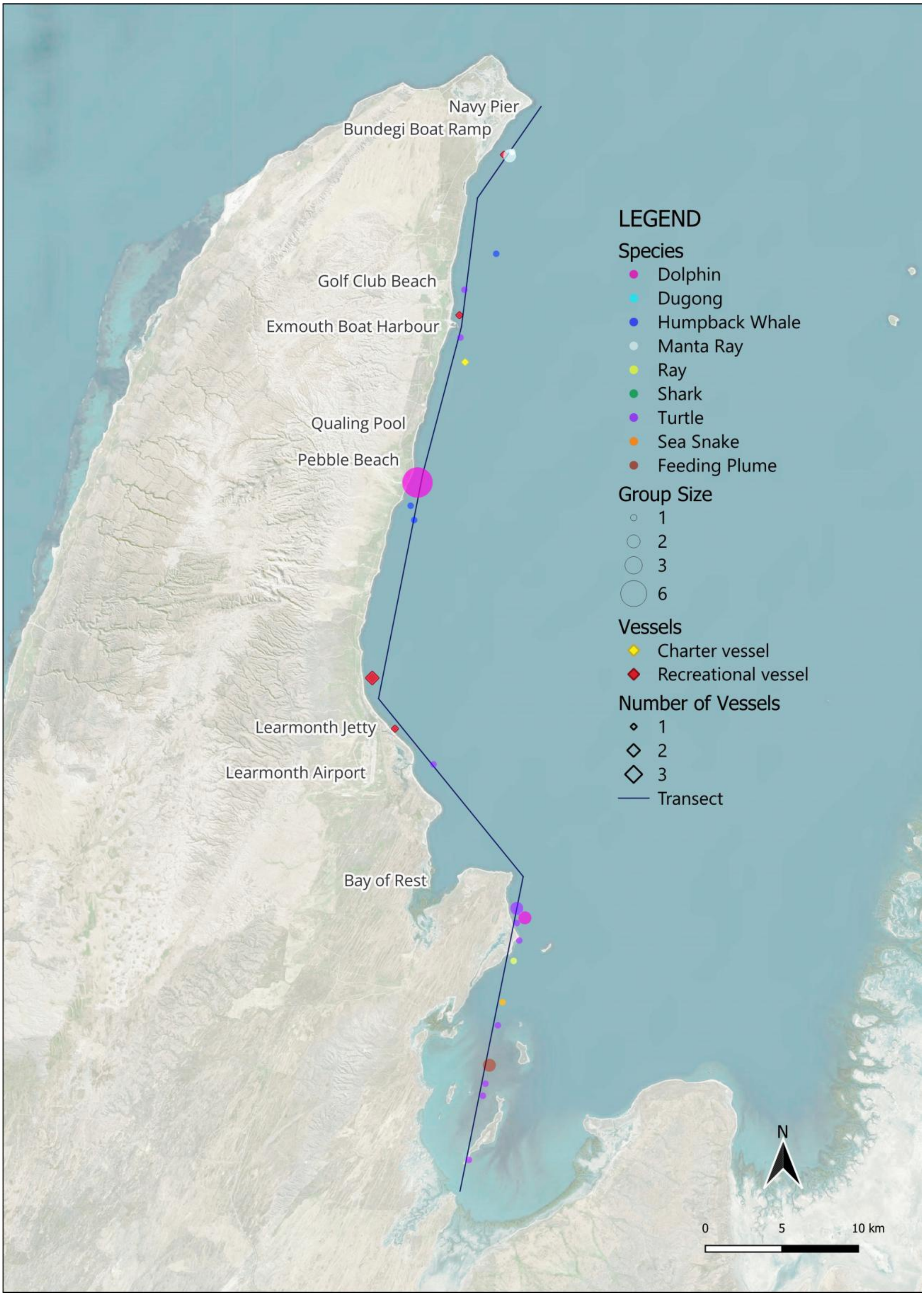

Figure 8-1. Distribution of marine megafauna and vessels observed in Exmouth Gulf during survey 1 (28/07/2023).

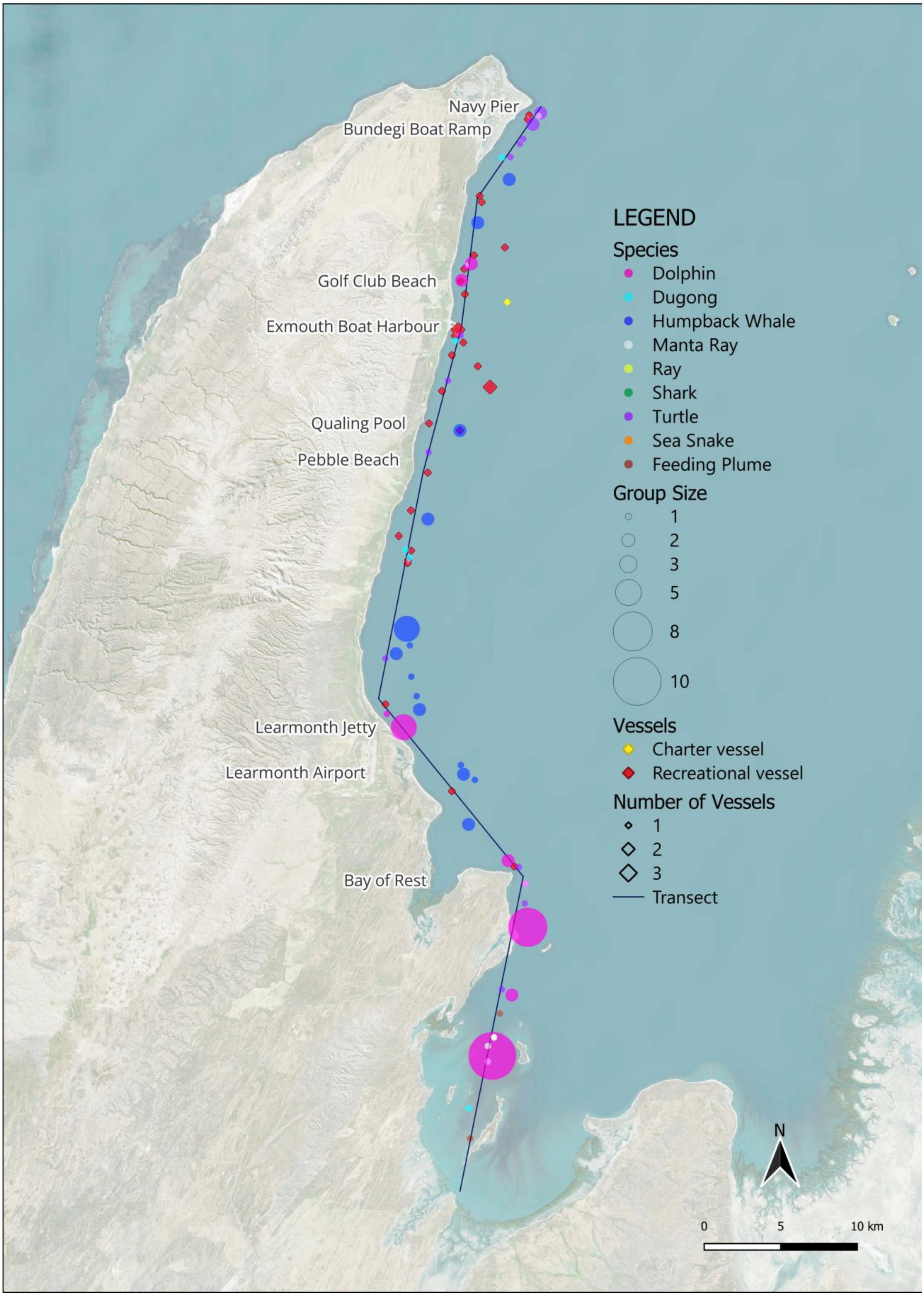

Figure 8-2. Distribution of marine megafauna and vessels observed in Exmouth Gulf during survey 2 (31/07/2023).

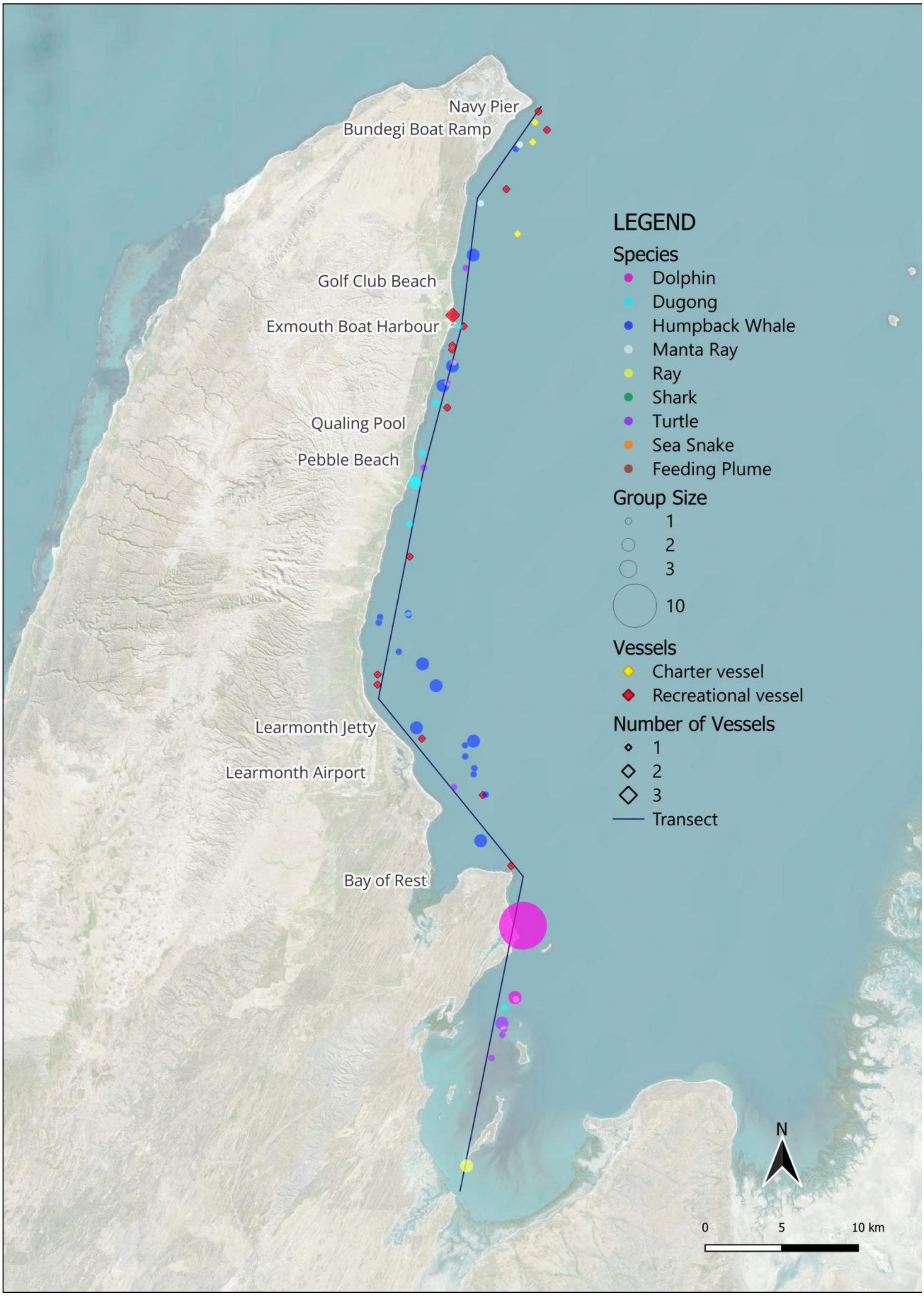

Figure 8-3. Distribution of marine megafauna and vessels observed in Exmouth Gulf during survey 3 (08/08/2023).

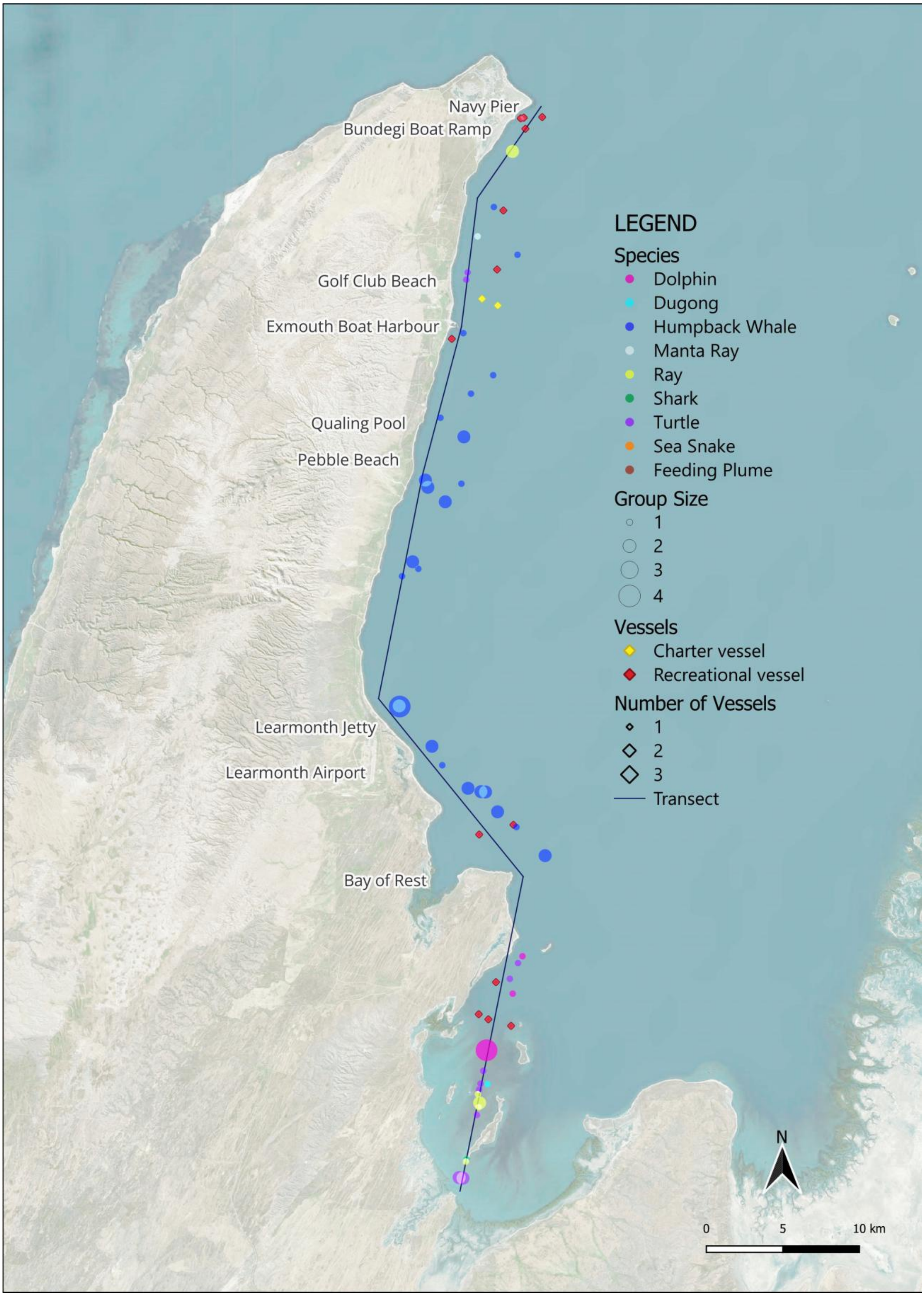

Figure 8-4. Distribution of marine megafauna and vessels observed in Exmouth Gulf during survey 4 (14/08/2023).

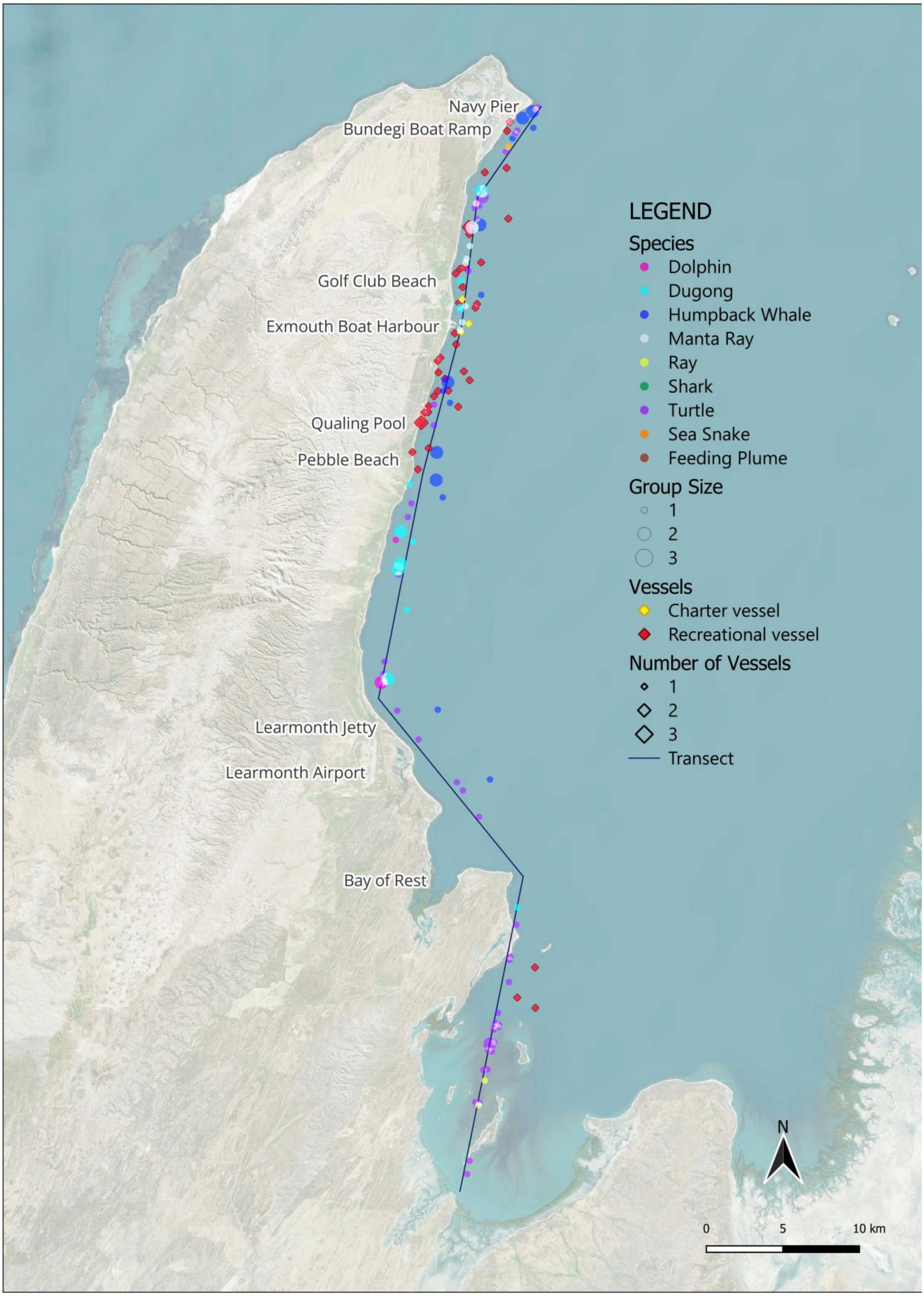

Figure 8-5. Distribution of marine megafauna and vessels observed in Exmouth Gulf during survey 5 (22/08/2023).

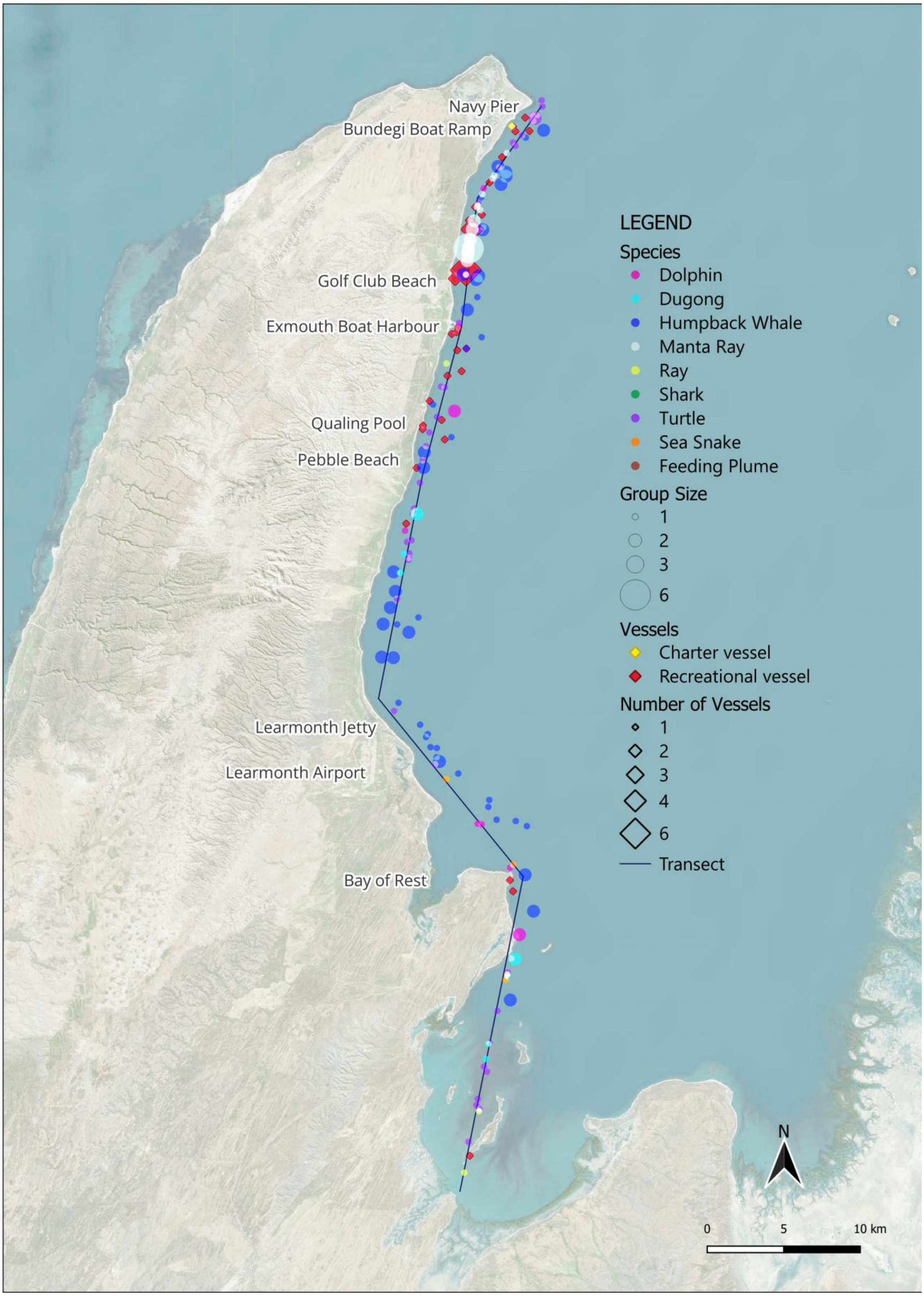

Figure 8-6. Distribution of marine megafauna and vessels observed in Exmouth Gulf during survey 6 (31/08/2023).

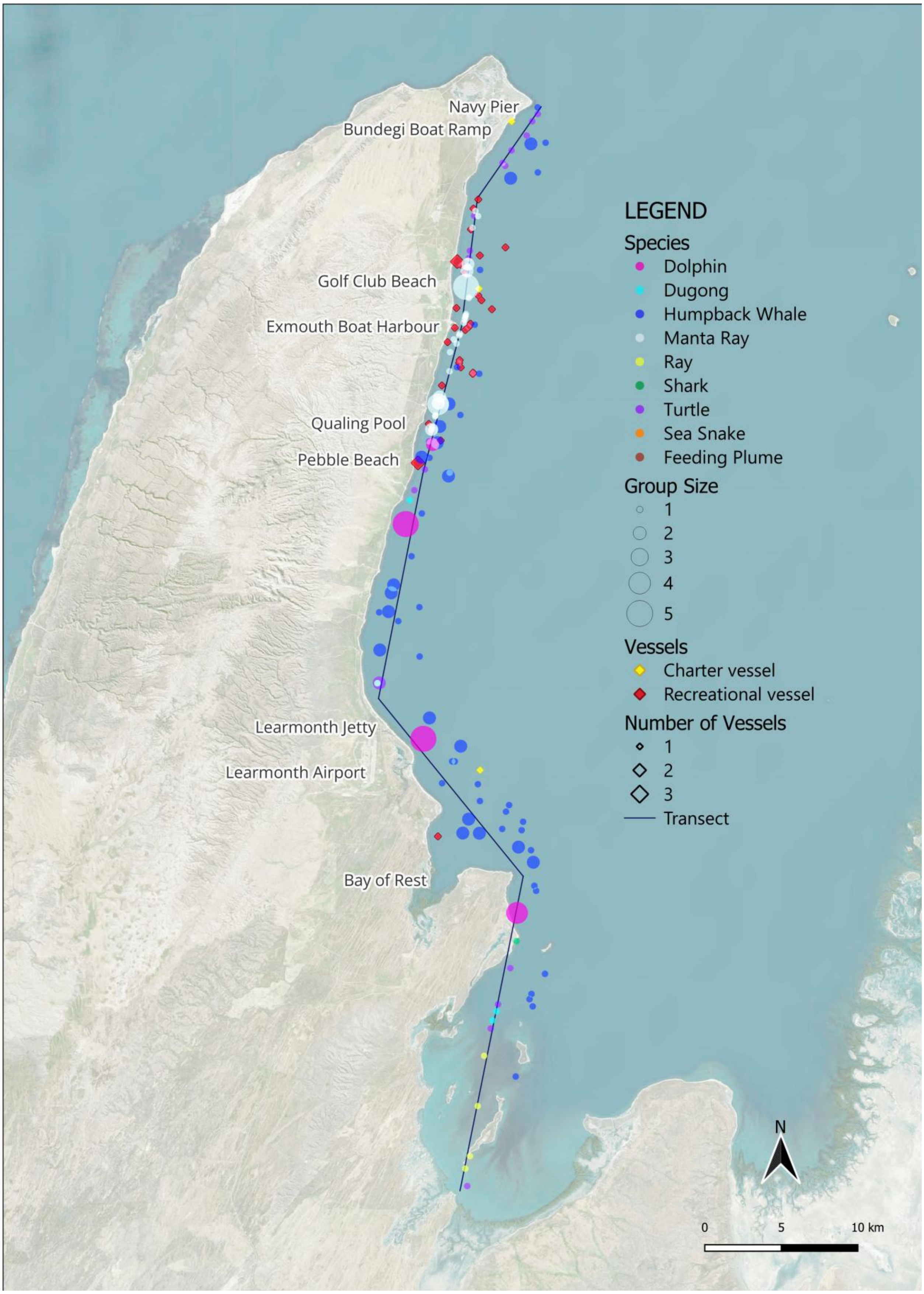

Figure 8-7. Distribution of marine megafauna and vessels observed in Exmouth Gulf during survey 7 (09/09/2023).

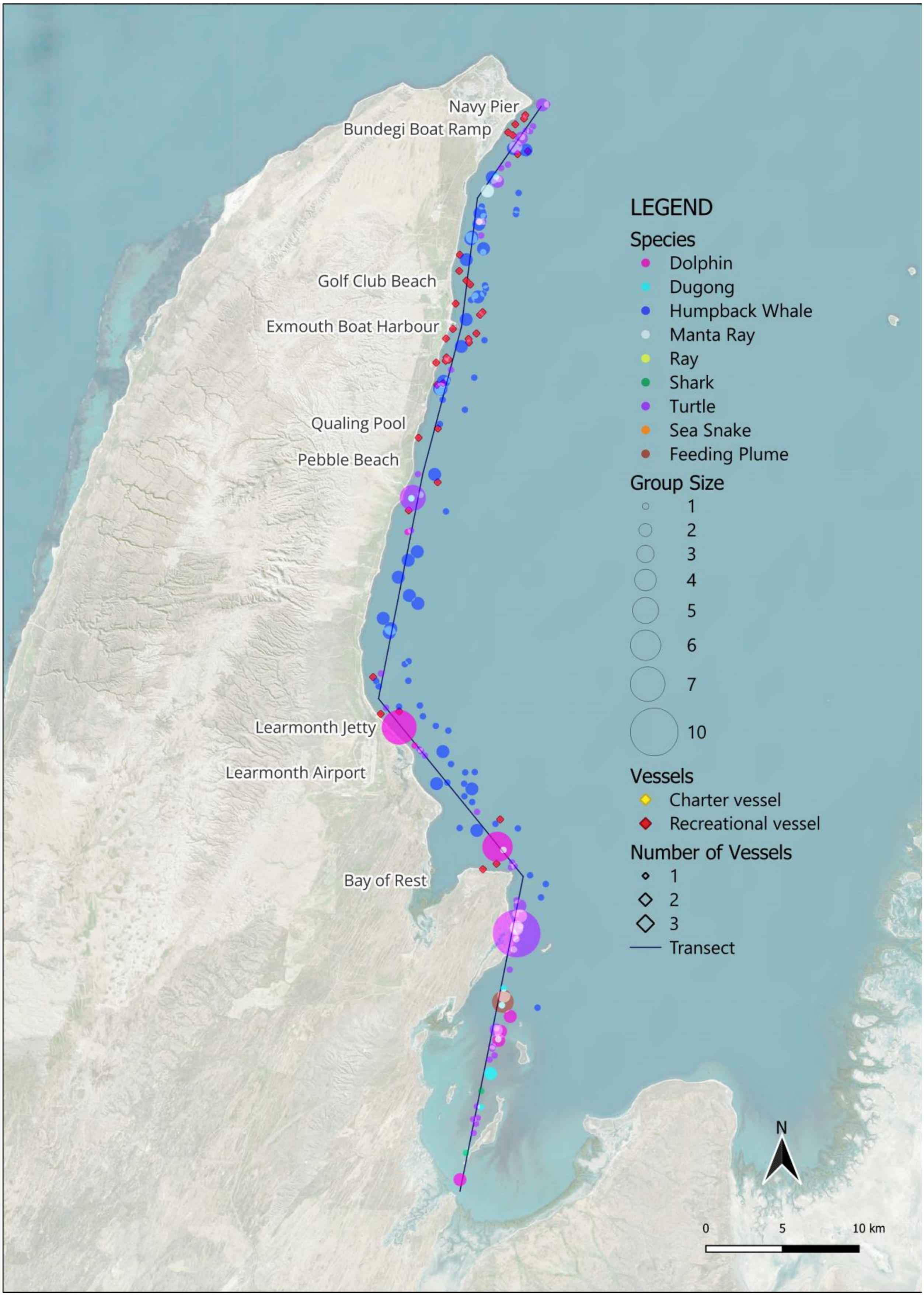

Figure 8-8. Distribution of marine megafauna and vessels observed in Exmouth Gulf during survey 8 (16/09/2023).

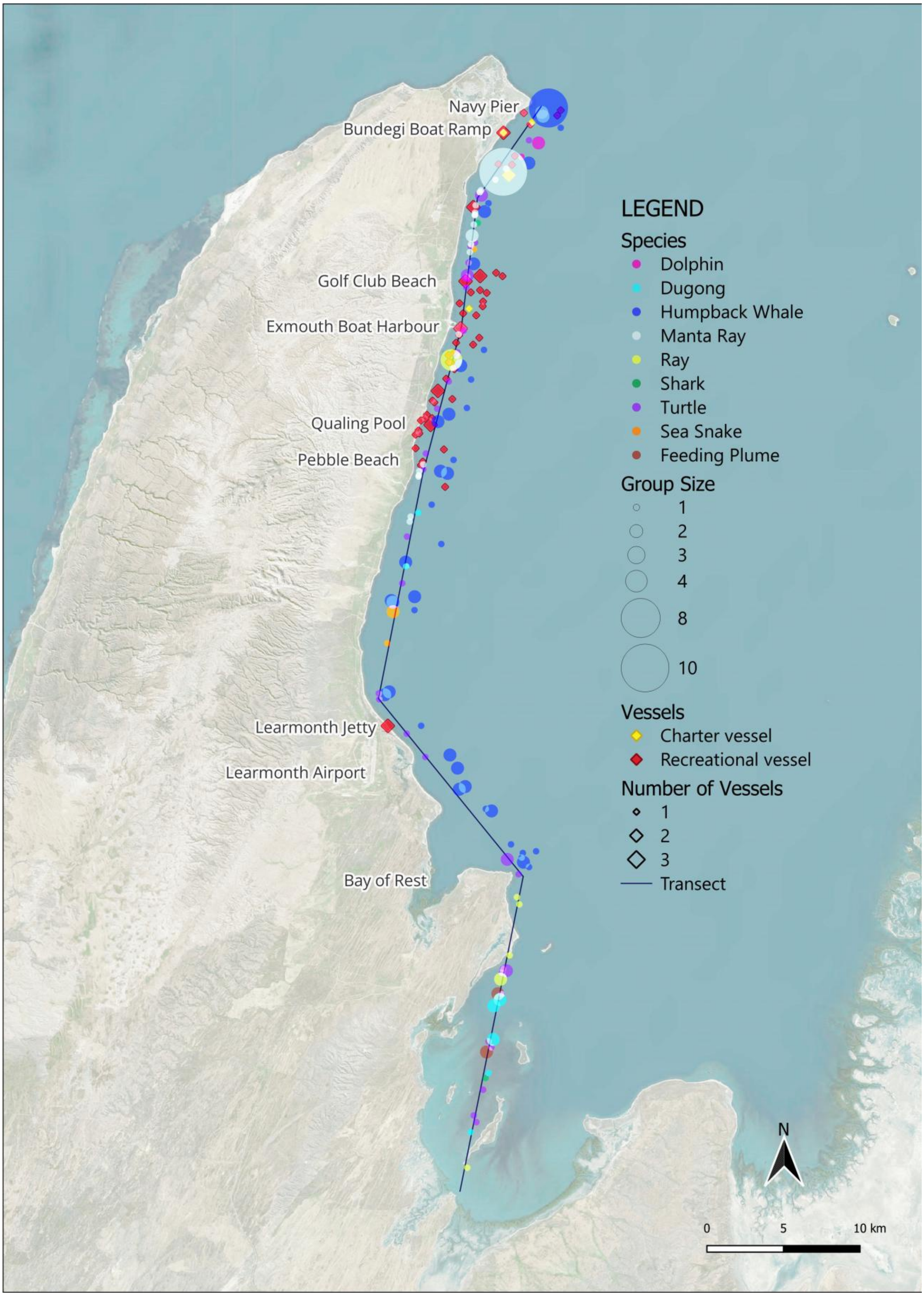

Figure 8-9. Distribution of marine megafauna and vessels observed in Exmouth Gulf during survey 9 (26/09/2023).

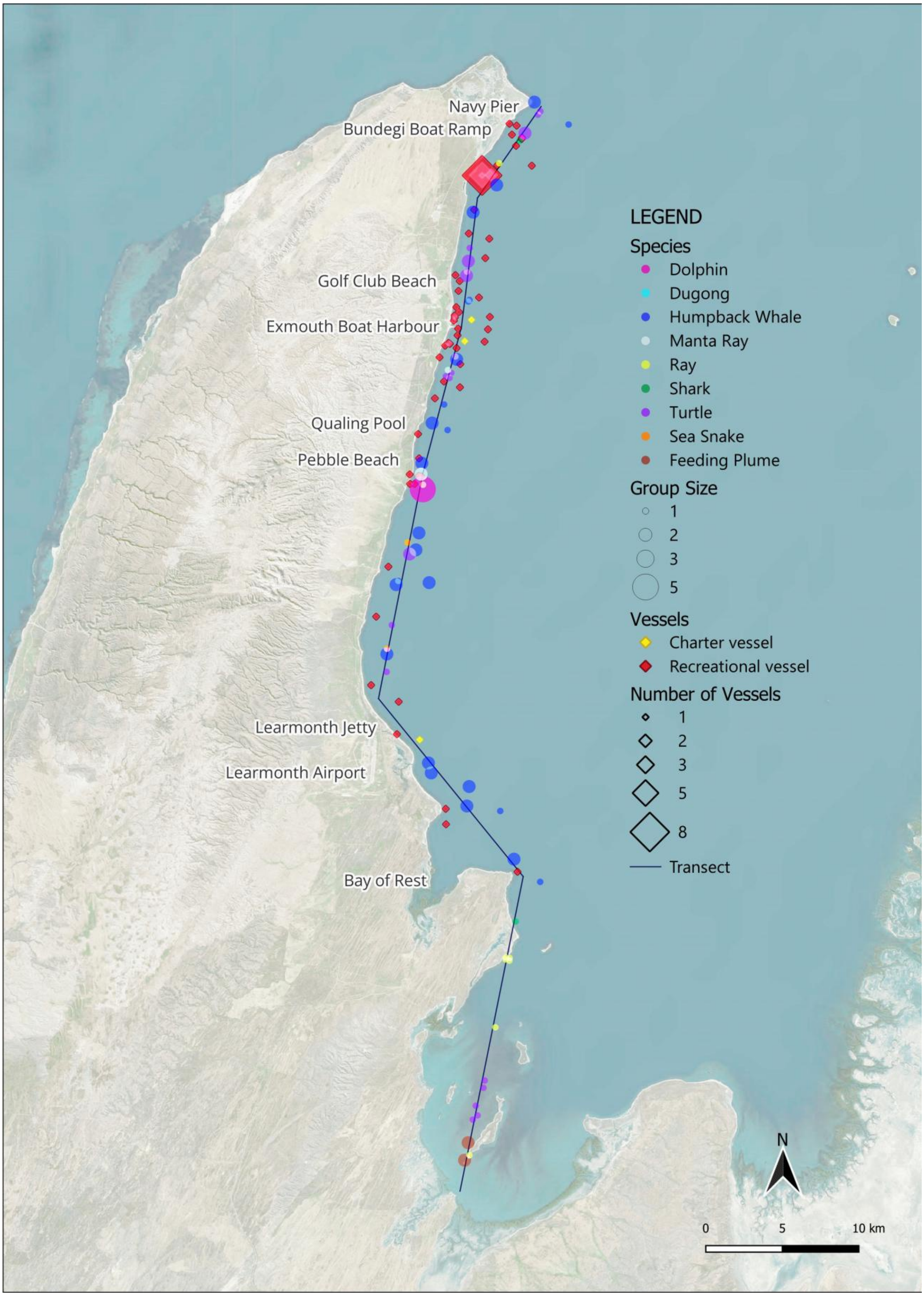

Figure 8-10. Distribution of marine megafauna and vessels observed in Exmouth Gulf during survey 10 (05/10/2023)

Absolute abundance and intergroup distances of humpback whales (*Megaptera novaeangliae*) in Exmouth Gulf, Western Australia

Absolute abundance and intergroup distances of humpback whales (*Megaptera novaeangliae*) in Exmouth Gulf, Western Australia

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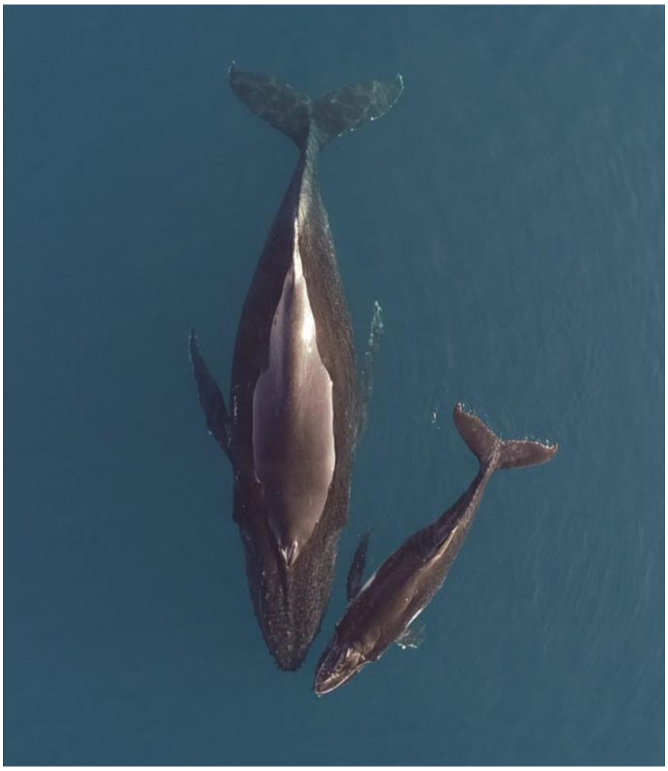

Images: Humpback whales in Exmouth Gulf, Western Australia (photos taken by Lyn Irvine).

Irvine Marine Fauna Research

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Date presented: February 2025

Citation: Irvine, L.G., Tucker, J., Irvine, W.D., and Salgado Kent, C. 2025. Absolute abundance and intergroup distances of humpback whales (*Megaptera novaeangliae*) in Exmouth Gulf, Western Australia. Report to the Department of Water and Environmental Regulation. Perth, Western Australia. 22pp

In loving memory of Eric 'Rollo' Roulston.

For over two decades, Rollo's expert piloting of aerial surveys across Western Australia, spanning from Exmouth Gulf and Ningaloo Reef to the Kimberley, were the wings beneath our humpback whale research. His unwavering standards and meticulous skill ensured the reliability of the data that formed the foundation of our science.

Generous in character, Rollo welcomed our scientists aboard his whale shark spotter planes. This collaboration in 2013 led to the discovery of neonate calves at Ningaloo and the expansion of known humpback calving grounds from the Kimberley to Ningaloo. This pivotal finding directly contributed to the establishment of a mother-calf protection zone in the Ningaloo Marine Park, safeguarding these vulnerable whales and supporting the local ecotourism industry.

The 2018 Exmouth Gulf aerial surveys highlighted his dedication and strong work ethic. Travelling from Shark Bay to Exmouth for each survey flight, Rollo's efforts were instrumental in achieving the significant abundance estimate of 2,980 humpback whales - a result impossible without his commitment.

May his generosity and dedication forever inspire us, and may his memory soar through the skies he so expertly navigated.

1. Executive Summary

Exmouth Gulf, located on the northwest coast of Western Australia, is an ecologically significant area (Sutton and Shaw, 2021) that supports large numbers of humpback whales. Its role as a key nursery for humpback whales has been internationally recognised by the Marine Mammal Protected Areas Task Force (IUCN-MMPATF, 2022), which has designated it as an Important Marine Mammal Area (IMMA), and nationally by the Department of Climate Change, Energy, the Environment and Water (DCCEEW), which has classified it as a Biologically Important Area (BIA) for humpback whale resting and migration. However, the high abundance of whales during the breeding season presents challenges for the effective application of conservation guidelines, highlighting the need for evidence-based management strategies.

To address these challenges and support informed decision making, an aerial survey program was conducted over Exmouth Gulf during the 2018 humpback whale breeding season. The program aimed to estimate absolute abundance, assess intergroup spacing, and track seasonal changes in these factors. Between 8 August and 2 November 2018, nine aerial surveys were conducted covering the entire Gulf. Key findings include:

- **Abundance:** Absolute abundance estimates ranged from 216 to 2,980 whales per survey.
- **Composition:** Lactating mothers and calves were recorded in every survey, confirming the Gulf's role as a key nursery area.
- **Distribution:** Humpback whales were distributed throughout the entire Gulf, except for the shallow waters along the eastern and southern shores.
- **Seasonal peak:** Whale numbers peaked in mid-late September, with the highest estimated abundance (2,980 whales) recorded on 20 September.
- **Intergroup spacing:** As abundance increased, whale density increased, and intergroup distances decreased.
- **Regulatory distances:** At peak abundance, intergroup distances fell below key regulatory approach limits, with the following percentages of groups observed within each threshold:
    - **100 m** (minimum side approach distance under Western Australian Biodiversity Conservation Regulations and for non-calf groups under Australian National Guidelines) for 8.2% of groups.
    - **300 m** (minimum front and rear approach distance under Western Australian Biodiversity Conservation Regulations and for calf groups under Australian National Guidelines) for 25.8% of groups.
    - **600 m** (minimum distance required between groups for vessels to manoeuvre between them while maintaining a 300 m buffer) for 47.2% of groups

These findings reinforce Exmouth Gulf's importance as critical habitat for humpback whales, particularly for mothers and calves during a key stage in calf development. However, the high whale density during peak season raises concerns about the feasibility of enforcing existing approach distance regulations under the Western Australian Biodiversity Conservation Regulations (2018) and Australian National Guidelines for Whale and Dolphin Watching (2017). Given the close proximity of whale groups, maintaining regulatory separation distances is not practically achievable during periods of high whale abundance.

To mitigate risks such as vessel strikes and noise disturbance, effective management strategies would include seasonal restrictions on vessel activities, speed limits, and exclusion zones in critical nursery areas. These measures are essential for ensuring the long-term protection of humpback whales in Exmouth Gulf and will become more important as future development proposals emerge.

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2. INTRODUCTION

Exmouth Gulf (the Gulf), located on the northwest coast of Western Australia, is an area of high ecological value (Sutton and Shaw, 2021) that supports large numbers of humpback whales (*Megaptera novaeangliae*) (Irvine and Salgado Kent, 2019). It serves as critical habitat for the Breeding Stock D (BSD) humpback whales, one of the largest humpback whale populations globally (Branch, 2011, Salgado Kent et al., 2012, International Whaling Commission, 2014). The Gulf's role as a nursery for BSD humpback whales has been internationally recognised by the Marine Mammal Protected Areas Task Force (IUCN-MMPATF, 2022), which designating it as an Important Marine Mammal Area (IMMA), and nationally by the Department of Climate Change, Energy, the Environment and Water (DCCEEW), which classified it as a Biologically Important Area (BIA) for humpback whale resting and migration.

Despite this recognition, little is known about the total number of humpback whales using the Gulf at any given time, or how this varies across the breeding season. Accurate abundance estimates are essential for assessing the effectiveness of conservation measures and informing management strategies for protecting threatened and endangered species. Such estimates are fundamental to conservation assessments and policies, such as the International Union for Conservation of Nature (IUCN) Red List (Hammond et al., 2021) and legislation such as the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act).

Humpback whales occupy the Gulf on a seasonal basis, with occasional sightings as early as June, but typically present between July and November. Peak numbers occur between late September and early October, coinciding with the arrival of southbound mother-calf groups from the Kimberley region (Jenner et al., 2001, Irvine and Salgado Kent, 2019). While relative abundance (i.e., the number of individuals observed but not corrected for detection biases) across the breeding season has been documented from aerial sureys in 2018 (Irvine and Salgado Kent, 2019), absolute abundance (i.e., the total number of individuals corrected for detection biases (DCCEEW, 2024)) over the breeding season remains unknown. A previous aerial survey in 2017, optimised for dolphin sightings, provided an absolute abundance estimate of 2,900 – 3,900 humpback whales at peak occurrence (Tucker, 2023).

Relative abundance data provide useful insights into variations in abundance over space and time, but underestimate the true number of animals in the area. They do not account for lower detection rates of animals at greater distances from the aircraft, or biases due to availability (whales submerged and thus not visible to observers) and perception (whales available for detection but missed by observers due to observation conditions or by chance) (Hammond et al., 2021). Additionally, whale density and intergroup spacing are not well know, yet are essential for conservation planning, as management strategies often rely on maintaining minimum separation distances between wildlife and human activities.

Under the Western Australian Biodiversity Conservation Regulations (2018), minimum separation distances between vessels and whales are 300 m within a 60° arc to the front or rear of a whale and 100 m to the side of a whale. Similarly, the Australian National Guidelines for Whale and Dolphin Watching (2017) stipulate minimum approach distances of 300 m for groups with calves and 100 m for groups without calves (Commonwealth of Australia, 2017). These separation distances serve as key mitigation measures in Marine Fauna Management Plans (MFMPs) for development proposals. For example, the Ashburton Salt Project in Exmouth Gulf, applies national guidelines requiring vessels to stay at least 300 metres from humpback whale groups with calves (Commonwealth of Australia, 2017, O2 Marine, 2022). However, the effectiveness of these mitigation measures depends on the natural spacing between whale groups.

This study aims to address these knowledge gaps by estimating the absolute abundance, density and intergroup distances of humpback whales in Exmouth Gulf and assessing how these patterns change throughout the season. Using data from aerial surveys conducted in 2018, these findings will enhance understanding of the Gulf's importance to BSD humpback whales and support evidence-based conservation and management strategies.

3. MATERIALS AND METHODS

3.1. Study Area

Exmouth Gulf is a northward facing embayment situated on the eastern side of North West Cape spanning latitudes 21°45' and 22°33' (**Figure 3-1**). Covering an area of approximately 4000 km^2, the Gulf is characterised by relatively turbid waters (Cartwright et al., 2021) and shallow depths, with a mean depth of less than 20 metres.

The waters are shielded from open-ocean swells by the protective barrier formed by North West Cape and the islands at the Gulf's entrance (Fitzpatrick et al., 2019).

Exmouth Gulf is recognised by DCCEEW as a BIA for humpback whale resting and migration (www.dcceew.gov.au/environment/marine/marine-bioregional-plans/marine-planning-spatial-information).

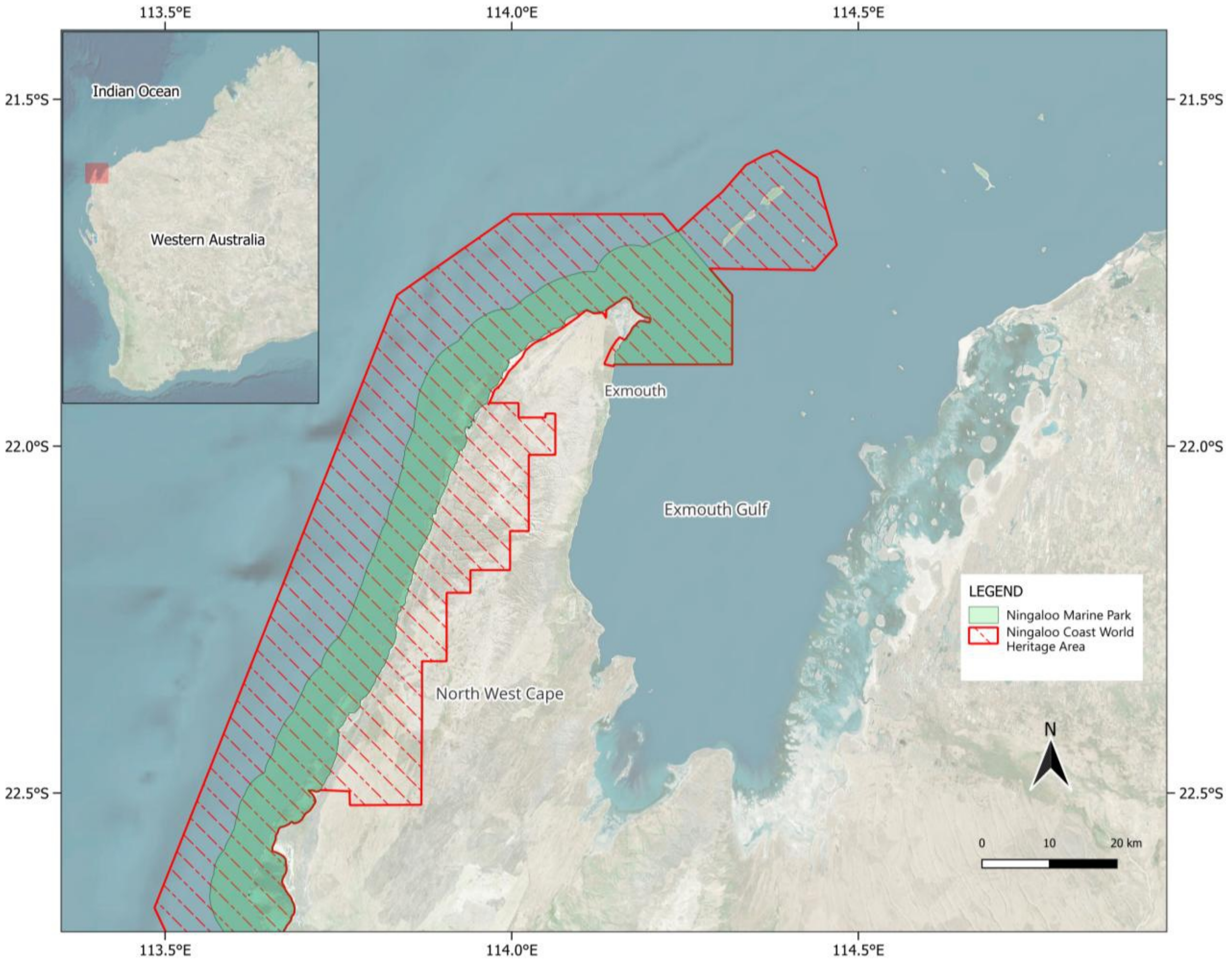

Figure 3-1. Location of the study area of Exmouth Gulf, along the north-west coast of Western Australia.

3.2. Survey Design

The aerial surveys were designed to optimise sampling for humpback whales, ensuring full coverage of the Gulf while complying with the assumptions of distance sampling. The survey design consisted of 9 box-end line transects, spaced 10 km apart, running east-west between the Gulf's eastern and western edges (**Figure 3-2**).

Surveys were originally planned to begin in early August and continue until early November; however, logistical constraints delayed the start until the second week of August. All surveys were conducted between 8 August and 2 November 2018, approximately every 10-12 days, when weather conditions were favourable.

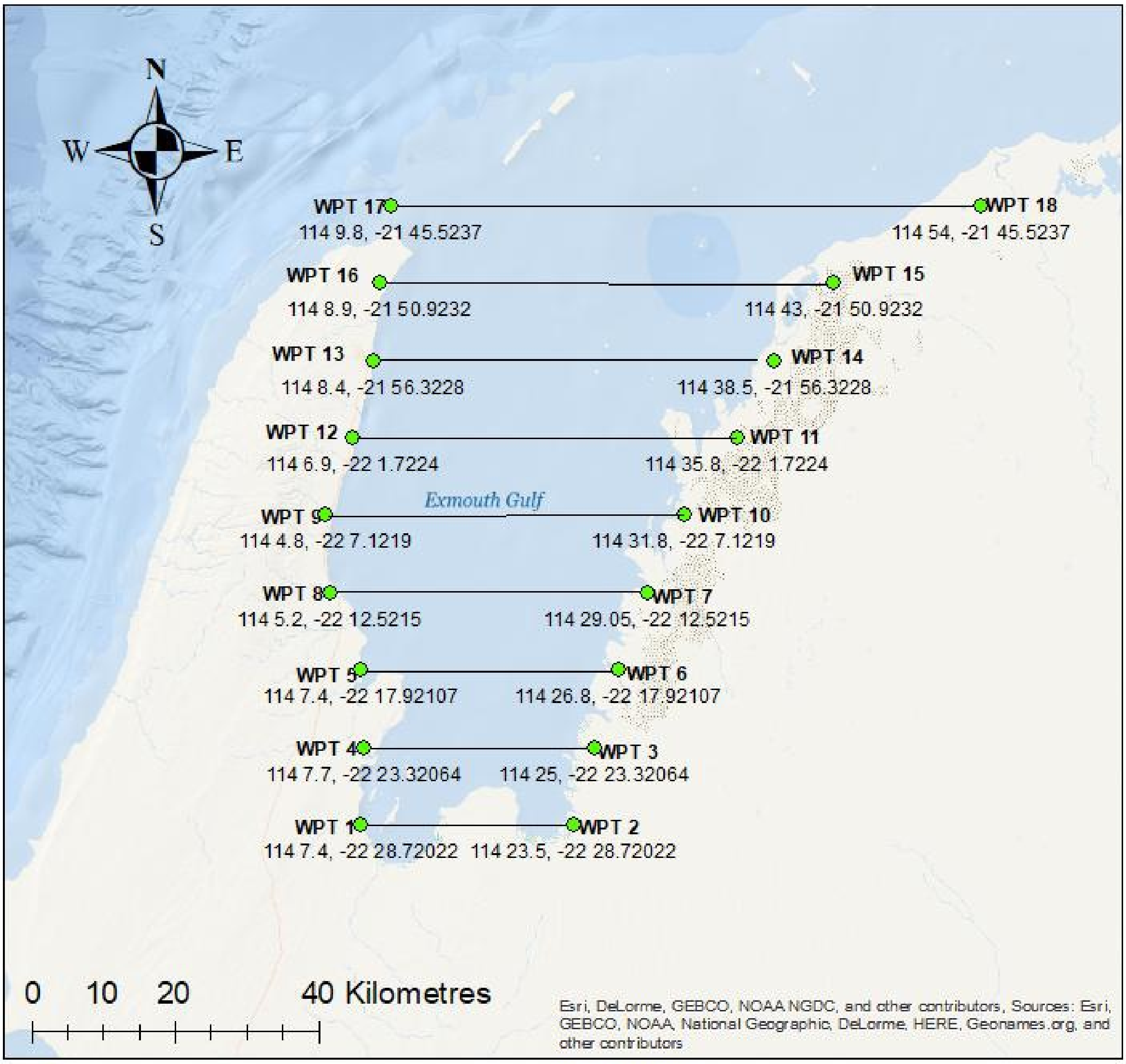

Figure 3-2. Map of the aerial survey design for humpback whales in Exmouth Gulf. Source: (Irvine and Salgado Kent, 2019).

3.3. Data Collection

The surveys were conducted using a twin engine, high wing aircraft (Cessna 337), flying at an altitude of 305 m (1000 ft) at a speed of 204 km hr^{-1} (110 knots). Survey personnel consisted of a pilot and four observers linked via an intercom system that could be isolated from the pilot when necessary. The two primary observers were seated in the middle seats of the aircraft and visually screened from the secondary observers in the rear seats. The primary and secondary observers were acoustically isolated from each other by connecting them to two separate intercoms. Observations were recorded on a time-coded digital sound recorder synchronised to a hand-held GPS that provided coordinates every second during the flight. All devices (including a digital camera) were calibrated to ±1 sec accuracy prior to each flight. Angle of drift of the aircraft from the flight path (Lerczak and Hobbs, 1998) was recorded by the pilot.

Two modes were used during the surveys: i) passing mode where observations were recorded without deviating from the transect line; and ii) closing mode where the aircraft broke from transect to collect more detailed information about an observation. Once the information was collected in closing mode, passing mode was resumed by returning to the location where the aircraft broke from transect. Passing mode was used on all transects in the aerial surveys. The aircraft transitioned to closing mode when a humpback whale group was sighted within 600 m either side of the transect, to confirm group composition. If the whale group sighted within 600 m of the transect was sighted clearly, the group was not circled.

3.3.1 Passing mode

Observers recorded the location of each group sighted, in relation to the aircraft by recording the vertical angle down from the horizon (using *Suunto* PM-5/360PB clinometers), and the horizontal angle (using a compass board) from the aircraft's travel direction to the whale. The position of each group of whales was calculated post survey following Salgado-Kent *et al.* (2012). In addition to location, observers recorded group size, group composition, behaviour, direction of travel, and calf colour (light grey, mid-grey, dark grey or adult colour). Group composition was described in terms of the number of adults and calves present. Here, a calf was defined as a whale within close proximity to another whale and visually estimated to be less than 2/3rds of the length of the accompanying animal (Clapham, 1999). Behaviour was categorised as travelling, milling, resting or undetermined.

At the beginning of each transect, the following environmental conditions were recorded: sea state (Beaufort scale), wind speed (knots), wind direction, cloud cover (oktas), visibility, turbidity and glare intensity and coverage on each side of the aircraft. These conditions were updated during the transect whenever they changed. Surveys were conducted in weather conditions of Beaufort sea state ≤3 as the high windspeed and extensive white caps in higher Beaufort conditions (sea state ≥4) typically restrict sightings to surface active individuals (e.g. breaching or tail slapping).

3.3.2 Closing mode

The aircraft was directed to fly directly overhead the group to i) obtain an accurate assessment of the number of individuals in each group, ii) accurately determine group composition, and iii) assess calf colour as an indicator of developmental stage.

3.4. Analyses

3.4.1 Survey and study area calculation

ArcMap software (Redlands, 2012) was used to calculate survey effort and the total study area. Tracks flown during the surveys were plotted and trimmed to the coast to calculate the length of each transect. The northern boundary of the study area was defined as a parallel line 5 km north of the northernmost transect (transect 9). The total study area was calculated using the XTools Pro v.21.0 expansion (XTools, 2021) in ArcMap.

3.4.2 Detection function and abundance estimation

Abundance analyses were completed using R Software (R Core Team, 2022), run through R Studio v2022.02.0+443 (R Core Team, 2022). The 'destPoint' function, in the package *geosphere* (Hijmans, 2024), was used to calculate the position (longitude and latitude) of each whale group sighting. This requires radial distances (d) from the observer's position on the track line to each group sighted to be calculated, as per the following equation:

$$d = h * \tan(90 - \alpha)$$

where h is the survey altitude (304.8 m) and α is the declination angle to a sighting when abeam (Lerczak and Hobbs, 1998). Angles measured by the observers to the sighted groups were corrected to account for the aircraft's course and drift as follows:

$$AW = AC + MHA \pm DA$$

where AW is the true bearing to the observed group, AC is the course of the aircraft, MHA is the horizontal angle measured by observers and DA is the drift angle of the aircraft, adjusted depending on which side of the aircraft the group was sighted (Lerczak and Hobbs, 1998).

To estimate humpback whale abundance in the Gulf, Distance Sampling techniques (Buckland et al., 2001, Buckland et al., 2004) were used. Estimates of group abundance ($\widehat{N}_{groups}$) were calculated using a Horvitz-Thompson- like estimator (Huggins, 1989):

$$\widehat{N}_{groups} = \frac{n}{p(x)} \frac{A}{2Lw}$$

where *n* is the number of detections during a survey, *A* is size of study region, *p(x)* is the average probability of detection (estimated across all surveys), *L* is the total survey effort, and *w* is the perpendicular right-truncation distance.

To estimate the probability of detecting a group with increasing distance from the trackline, g(x), a detection function was fitted using the multiple-covariate distance sampling (MCDS) function in the *mrds* package for R (Buckland et al., 2001, Marques and Buckland, 2004, Miller et al., 2019). A right truncation distance of 5.5 km was applied, while left truncation was not used as it did not improve the model fit. Both half-normal and hazard rate key functions (without adjustment terms) were considered with various covariate combinations, including sea state, glare, turbidity, observer, group size, sighting cue, and perpendicular distance. Functions were visually assessed, and models were ranked by Akaike's Information Criterion (AIC), with those within ≤3 AIC units considered equally supported (Mannocci et al., 2017). The most parsimonious model was selected, given it satisfied the Cramer-Von Mises goodness of fit test.

The final model selected was an Independent Observer (IO) configuration, in which two observers in tandem on each side of the aircraft (port and starboard) search independently of each other. The IO configuration assumes that the whales did not move in response to the aircraft between detections made by the tandem observers.

Detections were recorded as binary outcome (i.e., detected or not detected by the second observer), and the detection probabilities were modelled as logistic function (Huggins, 1989) with environmental covariates and perpendicular distance included (Buckland et al., 1993) where models were improved by accounting for variations in detection probability.

The data were analysed under a Point Independence (PI) assumption, which was appropriate because dependence in the detections (i.e., increasing correlation between observers' detections at greater distances) could be accounted for by including the relevant covariates in the mark-recapture (MR) model.

Abundance estimates were corrected for availability using drone focal follows conducted in the Gulf in 2024 (as no other data were available from the same year of the survey, or any other year, for whale groups in Exmouth Gulf). Availability, including time spent at the surface, is expected to vary with group composition and behaviour (e.g., groups with calves versus those without, resting versus surface-active behaviour).

A comparison of group composition between the aerial survey (2018) and drone datasets used to calculate availability (2024) showed no significant difference in the proportion of groups with calves (means = 0.39 and 0.35, respectively; χ-squared = 1.14e-29, df = 1, p = 1). However, availability estimates based on the drone focal follow data used in this study may be biased due to sampling limitations. The dataset included only groups that could be tracked for at least one full dive and surface interval. Consequently, groups that spent long periods either at the surface or underwater – such as resting mother-calf pairs (see Bejder et al., 2019) – were not included.

In the absence of published drone group focal follow data that include resting mother-calf pairs, the drone data used here were considered to provide the best available representation of groups detected during aerial surveys. These data are specific to Exmouth Gulf and correspond to the period of seasonal occupancy, capturing the relevant breeding behaviours, rather than observations from other locations or different stages of the species' reproductive cycle.

Future analyses should incorporate availability estimates that account for all group compositions and behaviours to improve correction accuracy. This is particularly important when considering the occupancy patterns in the Gulf, where non-calf groups dominate in August, followed by a high number of calf groups in September and October (Irvine and Salgado Kent, 2019). Incorporating these seasonal variations will enable more accurate corrections to be applied at the appropriate times.

3.4.3 *Availability*

For a group to be 'available' for detection by an observer, it must be at or near the water's surface (i.e., visible). To estimate the probability of groups being available for detection, drone focal follows were used to define durations in which groups were visible and not visible to observers over dive cycles. The non-instantaneous availability estimator developed by Laake et al. (1997) and adapted further (see equation below) by Salgado Kent et al. (2012) was applied. This estimator also accounts for the period of time a given area remains within an observer's field of view of during an aerial survey, as given by the equation:

$$\hat{p}(a) = \frac{E(s)}{E(s) + E(d)} + \frac{E(d)[1 - e^{\frac{-t}{E(d)}}]}{E(s) + E(d)}$$

Where $E(s)$ is the expected surfacing time of a pod, $E(d)$ is the expected dive duration and t is the time that the pod is within the detectable range of the observer, given the physical constraints of the aircraft. t is a function of the forward and aft viewing angles of the perpendicular line from the centrepoint of the aircraft, given the viewing area of an observer is semicircular with a fixed radius (McLaren, 1961). t is calculated as:

$$t = \frac{d_1 + d_2}{v}$$

where v is the velocity of the aircraft and $d_1 + d_2$ is the distance covered by the animal within the observer's detection range (time window). These distances were calculated trigonometrically.

To estimate the $E(s)$ and $E(d)$ of humpback whales in the Gulf, we analysed data collected by Remotely Piloted Aircraft (RPA) from August – October 2024. These RPA focal follows were carried out haphazardly within the study area using a DJI Phantom 4 Pro launched from a 7m vessel. The primary objective of the flights was to collect photogrammetric and behavioural data of humpback whales (as it was work being conducted as part of a separate project).

Each flight was approximately 15 minutes in duration, dictated by the drone battery life, and was conducted at an altitude of 30m. However, for larger groups (four or more individuals) the altitude was increased to 50m to ensure that the entire group could be captured within the frame. Alongside the RPA footage, additional data on group composition, behaviour and environmental conditions (including water turbidity and depth) were recorded.

Forty groups were included in the analysis for availability. The RPA footage was timestamped, and dive/surface intervals were calculated to the second. Dive times were defined as the time between the last individual of the group diving out of visibility and the first individual of the pod reappearing and becoming visible. Surface intervals were defined as the time between the first individual becoming visible, breaking the surface, and remaining continuously visible until the last individual dived out of visibility. For the purpose of this analysis, a whale was considered 'visible' when any clearly defined body features were discernible below the water's surface, as these allowed for confirmation of species identity. These features included:

- On the dorsal surface: rostrum ridge, blowhole, outline of upper jaw, dorsal fin, tail notch, or trailing edge of the fluke or pectoral fins.
- On the ventral surface: ventral grooves, genitals, clear outline of dark markings/pigments.

Timestamps were independently quality checked, with an error margin of 2 seconds being deemed acceptable. Dive/surface intervals were bootstrapped (with replacement, B=1000 pseudo samples) to estimate means. To ensure sample independence, each focal group was sampled only once, even when multiple dive-surface events were recorded.

Coefficient of variation

The overall population coefficient of variation (CV) was calculated for each survey using the Delta method (Buckland et al., 2004) to incorporate the CV for the availability parameter with those of the abundance estimates calculated using the *mrds* package (corrected for distance from the trackline, group size and perception bias).

Additional option for availability of resting pods

Due to the limited battery life of the drones, focal-follow data could not be collected for resting groups, requiring an alternative data source. To address this, published information from high-resolution depth profile data from Digital Acoustic Recording Tags (DTAGs) (Bejder et al., 2019) was used to obtain an idea of how abundance estimates might differ if different availability corrections were applied to resting groups and non-resting groups. These data, collected in Exmouth Gulf in 2017, targeted resting humpback whale mother-calf groups (Videsen et al., 2017, Bejder et al., 2019).

It is important to note that DTAGs were applied only to resting mothers in the study. Therefore, using depth profile information from these data as proxies for resting group availability assumes that the availability of a mother, when within one metre of the water surface, is representative of the entire mother-calf pair (and any other individuals in the group). Additionally, raw time-depth data were not available at the time of preparing this report, preventing the calculation of complete estimates with coefficient of variation (CV) values. Despite these limitations, evaluating the potential difference in absolute abundance estimates by accounting for resting groups separately was considered relevant here, as their availability differs from that of non-resting groups.

3.4.4 Intergroup distance and density estimates

We defined intergroup distance as the distance between each humpback whale group and its nearest neighbour. We defined a humpback whale group as a singleton or two or more humpback whales within one to two body lengths of each other, generally moving in the same direction and at the same rate of travel (Whitehead, 1983, Corkeron et al., 1994). The distance between groups was measured in ArcGIS Pro 3.3 using the NEAR_DIST function which calculates the distance from each feature to the next closest feature.

The dataset was truncated to groups sighted between 111m and 1200m from the aircraft as this range was consistent with past estimates of uniform detectability at distance from the aircraft where all humpback whales are detectable by the observers (Tucker, 2023). Note that these measures do not account for groups that may have been unavailable for detection. For this reason, density estimates that correct for detectability (including availability and perception bias, as per methods described for abundance estimation above) are included in this report.

Frequency histograms were generated in the *ggplot2* package in R (Wickham, 2016), with intergroup distances grouped into 100 m bins. This binning allowed for comparison with state and commonwealth guidelines on separation distances and minimum approach distances (100 m and 300 m) as outlined in the Western Australian Biodiversity Conservation regulations (2018) and the Australian National Guidelines for Whale and Dolphin Watching (2017).

4. RESULTS

Nine aerial surveys were conducted between 8 August and 2 November 2018, covering a total survey effort of 3,392 km and a cumulative area of 37,312 km^2 over the season. In total, 1,661 humpback whale groups were observed, comprising 2,772 individuals, including 688 calves (**Table 4-1**).

Table 4-1. Summary of humpback whale sightings and survey effort for each survey.

Date	Survey Number	Humpback groups	No. whales	No. calves	Survey Effort (km)	Study Area (km²)
8/08/2018	1	60	93	9	427	4701
18/08/2018	2	79	120	6	371	4085
27/08/2018	3	165	257	30	371	4077
8/09/2018	4	167	263	44	371	4079
20/09/2018	5	446	754	166	374	4119
2/10/2018	6	340	607	196	370	4067
12/10/2018	7	249	424	154	370	4067
23/10/2018	8	118	199	68	370	4066
2/11/2018	9	37	55	15	369	4051
Total	9	1661	2772	688	3392	37312

4.1. Distribution

Humpback whale distribution in Exmouth Gulf has been previously reported by Irvine and Salgado Kent (2019) and is summarised here. Whales were broadly distributed throughout the Gulf, except in the shallow waters along the southern and eastern shores. Calf groups were more concentrated in the southern two-thirds of the Gulf, mainly in the central and western portions (**Figure 4-1**).

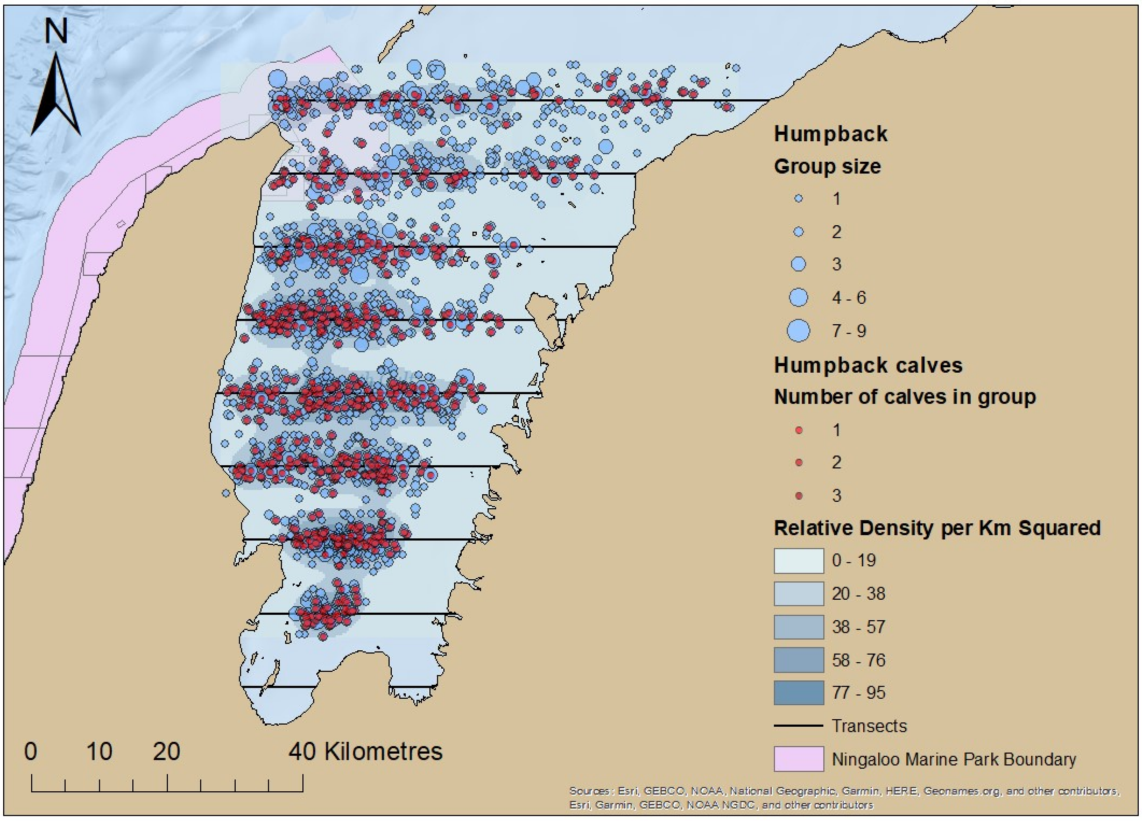

Figure 4-1. Distribution of humpback whales in Exmouth Gulf during aerial surveys between 8 August and 2 November 2018. Source: (Irvine and Salgado Kent, 2019).

Humpback whale distribution varied temporally throughout the breeding season (Appendix: **Figure 10-1 - Figure 10-9**). During early August, humpback whales were concentrated in the northern and western areas of Exmouth Gulf. By late August, their distribution had expanded southward, with high densities observed mainly in the central to western regions of the Gulf. This expansion continued into September, with the distribution encompassing nearly the entire Gulf, other than the shallow waters along the eastern and southern shores. In mid-October the distribution began retreating from the north-east, with whales primarily occupying the south-western three-quarters of the Gulf. By November, their distribution had contracted further, with most whales concentrated in the western areas of Exmouth Gulf.

4.2. Group size and composition

Humpback whale group sizes ranged from 1 to 9 individuals, with a mean of 1.67 (±0.69). Calves were present in 41% of all observed humpback whale groups.

4.3. Abundance (corrected for distance and perception bias)

The best-fitting MRDS model included a half-normal detection function, and three covariates: distance, group size, and group composition by cue (Cramer-von Mises test: 0.34, p = 0.11). The average detection probability was 0.41 (CV = 0.02). The model indicated that individual tandem observers detected 82% (CV = 0.02) of whale groups on the trackline, while combined, they detected 96% (CV = 0.01).

The distribution of perpendicular distances of groups detected from the trackline and the fitted detection function are presented in **Figure 4-2**. Abundance estimates corrected for detectability and perception bias (those adjusted for distance from the trackline, group size and composition and perception bias but not availability bias) are presented in **Table 4-2**. These abundance estimates ranged from 117 (CV = 0.24) to 1,616 (CV = 0.14) individuals per survey (**Table 4-2**).

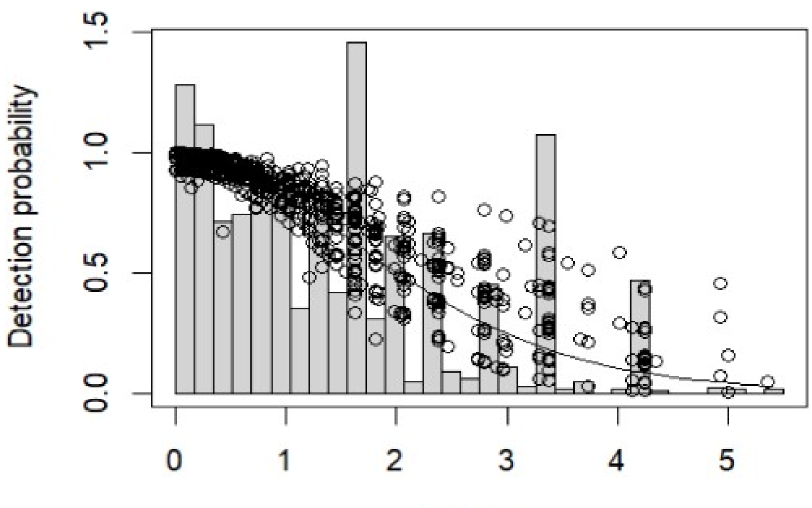

Figure 4-2. Histogram of perpendicular distance (m) and fitted detection functions for best AIC selected model.

Table 4-2. Density and abundance estimates for humpback whale groups and individuals in Exmouth Gulf, corrected for detectability (not corrected for availability bias).

		No. groups				No. individuals			
Date	Survey	D	CV(D)	N	95%CI	D	CV(D)	N	95%CI
8/08/2018	1	0.03	0.24	108	63 - 184	0.04	0.28	154	82 - 289
18/08/2018	2	0.05	0.36	164	74 - 364	0.07	0.34	239	112 - 514
27/08/2018	3	0.11	0.13	389	290 - 522	0.16	0.13	595	448 - 792
8/09/2018	4	0.10	0.10	368	292 - 464	0.16	0.10	567	448 - 717
20/09/2018	5	0.27	0.15	970	694 - 1354	0.45	0.14	1616	1170 - 2231
2/10/2018	6	0.21	0.11	767	594 - 990	0.38	0.11	1362	1060 - 1751
12/10/2018	7	0.15	0.28	542	289 - 1019	0.25	0.29	922	485 - 1755
23/10/2018	8	0.07	0.23	263	158 - 438	0.12	0.23	442	264 - 743
2/11/2018	9	0.02	0.23	80	47 - 135	0.03	0.24	117	68 - 202

D density = (individuals km^2), CV(D) = coefficient of variation of density, N = abundance estimate, *95%CI* = 95% confidence interval.

4.4 Availability Probability

Based on drone survey data, non-resting humpback whale groups were estimated to be visible at or just below the surface of the water, and available for detection by aerial observers, 54.19% of the time (CV = 0.0002). To account for individuals that were submerged and not available for detection during the surveys, a correction factor of 1.85 was applied to the population estimates corrected for detectability.

To explore how abundance estimates might vary with different availability correction factors for resting and non-resting groups, we applied the drone-based correction factor of 1.85 (described above) to non-resting groups, and a DTAG-based correction value of 4 to resting groups. The DTAG-based value was derived from the reported proportion of time resting mothers in the Gulf spent within one metre of the surface (~25%) (Bejder et al., 2019).

While the drone-based correction factor was based on a probability estimate of availability using bootstrapped measurements, raw data were not available from the DTAG recordings at the time this report was prepared. Thus, a single sample statistic (i.e., proportion) was used to derive a correction factor. It is important to note that the DTAG-based correction factor carries the assumption that the depth profile of a single tagged mother represents its group and does not include an estimate of uncertainty. As such, results must be interpreted with caution and within these limitations.

4.5 Absolute abundance

The absolute abundance estimates, adjusted for detection probability, and perception and availability bias, are presented in (**Table 4-3**). Using a single availability correction factor for all groups (based on the drone surveys), the estimated absolute abundance of humpback whales in Exmouth Gulf ranged between 216 (CV = 0.24) and 2,980 (CV = 0.14), depending on the time of year. The highest estimated abundance during the peak occupancy period was 2,980 humpback whales (CV = 0.14) on 20 September 2018.

Whale abundance varied throughout the season, with low numbers in August, peaking in late September and then declining through October until early November, when the surveys concluded (**Table 4-3**). The total number of humpback whales using the Gulf over the entire breeding season could not be determined due to insufficient data on residency times.

Table 4-3. Density and abundance estimates of humpback whale individuals in Exmouth Gulf, corrected for availability bias.

		No. individuals (using drone-based availability)				No. individuals (using drone and DTAG-based availability)	
Date	Survey	D	CV(D)	N	CV	D	N
8/08/2018	1	0.08	0.28	285	0.28	0.08	291
18/08/2018	2	0.12	0.34	442	0.34	0.13	447
27/08/2018	3	0.30	0.13	1098	0.13	0.31	1149
8/09/2018	4	0.29	0.10	1045	0.10	0.33	1180
20/09/2018	5	0.82	0.14	2980	0.14	0.99	3572
2/10/2018	6	0.69	0.11	2513	0.11	0.84	3012
12/10/2018	7	0.47	0.29	1701	0.29	0.69	2537
23/10/2018	8	0.23	0.23	817	0.23	0.27	1008
2/11/2018	9	0.06	0.24	216	0.24	0.06	228

D density (individuals km^2), CV(D) = coefficient of variation of density, N = abundance estimate, CV = coefficient of variation of abundance.
*NB. CVs for D and N using availability from both drone and DTAG data are not reported here as raw data for DTAG data were not available to estimate the population availability parameter for resting groups and incorporate its uncertainty.

If the approach in applying distinct availability correction factors to resting and non-resting groups were representative of the population (i.e., if the reported sample proportion of time DTAG-tagged mothers spent within one metre of the surface was representative of all resting groups), the absolute abundance would be greater than estimates based on a single correction factor. Using this approach, the estimated absolute abundance of humpback whales in Exmouth Gulf would range from 228 and 3,572, depending upon the survey (**Table 4-3**). The maximum of 3572 humpback whales at peak occupancy represents an increase of 592 individuals compared to the estimate derived using a single availability correction factor across all groups.

4.6 Intergroup distances

The mean intergroup distance for humpback whales was 1,214 ± 1,265 m (**Table 4-4**) and varied throughout the season, depending on whale abundance (Appendix: **Figure 10-1 - Figure 10-9**). Specifically, mean intergroup distances decreased as whale abundance increased and increased as abundance declined (**Table 4-4**). Minimum and maximum intergroup distances followed the same pattern. The lowest recorded intergroup distance was 20 m at peak occupancy on 20 Sept 2018, when an estimated 2,980 whales occupied the Gulf. Conversely, the highest intergroup distance was 14,271 m on 8 Aug 2018, when only 285 whales were estimated in the Gulf.

Table 4-4. Minimum, maximum and mean (± SD) intergroup distances for humpback whales.

Date	Survey Number	Min (m)	Max (m)	Mean ± SD (m)	Total abundance
8/08/2018	1	690	14271	2776 ± 2612	285
18/08/2018	2	189	4873	2330 ± 1621	442
27/08/2018	3	55	4646	1585 ± 1109	1098
8/09/2018	4	28	7270	1525 ± 1349	1045
20/09/2018	5	20	3037	832 ± 655	2980
2/10/2018	6	45	3682	851 ± 643	2513
12/10/2018	7	56	6476	1092 ± 1181	1701
23/10/2018	8	305	10342	1895 ± 1997	817
2/11/2018	9	439	6471	1968 ± 1583	216
	All surveys	20	14271	1214 ±1265	

Over the duration of the breeding season, most humpback whales (93.4%) were located within 3000 m of their nearest neighbour, though intergroup spacing changed over time. In early August (survey 1) when whale abundance was low, 77.8% of whales were within 3000 m of the nearest neighbour, and none were within 600 m. By late September (survey 5) during peak abundance, 99.4% of whales were within 3000 m of their nearest neighbour while 47.2%, 25.8% and 8.2% were within 600 m, 300 m and 100 m respectively (**Figure 4-3**).

During periods of highest abundance (surveys 5 – 7), a high percentage of groups were spaced at less than 600 m, with 39.6 - 47.2% under 600 m, 8.1 - 25.8% under 300 m and 1.8 - 8.2% under 100 m. Minimum intergroup distances were below 600 m on all surveys between 18 August and 2 November (surveys 2-9), below 300 m in all surveys between 18 August and 12 October (surveys 2-7) and below 100 m in all surveys between 27 August and 12 October (surveys 3-7) (**Figure 4-3**).

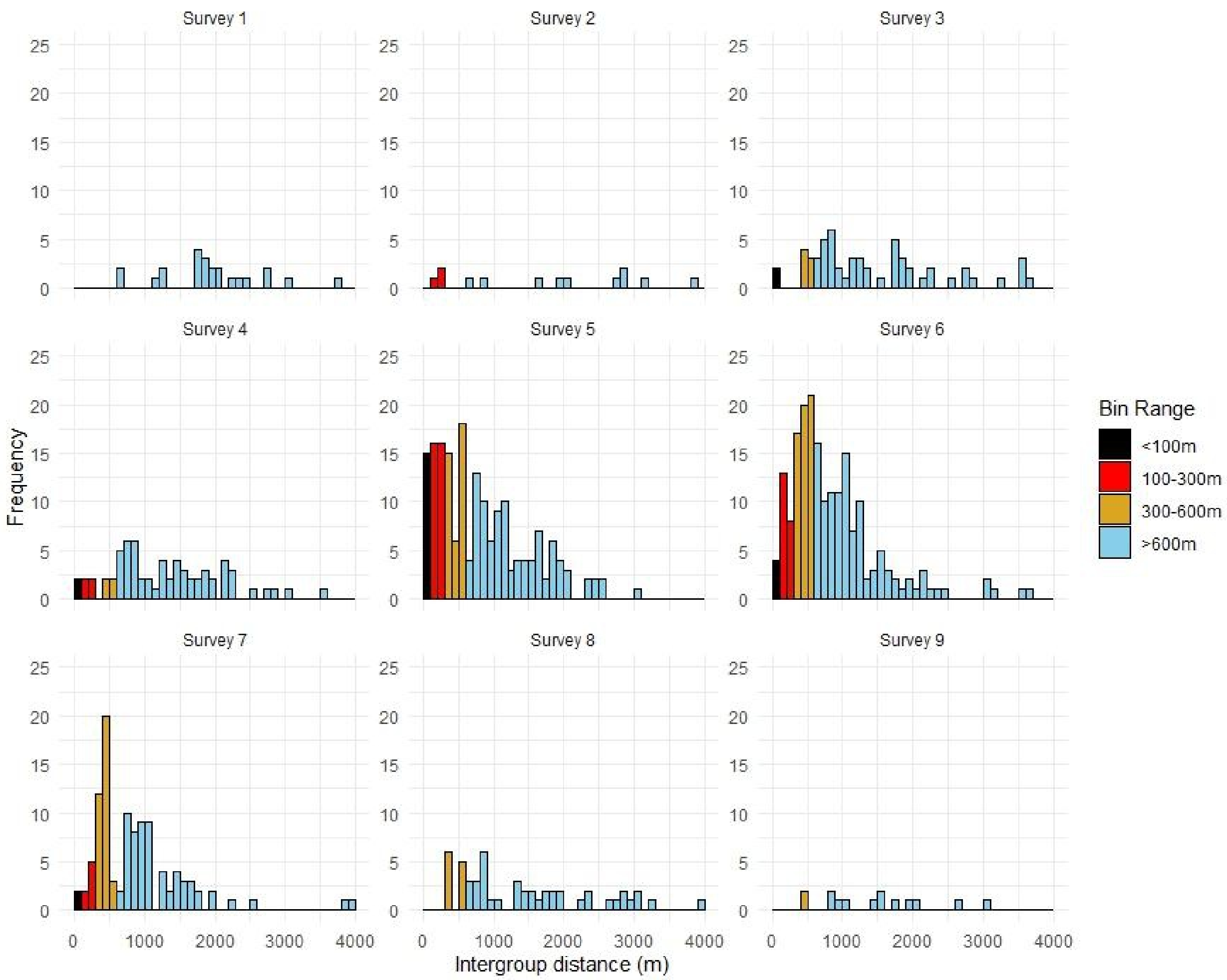

Figure 4-3. Frequency histogram of intergroup distances between humpback whale groups for each aerial survey.

5. Discussion

The results of this study provide estimates of humpback whale abundance and intergroup distances in Exmouth Gulf during 2018. Our findings confirmed that large numbers of humpback whales, including calves, occupied the Gulf between August and November, and were distributed across most areas, except for the shallow waters of the eastern and southern shores. Peak abundance occured in mid- to late September, coinciding with the peak of the BSD humpback whale southern migration along the Western Australian coast (Jenner et al., 2001). At this time, it was estimated that approximately 3,000 whales (2,980 CV = 0.14) were present in the Gulf, with densities reaching 0.82 whales / km^2. During peak occupancy, humpback whale groups were spaced at an average of 831 ± 666 m apart, with some groups as close as 20 m. These intergroup distances, and their variability over the period of occupancy, have implications for management and mitigation strategies that rely on minimum separation distances between wildlife and human activites.

This study provides the first absolute abundance estimates for humpback whales in Exmouth Gulf over the breeding season, using aerial surveys specifically designed for this species. A recent study by Tucker (2023) estimated humpback numbers between 2900 - 3900 during the 2017 peak period in the Gulf, based on aerial surveys optimised for dolphin sightings. While both estimates are relatively comparable, discrepancies may stem from differences in survey methodology and availability bias corrections. The Tucker (2023) study used the best available data at the time, which included RPA focal follow data from North Stradbroke Island, Queensland (Hodgson et al., 2017) to estimate availbility. However, these data were from a different population and location, where behaviours may differ from those in the Gulf. Additionally, boat-based observational data from west of North West Cape (outside the Gulf; Jenner & Jenner data, unpublished) were used for comparison of availability estimates. While spatially more relevant, these boat-based estimates did not reflect observer visibility from an aerial perspective, and are known to underestimate availability, potentially leading to overestimation of abundance (Sucunza et al., 2018).

In contrast, our study used drone focal-follow data collected in Exmouth Gulf in 2024, providing a location-specific and more relevant availability correction for aerial surveys in the Gulf. This approach accounted for whale visibility rather than surfacing behaviour, reducing potential bias in abundance estimation. To explore alternative availability bias corrections, we applied data from DTAGs (Digital Acoustic Recording Tags) deployed on resting mothers (Bejder et al., 2019). While these data assume that the DTAG-tagged mothers' surface time accurately represents resting groups in the population, they illustrate how different availability bias corrections can affect abundance estimates. Given that a high percentage of groups in Exmouth Gulf are resting mother-calf pairs, the abundance estimate using this correction (3,572) may be more representative of the true (actual) number of whales using the Gulf. However, further research is required to verify this estimate. Encouragingly, this estimate falls within the range of abundance estimates produced by Tucker (2023), which lends it support. Addressing the knowledge gap in availability data for resting mother-calf groups in Exmouth Gulf should be a priority for future research.

Previous theoretical carrying capacity estimates for Exmouth Gulf, based on aerial survey data collected in 2004 and 2005, ranged from 1,187 – 1,482 humpback whales at any given point in time, based on minimum intergroup distances in high density areas (Braithwaite et al., 2012). However, the authors suggested that as the BSD population increased, whales may adapt by reducing their average spacing distance. Our findings support this, as the 2018 peak abundance of 2,980 whales more than doubled the previously estimated carrying capacity, while the mean intergroup distance (1,214 ±1,265 m) was substantially lower than the ~2 km calculated in the 2004 - 2005 surveys.

Humpback whale spacing behaviour in the Gulf has also been investigated using 2004-2005 aerial survey data, which indicated that humpback whale groups tend to aggregate rather than distribute randomly. Despite variations in density, the total space occupied in the Gulf remained relatively constant, suggesting that all suitable habitat is utilised (Braithwaite et al., 2012). Consequently, as whale numbers increase, density also increases until the Gulf reaches its carrying capacity (Braithwaite et al., 2012).

Our study indicates a substantial increase in humpback whale density between 2005 and 2018, with the mean density in 2018 exceeding previous estimates. Whether Exmouth Gulf has reached its carrying capacity or if density will continue to increase remains uncertain. However, the observed increase in density and corresponding decrease in intergroup distance is likely linked to the continued growth of BSD, which was estimated to be increasing at over 10% per year from 2001-2008 (Salgado Kent et al., 2012). Notably, the number of whales observed in 2018 was approximately four times greater than that recorded in the 2004-2005 surveys.

It is important to note that the intergroup distances reported here are based on uncorrected observations from aerial surveys and do not account for submerged whales that were unavailable for detection. Given that intergroup distances decrease with increasing abundance, the reported values are likely conservative.

5.2. Management Implications

Humpback whales occupy almost the entire Gulf other than the shallow waters along the eastern and southern shores. Given that all the available space is used, any further increase in abundance will either reduce intergroup distances, or push whales into areas beyond the Gulf. If the BSD population continues to grow, competition for suitable habitat in the Gulf will also likely increase.

At the same time, the availability of suitable resting space in the Gulf may decline as anthropogenic disturbances increase, such as industrial or coastal developments and increasing vessel activity. If the Gulf reaches its carrying capacity, resting areas will need to expand into other coastal regions. This expansion could extend to nearby locations such as Onslow, where coastal industries and vessel traffic may pose additional risks to humpback whales. The risks of increased vessel activity are outlined below.

Vessel strikes and humpback whale vulnerability

Vessel strikes are recognised as a significant threat to whale populations worldwide, often resulting in injury or death (Peel et al., 2018). A global database indicates that 18% of reported vessel strikes occur in Australian waters, with humpback whales being the most commonly affected species (Peel et al., 2018). High-density aggregation sites are considered high risk areas for vessel strike (Cates et al., 2017).

During the humpback whale breeding season, Exmouth Gulf supports exceptionally high whale densities, which may continue to increase as the BSD population grows and the Gulf approaches its carrying capacity. Many of these whales are mothers nursing their calves. During this time, mothers spend extended periods at or near the surface, increasing their vulnerability to vessel strikes as they remain within the reach of vessel hulls (Bejder et al., 2019). This risk was evident during the 2024 breeding season, when several lactating humpback whale mothers in the Gulf were observed with injuries consistent with vessel strikes (**Figure 5-1**).

Figure 5-1. Lactating humpback whale mothers in Exmouth Gulf with recent injuries consistent with vessel strikes: (a) top and side views of a large wound on the mid-dorsal surface, photographed on 13 September 2024; and (b) top and side views of a fresh wound on the dorsal fin, photographed on 7 October 2024. (Photos: Lyn Irvine)

Impacts of vessel noise on humpback whales

Like all cetaceans, humpback whales use sound for communication, navigation and predator avoidance. However, vessel noise from shipping and smaller vessels overlaps with the frequencies used by whales, potentially causing injury such as temporary or permanent shifts in hearing threshold (TTS, PTS), behavioural disturbance, acoustic masking, stress and habitat displacement (Erbe et al., 2019).

In Exmouth Gulf, vessel noise has been shown to alter the behaviour of resting mother-calf pairs, leading to reduced resting time, increased respiration rates and faster swim speeds (Sprogis et al., 2020). These behavioural changes can impact calf development, as energy is diverted from essential processes such as suckling and calf growth to other energy-intensive activities such as avoidance behaviours (Bejder et al., 2019). Mothers and calves rely on low-level vocalisations to maintain close contact, but acoustic masking of these vocalisiations may increase the risk of separation, reducing suckling rates and ultimately affecting calf growth and development (Videsen et al., 2017).

Management strategies and intergroup distances

Management strategies aimed at mitigating vessel disturbance typically rely on maintaining separation distances between vessels and whales. The observed spacing between humpback whale groups has direct implications for Marine Fauna Management Plans, particularly those that depend on separation distances to minimise disturbance.

Under the Western Australian Biodiversity Conservation Regulations (2018), vessels must maintain a minimum separation distance of 300 m within a 60° arc to the front or rear of a whale and 100 m to the side. The Australian National Guidelines for Whale and Dolphin Watching (2017) specify minimum approach distances of 300 m for whale groups with calves and 100 m for whale groups without calves.

During periods of low whale abundance, vessels can typically navigate around closely spaced groups. However, during periods of high abundance, whales occupy almost the entire Gulf, making it difficult for vessels to avoid passing between groups. To comply with these regulations, whale groups must be at least 600 m apart, allowing vessels to manoeuvre between them without violating the minimum approach distances.

Survey data indicate that between mid-August and early November, intergroup distances are often below regulatory requirements. During periods of high abundance, a substantial percentage of humpback whale groups are spaced at less than 600 m apart, making full compliance with regulations impossible for much of the breeding season. This raises concerns about potential disturbance, displacement, and increased risk of vessel strikes.

Given these findings, impact assessments for proposed developments in Exmouth Gulf must incorporate mitigation strategies that address the limited intergroup distances of humpback whales to be effective.

6. CONCLUSION

Exmouth Gulf is an important habitat for humpback whales between July and November, providing sheltered waters for mothers and calves, during a critical stage in calf development. However, the high abundance of whales during the breeding season poses challenges for implementing minimum approach distances outlined in the Western Australian Biodiversity Conservation Regulations (2018) and Australian National Guidelines for Whale and Dolphin Watching (2017). Given the close proximity of whale groups, these guidelines may not be sufficient to mitigate risks in Exmouth Gulf. To reduce the likelihood of vessel strikes and noise disturbance, effective management strategies would include measures such as restricting vessel activities during periods of high whale abundance, implementing speed limits, and establishing exclusion zones in critical nursery areas.

7. KNOWLEDGE GAPS AND RECOMMENDED FUTURE WORK

The following knowledge gaps have been identified:

- Availability data for resting mother-calf groups in Exmouth Gulf

There is currently a lack of data on the availability of resting mother-calf groups in Exmouth Gulf for detection during aerial surveys. Availability bias corrections rely on accurate measures of the time whales spend at or near the surface, yet existing data for resting mother-calf groups are limited. Future research should focus on collecting detailed availability data using relevant technologies, such as drone-based studies to improve the accuracy of abundance estimates and enhance management strategies.

- Residency periods for humpback whales in Exmouth Gulf

The total number of humpback whales using Exmouth Gulf over the breeding season cannot be determined without accurate data on individual residency periods. Current abundance estimates reflect the number of whales present at a given time but do not account for movement in and out of the Gulf throughout the breeding season. Understanding the duration for which different components of the population remain in the Gulf is essential for estimating total seasonal abundance and occupancy. Future studies should employ techniques such as photo-identification or satellite tagging to track individual residency durations and movement patterns. This information is essential for refining population estimates and ensuring effective conservation and management efforts in Exmouth Gulf and for the broader population.

8. Acknowledgements

We acknowledge the Traditional Owners of Exmouth Gulf, where this research was conducted - the Baiyungu, Yinnigurrura, and Thalanyji people - and pay our respects to their Elders past and present. This report was commissioned by the Department of Water and Environmental Regulation (DWER) as part of informing the Exmouth Gulf Taskforce advice. We thank the Minderoo Exmouth Research Laboratory (MERL) for providing boating and accommodation support in Exmouth, and Alek Nowak for his skilful and energetic skippering. Our appreciation extends to the Exmouth DBCA office for their assistance with accommodation and logistics. A special thank you goes to Eric 'Rollo' Roulston from Norwest Air Work for his dedication to the surveys and his meticulous flying – those transects were impressively straight and level! We are also grateful to the aerial survey team – Katie Anderson, Gemma Francis and Andrea Lopez – for their focus and attention in the air, especially during the busy flights, and for their diligence in the arduous task of transcribing. We extend our gratitude to the Animal Ethics committee from Edith Cowan University (ECU) for their support. The project was approved by the ECU Animal Ethics committee (ECU-23899) as part of a broader study on marine mammal critical habitat, connectivity and health indices in the Oceania region. It was conducted under a licence from the Department of Biodiversity, Conservation and Attractions (FO25000283-4c). Finally, we are grateful to Alex Zerbini for his statistical advice and Wendy Thompson for her thorough review and valuable contributions to strengthening this report.

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10. APPENDICES

Appendix: Humpback Whale Observations each survey. Figures 10-1 to 10-9 have been previously reported in Irvine & Salgado Kent (2019).

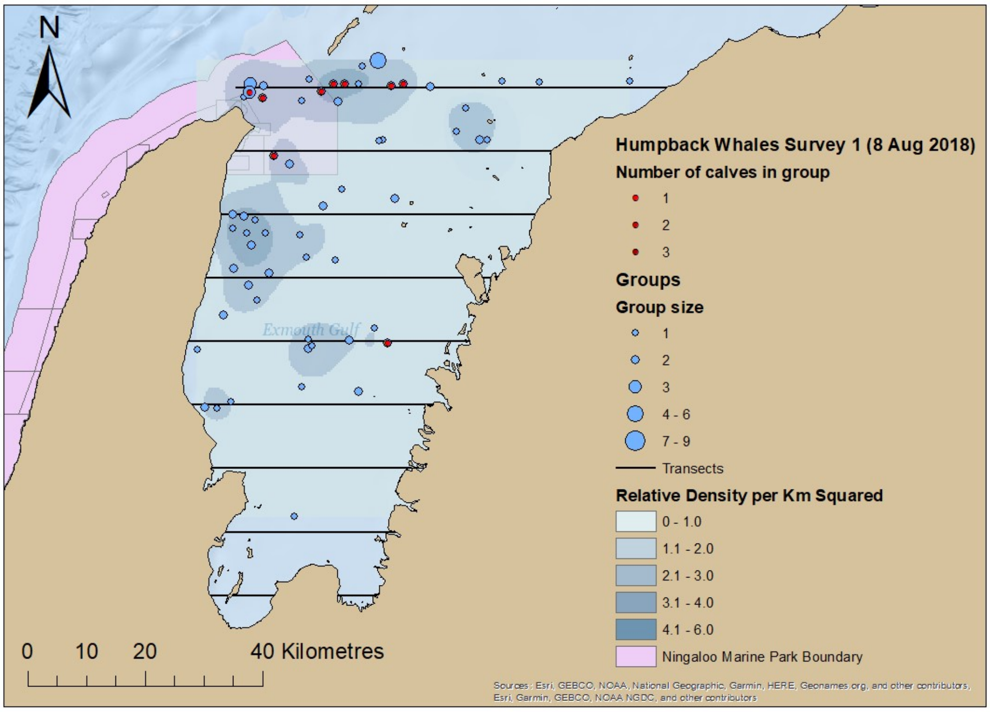

Figure 10-1. Distribution of humpback whales observed in Exmouth Gulf during survey 1 (8/08/2018).

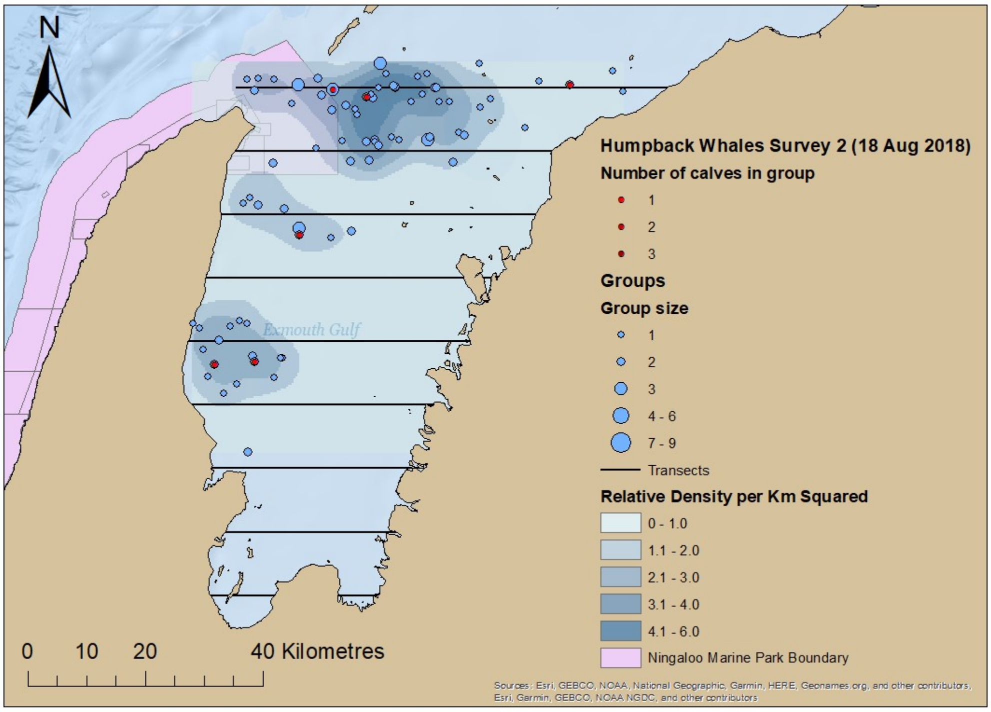

Figure 10-2. Distribution of humpback whales observed in Exmouth Gulf during survey 2 (18/08/2018).

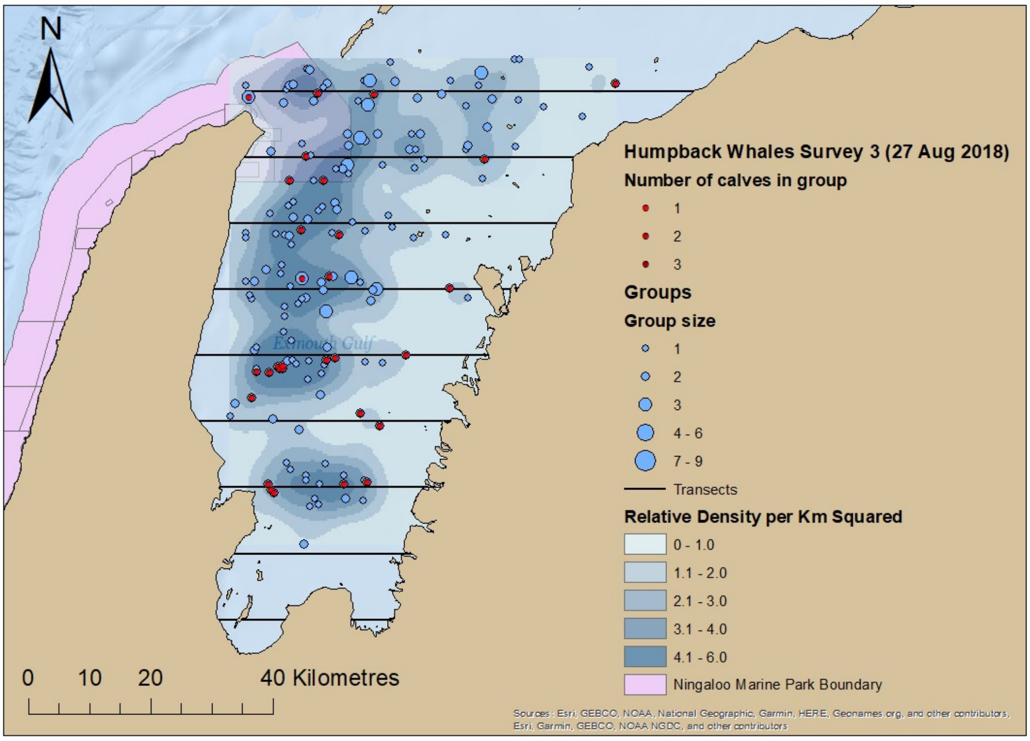

Figure 10-3. Distribution of humpback whales observed in Exmouth Gulf during survey 3 (27/08/2018).

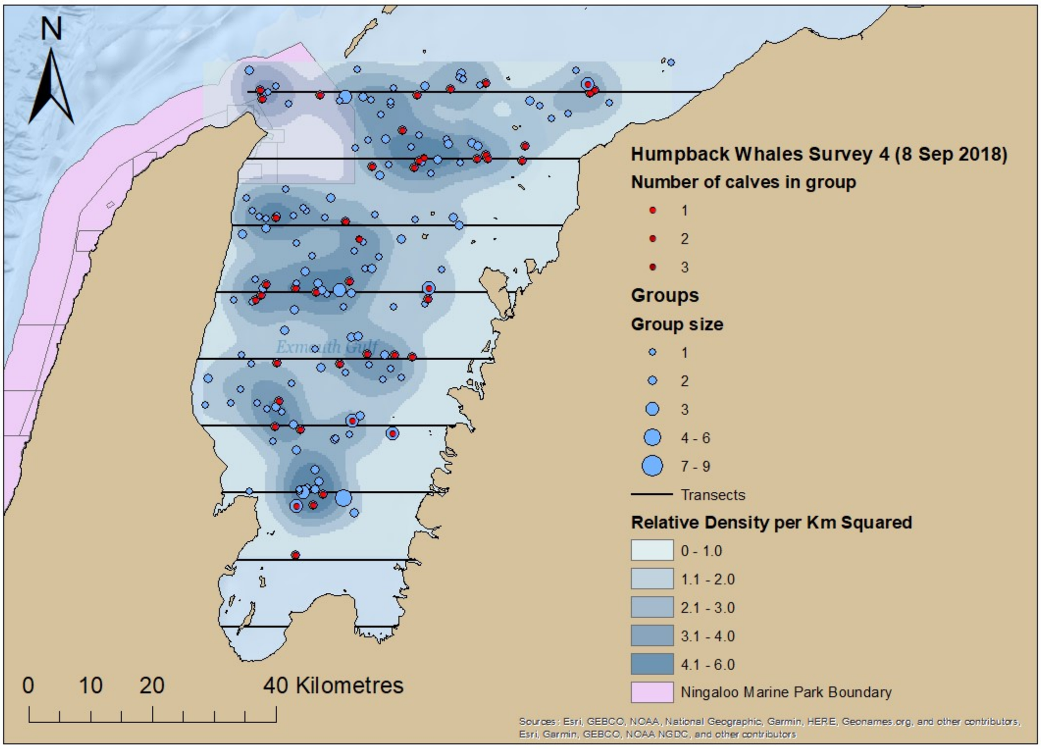

Figure 10-4. Distribution of humpback whales observed in Exmouth Gulf during survey 4 (8/09/2018).

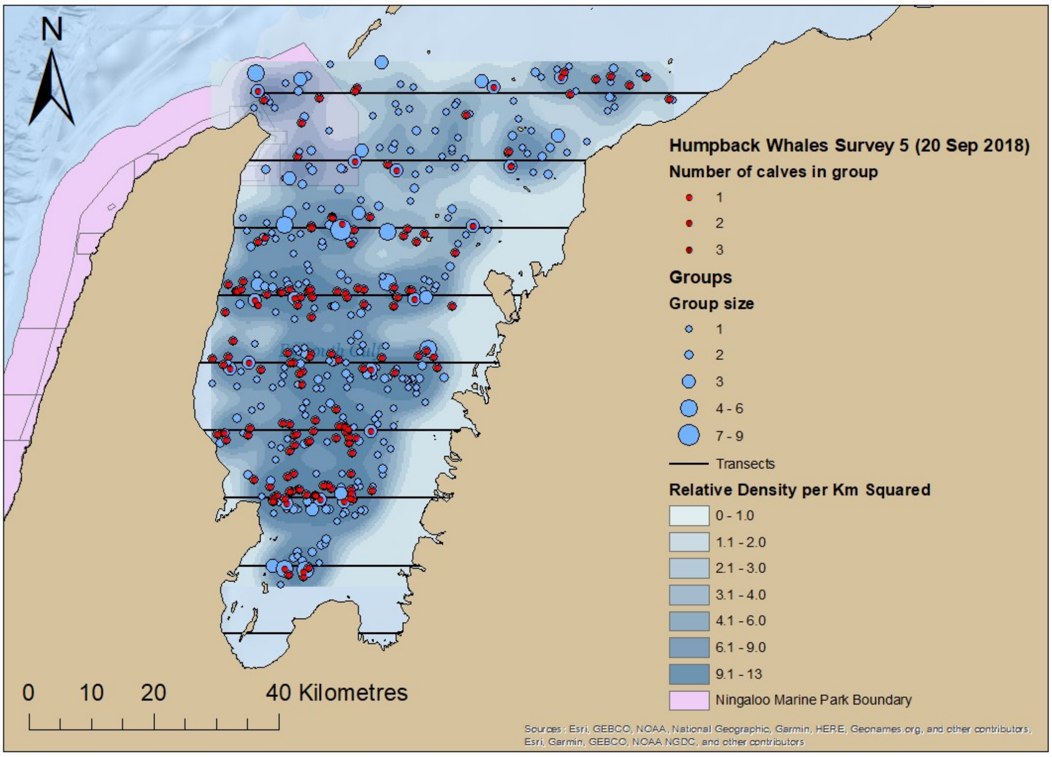

Figure 10-5. Distribution of humpback whales observed in Exmouth Gulf during survey 5 (20/09/2018).

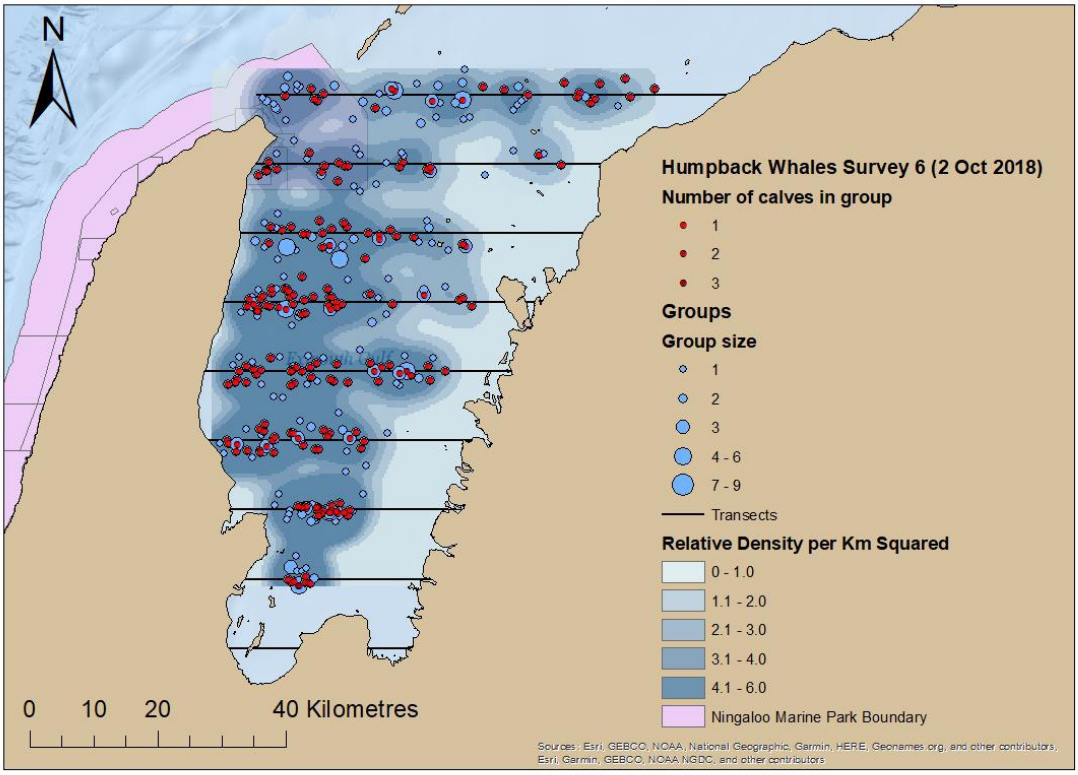

Figure 10-6. Distribution of humpback whales observed in Exmouth Gulf during survey 6 (2/10/2018).

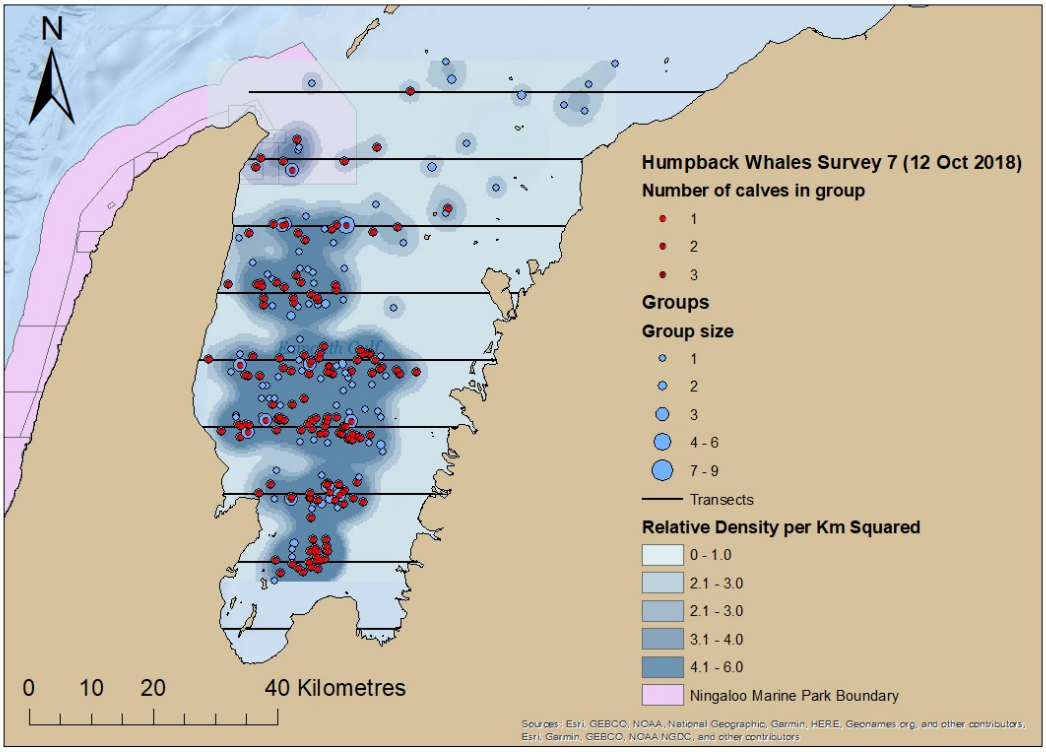

Figure 10-7. Distribution of humpback whales observed in Exmouth Gulf during survey 7 (12/10/2018).

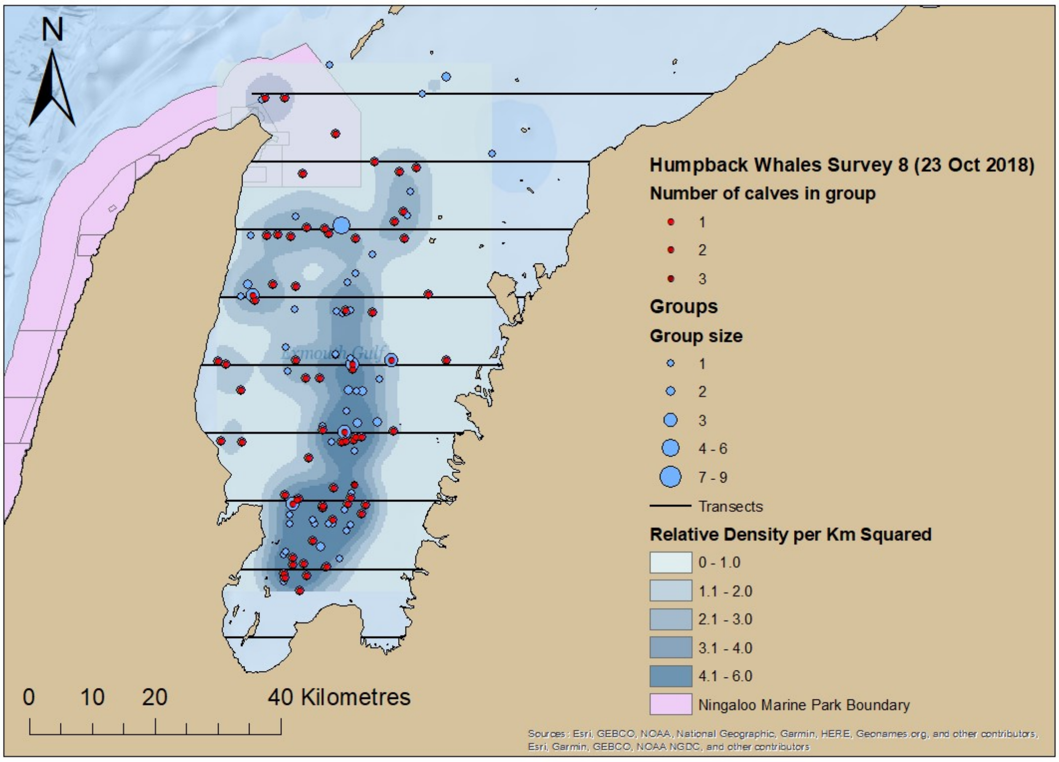

Figure 10-8. Distribution of humpback whales observed in Exmouth Gulf during survey 8 (23/10/2018).

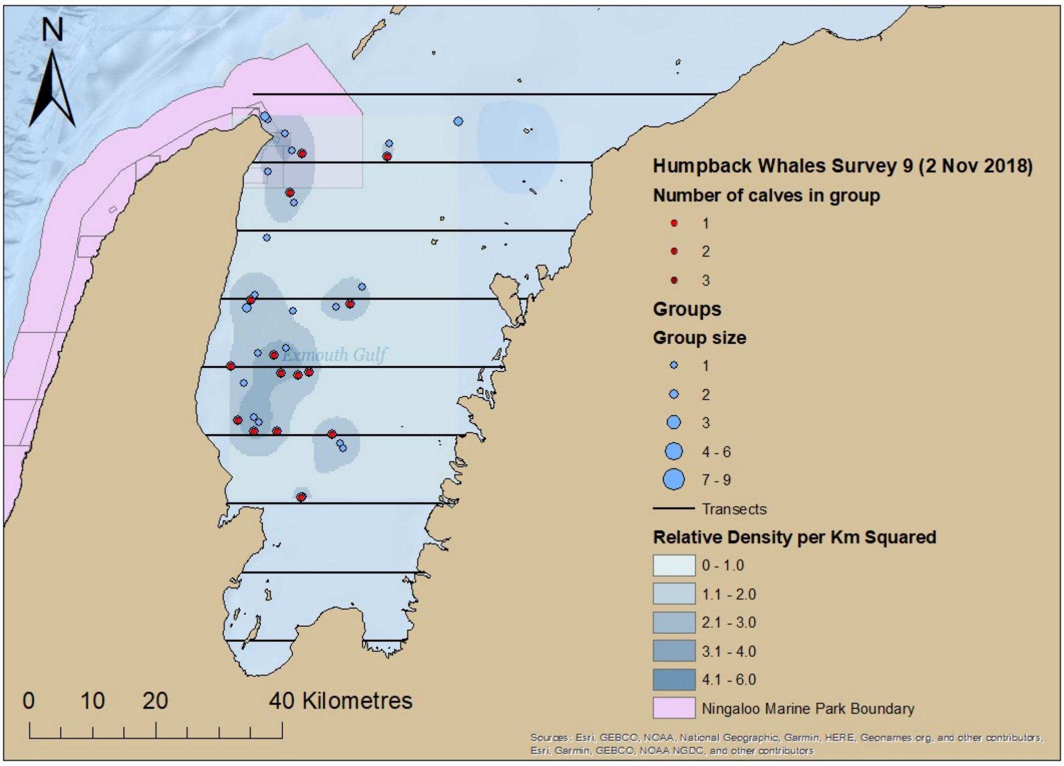

Figure 10-9. Distribution of humpback whales observed in Exmouth Gulf during survey 9 (2/11/2018).

Exmouth Gulf Baseline Acoustic Monitoring

Exmouth Gulf Baseline Acoustic Monitoring

Characterisation of Ambient Soundscape Including Marine Mammal Presence and Anthropogenic Contributions, Oct 2023 to Sep 2024

JASCO Applied Sciences (Australia) Pty Ltd

14th January 2025

Submitted to:

Exmouth Gulf Taskforce
Department of Water and Environmental Regulation
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P001751-001
Document 03620
Version 2.1 Final

Suggested citation:

Maxner, E.E., A.L. Richardson, N. Nunes, L.A.E. Huijser, J.J.-Y. Delarue, C.C. Wilson, C.D. Jolliffe, and C.R. McPherson. 2025. Exmouth Gulf Baseline Acoustic Monitoring: Characterisation of Ambient Soundscape Including Marine Mammal Presence and Anthropogenic Contributions, Oct 2023 to Sep 2024. Document 03620, Version 2.1 Final. Technical report by JASCO Applied Sciences for Western Australian Government.

Report approved by:

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1.0 DRAFT	Senior Scientific Reviewer	Capri Jolliffe	25 October 2024
2.0 FINAL	Senior Scientific Reviewer	Capri Jolliffe	19 December 2024
2.1 FINAL	Senior Scientific Reviewer	Capri Jolliffe	14th January 2025

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Executive Summary

JASCO Applied Sciences (Australia) Pty Ltd (JASCO) was contracted by the Western Australian Government's Department of Water and Environmental Regulation to conduct a baseline acoustic monitoring program (hereafter referred to as 'the program') using an underwater acoustic recorder in the Exmouth Gulf. The recorder was deployed in the western side of the Gulf to collect data on the baseline ambient noise conditions within one area of the Gulf. While the data collected does not provide a quantitative baseline for the entire area of the Gulf, the program has provided valuable information on the suite of anthropogenic, biotic and abiotic contributors to the soundscape that are likely to be broadly applicable throughout the Gulf. Throughout the report, the term Gulf will be used to refer to the study area, noting the study area did not cover the entirety of the Exmouth Gulf, but represents one sample site within the Exmouth Gulf. The primary purpose of the program was to inform the Exmouth Gulf Taskforce in characterising the Exmouth Gulf's marine soundscape. The program's specific objectives were to characterise the acoustic environment over a one-year period, to quantify marine mammal presence using acoustic detections, and to characterise the contributions from current anthropogenic activities. The data collected on marine mammals and vessels could be analysed in more detail in the future to achieve specific goals, such as informing impact assessments and project planning.

Two six-month monitoring periods were planned using an Autonomous Multichannel Acoustic Recorder (AMAR) located at a 15 m depth in the Exmouth Gulf, within humpback whale migratory and resting Biologically Important Areas (BIAs) and within a southern right whale reproduction BIA (see Figure 1). During the service trip after the first monitoring period, which lasted from 25 April 2023 to 1 October 2023, it was noted that the AMAR had stopped recording after nine days, approximately 186 days earlier than the estimated end-of-life of the batteries in the unit. The second monitoring period lasted from 1 October 2023 to 25 March 2024 (herein Period 1), and to meet the initial objective of one-year of acoustic monitoring, JASCO then deployed an AMAR for an additional six-month monitoring period from 25 March 2024 to 16 September 2024 (herein Period 2). This report presents the results of the analysis of acoustic data collected during the full-year monitoring period, 1 October 2023 and 16 September 2024.

The data collected provide a characterisation of the ambient soundscape of the southwestern portion of the Exmouth Gulf, including natural, anthropogenic, and biological sound sources. Only one recording station was included as part of this program, and the results of this program are thus limited to the south-western portion of the Gulf, however the results are likely to be broadly representative of the Exmouth Gulf. While the design of this study is not appropriate for differentiating spatial and temporal patterns of habitat use within the Gulf, it has facilitated an understanding of the different biological and anthropogenic sources of sound within the Gulf that can be broadly extrapolated to the Exmouth Gulf as a whole. Understanding finer scale patterns of species habitat utilisation, spatial and temporal presence would require multiple recording stations at different areas within the Gulf. The results of this study indicate that the soundscape of the southwestern Gulf was primarily dominated by biological sources with relatively little contribution from anthropogenic sound sources. Vessel traffic was the primary anthropogenic contributor within the acoustic data, however based on AIS data, heavy vessel traffic was restricted mostly to the northwestern side of the Exmouth Gulf with very limited traffic passing through the study area.

The main biological contributors to the soundscape were humpback whales and fish. Humpback whales were detected in the first monitoring period from the start until the end of October 2023. Humpback whales were detected again in Period 2 with acoustic detections from mid-July until the end of the recording period in September 2024. Fish were present throughout the year-long recording period. The large volume of detections confirms that the Exmouth Gulf is well used by this population seasonally. The year-long recording captured both the northbound and southbound migrations allowing for a better understanding of the period of use of the Exmouth Gulf by this species. Dolphins

were detected only occasionally during Period 1 but were more acoustically common during Period 2. appear to use the Exmouth Gulf primarily from mid-April until the recording end. It is possible, however, that snapping shrimp masked dolphin clicks, resulting in an underestimation of the number of detections. Further, while PAM is a proven and effective monitoring tool for dolphins, the detection range for clicks and whistles is much smaller than for lower frequency baleen whale vocalisations and thus detection relies on dolphins utilising the area around the recording station.

Weather conditions can influence the ambient soundscape primarily due to wind causing waves, which can increase sound levels above 100 Hz. Despite experiencing relatively high wind on many days over the recording period, weather does not appear to be the most substantial soundscape contributor of the area.

1. Introduction

1.1. Project Background

JASCO Applied Sciences (Australia) Pty Ltd (JASCO) was contracted by the Western Australian (WA) Department of Water and Environmental Regulation to conduct a baseline acoustic monitoring program (hereafter referred to as 'the program') using underwater acoustic recorders in the Exmouth Gulf. The primary purpose of the program was to inform the Exmouth Gulf Taskforce (Government of Western Australia 2024) in its mission to provide the Minister for Environment with high-level advice on the management of the Exmouth Gulf. JASCO's expertise was sought to characterise the Gulf's marine soundscape by fulfilling the following objectives:

- Characterise the acoustic environment over a period of one-year.
- Quantify marine mammal presence using acoustic detections.
    - Process data at a high level only and make available for future analysis.
- Characterise the contributions from current anthropogenic activities.
    - Make vessel data available for future analysis.

To achieve these objectives, the program used a JASCO Autonomous Multichannel Acoustic Recorders (AMAR; see Appendix A and www.jasco.com/amar) deployed for two six-month periods, for a total of a one-year, in the southwestern corner of the Exmouth Gulf at the location shown in Figure 1.

This report presents the combined results of the analysis of acoustic data collected between 1 Oct 2023 and 16 Sep 2024.

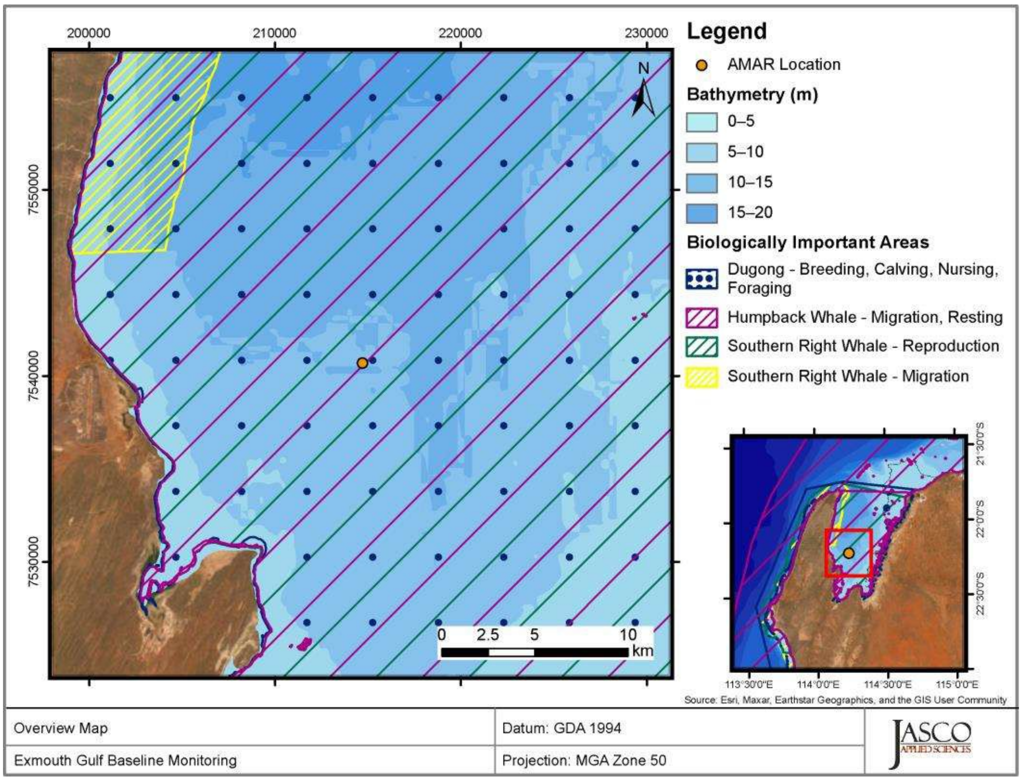


Figure 1. Map of the monitoring location in the Exmouth Gulf, with Biologically Important Areas for listed marine mammals for reference. The Autonomous Multichannel Acoustic Recorder (AMAR; orange dot) was moored at depth of 15 m.

1.2. Ambient Ocean Soundscape

The acoustic environment of a location is known as its soundscape. A soundscape is comprised of the cumulative contributions from abiotic (geophonic), biotic (biophonic), and human (anthrophonic) sound sources (Krause 2008). Ambient sound is defined as any sound present in the absence of human activity. It is also temporally and spatially specific (ISO 2017a). The Wenz (1962) curves in Figure 2 show the typical frequencies and spectral levels of many of these activities with additional Australian context being shown in the curves from Cato (2008) (Figure 3).

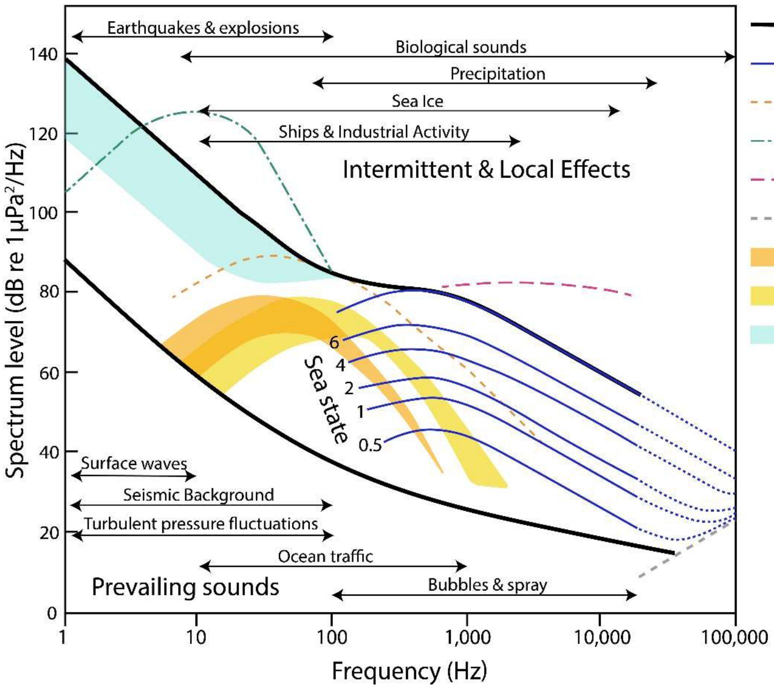


Figure 2. Wenz curves describing pressure spectral density levels of marine ambient sound from weather, wind, geologic activity, and commercial shipping (adapted from NRC 2003, based on Wenz 1962). The thick lines are the limits of prevailing ambient sound, which are included in some of the results plots to provide context.

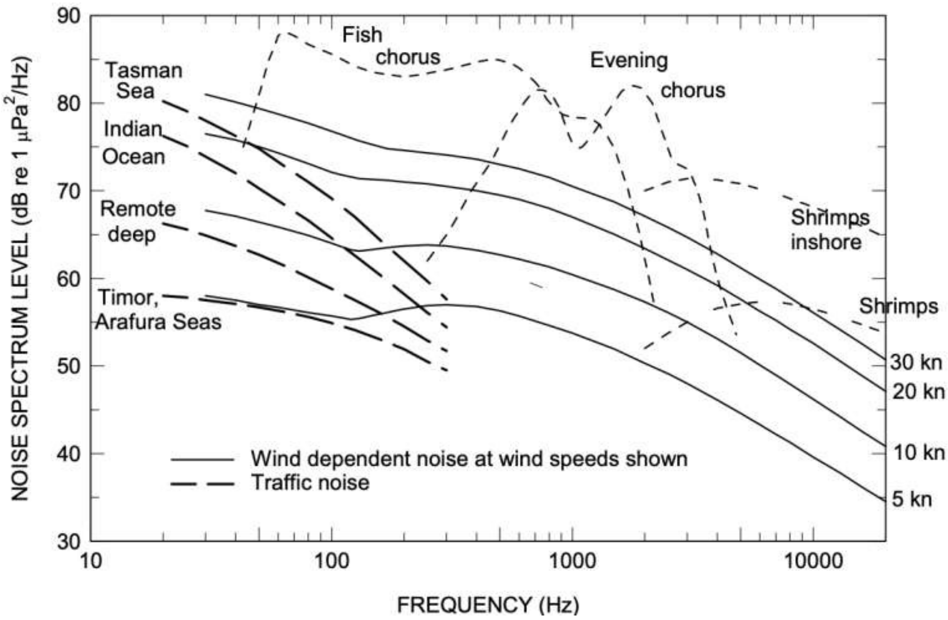


Figure 3. Summary of ambient noise spectra for the Australian region showing a wide range of traffic noise levels and biological choruses. Source: Cato (2008).

In the marine environment, the geophonic elements of a soundscape can act as proxies for oceanographic conditions. Knudsen et al. (1948) and Wenz (1962) demonstrated that increased sea state and wind speed commonly correlate with higher sound intensities across frequencies from 500 Hz to 30 kHz due to breaking whitecaps, surface flow noise, wave generation, cavitation, and pressure change (Urick 1983). Rainfall can elevate sound levels in the 1–15 kHz frequency range via sound from surface impacts and bubble entrainment (Heindsmann et al. 1955, Bom 1969, Scrimger et al. 1987).

Waves, currents, and seismic activity (such as earth movement and subsea landslides) can also be loud, though short-duration, geophonic contributors. While geophonic and biophonic contributors comprise the natural soundscape, the total soundscape also includes anthrophonic (related to human activity) sounds.

Human sound sources are diverse and can have large underwater acoustic footprints. The main sources are vessel noise, which is primarily caused by global shipping vessels, and seismic exploration for hydrocarbon deposits. The development of offshore wind farms and other coastal construction projects are also important sound sources, although more restricted in their impact areas.

Measuring ambient sound and characterising the soundscape of an area is complicated by non-acoustic processes that often appear in acoustic recordings. One such issue is flow noise, which is caused by pressure eddies and vortices produced by water moving along the surfaces of hydrophone pressure transducers. This is similar to the buffeting sounds recorded by microphones in the wind. Flow noise is not part of a marine soundscape (Strasberg 1979, Urick 1983), but its intensity may indicate current strength (Willis and Dietz 1961). Current or wave action can also induce mooring noise when moving components of a mooring create sound as they move or strum.

1.3. Anthropogenic Contributors to the Soundscape

Anthropogenic (human-generated) sound can be a by-product of vessel operations, such as engine sound radiating through vessel hulls and cavitating propulsion systems, or it can be a product of active acoustic data collection with seismic surveys, military sonar, hull-cleaning acoustic devices, and depth sounding as the main contributors. Marine construction projects often involve nearshore blasting and pile driving that can produce high levels of impulsive-type noise. The contribution of anthropogenic sources to the ocean soundscape has increased from the 1950s to 2010, largely driven by greater maritime shipping traffic (Ross 1976, Andrew et al. 2011). Recent trends suggest that global sound levels are leveling off or potentially decreasing in some areas (Andrew et al. 2011, Miksis-Olds and Nichols 2016). Oil and gas exploration with seismic airguns, marine pile driving, and oil and gas production platforms elevate sound levels over radii of 10 to 1000 km when present (Bailey et al. 2010, Miksis-Olds and Nichols 2016, Delarue et al. 2018).The extent of seismic survey sounds has increased substantially following the expansion of oil and gas exploration into deep water, and seismic sounds can now be detected across ocean basins (Nieukirk et al. 2004).

Based on AIS vessel traffic data, he main anthropogenic contributor to ambient sound expected in the present study was vessel traffic, which is mostly restricted to the northwestern side of the Exmouth Gulf and the approaches to Exmouth (Figure 4). It is important to note that AIS data is only representative of large and/or commercial vessels and thus it is likely that there are significant numbers of recreational vessels active within the Gulf that may operate closer to and within the study area.

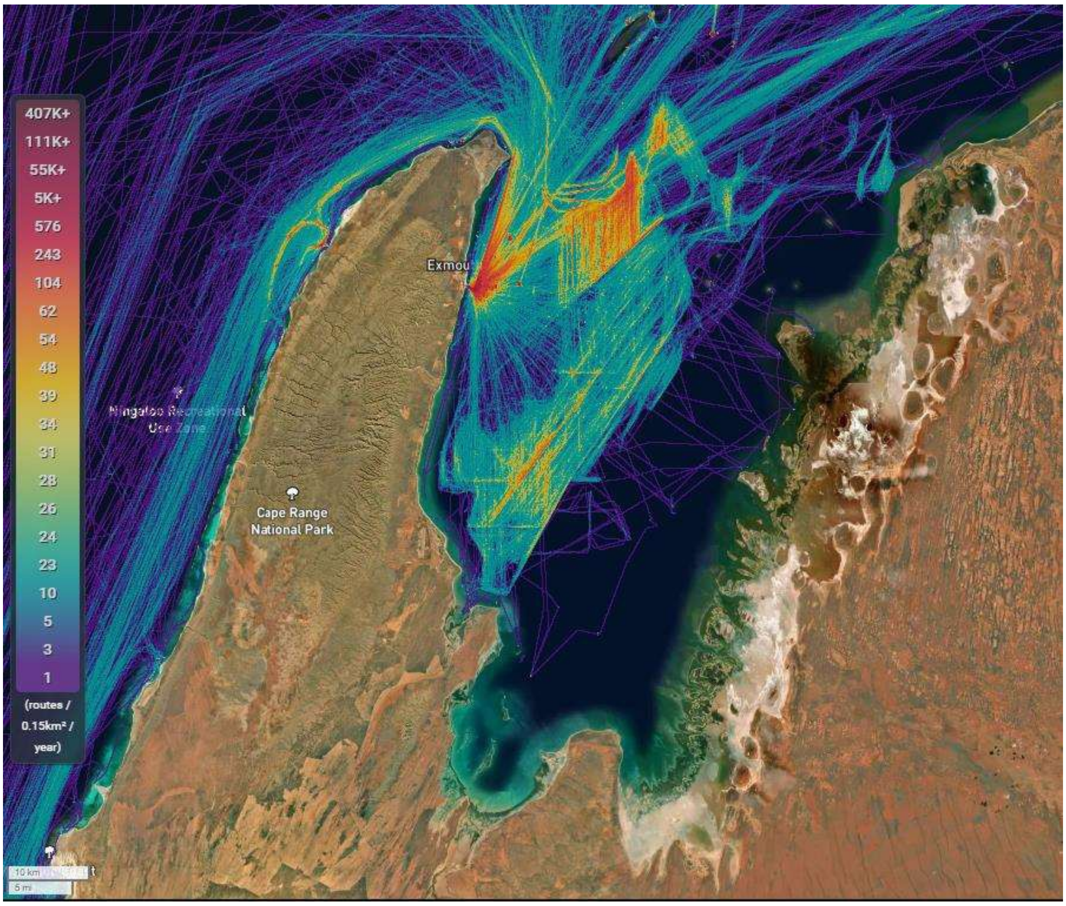


Figure 4. Vessel density map of the project area in 2023. Source: www.marinetraffic.com, accessed 25 Oct 2024.

1.4. Soniferous Marine Life and Acoustic Monitoring

The long-term monitoring of marine species in remote areas is challenging but is important for understanding the temporal and spatial distributions of animals and for designing conservation measures for species at risk. Visual monitoring techniques are important, but they can be spatially and temporally limited and rely on good visibility conditions. Given that most marine mammals produce sounds underwater, acoustic monitoring is generally an effective way to monitor for the presence of multiple species of marine mammals in remote environments year-round with most systems capable of long deployment times and with monitoring ranges that often exceed visual observation ranges. Compared to visual techniques, acoustic monitoring depends less on weather conditions and is unaffected by visibility. However, acoustic monitoring requires animals to make sounds and those sounds must be sufficiently loud to be detected. Because not all species vocalise regularly and vocalisation activity often depends on season, acoustic monitoring effectiveness varies by species and seasonally. For example, odontocetes such as dolphins not only produce sound to locate prey and sense their environment (echolocation), but are typically highly social and are considered to by highly vocally active species. Baleen whales on the other hand vocalise for reproductive and social reasons, and thus the level of vocal activity may vary largely by season and context. While only male whales 'sing', females still produce sounds, though are generally less vocally active and typically produce signals that have a lower source level and intensity.

Biological sources of sound are diverse, and many marine taxa produce sounds. Animals that are known to produce acoustic signals include crustaceans, fish, and marine mammals. Biophonic signals include those generated for communicating, navigating, breeding, and foraging by sound-producing species. Marine mammals have received the most attention in terms of the description of their vocal repertoire and acoustic behaviour. A complete list of marine mammals that occur in Australian waters has been compiled by the Department of Climate Change (2021), and Table 1 lists those most likely to occur in the Exmouth Gulf. This is not an exhaustive list of all potential species which could be present. Of the species that are likely to occur in the Exmouth gulf, all have been successfully detected with acoustic monitoring programs. However the range over which they can be detected and efficacy of detection varies. Humpback whales are prolific vocalisers and there is a high degree of confidence that if they are present they will be able to be detected over significant ranges. Dolphins are also prolific vocalisers and their presence is typically able to be detected acoustically, though over smaller ranges than humpbacks. Southern right whales do vocalise, however cows with calves typically produce very quiet sounds and are not as acoustically active as other baleen whales. The signals they produce are also similar to some of those produced by humpbacks and within the same frequency bands, which can make it difficult to differentiate the species in acoustic recordings, thus they may not always be able to be detected acoustically. Foraging dugongs have been detected acoustically though the detection ranges are very small and they cannot be reliably detected with acoustic monitoring.

Table 1. Marine mammals likely to occur in the study area based on records extracted from the Western Australian Government's Department of Biodiversity, Conservation and Attractions (DBCA) Threatened and Priority Fauna and Flora Database by Fitzpatrick et al. (2019) and from the Species Profile and Threats Database (SPRAT; DCCEEW 2016), including their status according to the Environment Protection and Biodiversity Conservation (EPBC) Act and probability of occurrence.

Species (common name)	Species (scientific name)	Threatened species	Migratory species	Listed species [1]	Presence [2]
Baleen whales					
Southern right whale	*Eubalaena australis*	Yes	Yes	Yes	KO, Migration, Reproduction
Humpback whale	*Megaptera novaeangliae*	No	Yes	Yes	KO, Resting, Migration
Toothed whales					
Australian snubfin dolphin	*Orcaella heinsohni*	No	Yes	Yes	KO
Australian humpback dolphin	*Sousa sahulensis*	No	Yes	Yes	KO
Spinner dolphin	*Stenella longirostris*	No	No	Yes	KO
Indo-Pacific bottlenose dolphin	*Tursiops aduncus*	No	No	Yes	KO
Sirenians					
Dugong	*Dugong dugon*	No	Yes	Yes	KO

[1] Baleen whales and toothed whales are listed under the EPBC Act as 'Cetacean'; dugong are listed as 'Marine'.
[2] KO: Species or species habitat known to occur within area. Migration: Migration route known to occur within area.

For an acoustic recording device to detect a marine mammal vocalisation, its received amplitude at the monitoring location must be above background noise levels in at least one of the vocalisation's frequency bands (although some more complex acoustic systems can detect sounds below background noise level). The distance over which vocalisations can be detected consequently depends on the background sound levels, source levels of the vocalisation (which often vary by season, sex, etc.), calling depth and distance of the animal, and the environment's acoustic propagation properties. Background or ambient sound levels vary due to fluctuations in natural sounds (e.g., wind, precipitation, waves, seismic activity, and biologic activity) and anthropogenic sounds (mainly vessels but also marine construction and oil and gas exploration). Acoustic propagation also varies seasonally due to changing temperature and salinity properties of the water column.

The vocalisations of some marine mammal species are well described in the scientific literature, while others are less understood with limited confirmed recordings and vocalisation descriptions. For those with inadequate signal descriptions, reliable systematic manual identification and automated detector processing of large data sets is challenging, simply because it is difficult to associate the species with the sounds observed. Erbe et al. (2017) provided a review of current knowledge on the vocalisations of marine mammals in Australian waters, and Table 2 details the sounds produced by the marine mammals listed in Table 1.

The biological focus of this study was on marine mammals. Marine mammal species that may be found in the Exmouth Gulf are listed in Table 1. Marine mammals are the main biological contributors to the underwater soundscape. For instance, fin whale songs can raise noise levels in the 18–25 Hz band by 15 dB for extended durations (Simon et al. 2010). Marine mammals, cetaceans in particular, rely almost exclusively on sound for navigating, foraging, breeding, and communicating (Clark 1990, Edds-Walton 1997, Tyack and Clark 2000). Although species differ widely in their vocal behaviour, most can be reasonably expected to produce sounds on a regular basis. Passive acoustic monitoring is therefore increasingly preferred as a cost-effective and efficient survey method. Seasonal and sex- or age-biased differences in sound production, as well as signal frequency, source level, and directionality all influence the applicability and success rate of acoustic monitoring, and its effectiveness must be considered separately for each species. The range over which marine mammals can be detected will vary between species, vocalisation type, recorder type and environments. It is impossible to accurately estimate detection ranges however baleen whale vocalisations in most environments can typically be detected at ranges of kilometres, whereas delphinid detections are limited to 10s to 100s of metres. Baleen whale cows with calves may vocalise at much lower source levels with detection ranges in 100s of metres.

Knowledge of the acoustic signals of the marine mammals expected in the study area varies across species. These sounds can be split into two broad categories: Tonal signals, including baleen whale moans and delphinid whistles, and echolocation clicks produced by all odontocetes mainly for foraging and navigating. Although the signals of most species have been described to some extent, these descriptions are not always sufficient for reliable, systematic identification, let alone to design automated detectors to process large data sets (Table 2). For instance, although the whistles of species in the subfamily *Delphininae* (small dolphins) have been described for most species, the overlap in their spectral characteristics complicates their identification by both analysts and automated detectors (Ding et al. 1995a, Gannier et al. 2010). In most cases, baleen whale signals can be reliably identified to the species level, although, seasonal variation in the types of vocalisations produced results in seasonal differences in the ability to detect these species acoustically. For example, the tonal signals produced by blue, fin, and sei whales tend to show lots of similarities in late spring and summer, but they are markedly different from September to April.

Table 2. List of vocalisations that have been described for key marine mammals listed in Table 1 and non-exhaustive list of supporting scientific publications.

Species	Vocalisations described	Reference(s)
Southern right whale	Upcalls, downcalls, gunshot calls, etc.	Cummings et al. (1972a), Cummings et al. (1972b), Payne and Payne (1972), Clark (1982), Hofmeyr-Juritz (2010), Tellechea and Norbis (2012), Ward et al. (2014), Dombroski et al. (2016), Vinding Petersen (2016), Webster (2015), Webster et al. (2016), Jacobs et al. (2019), Ward (2020)
Humpback whale	Song and non-song moans, grunts, whups, etc.	Payne and McVay (1971), Thompson et al. (1986), Au et al. (2006), Parsons et al. (2008), Dunlop et al. (2013), Garland et al. (2013), Rekdahl et al. (2015)
Australian snubfin dolphin	Echolocation clicks, whistles, burst pulses	Van Parijs et al. (2000), Berg Soto et al. (2014), Brown et al. (2017), Marley et al. (2017b), de Freitas et al. (2018)
Australian humpback dolphin	Echolocation clicks, whistles, burst pulses	Schultz and Corkeron (1994), Van Parijs and Corkeron (2001a), Van Parijs and Corkeron (2001b), Goold and Jefferson (2004), Wang et al. (2013), De Freitas et al. (2015), Fang et al. (2015), Brown et al. (2017)
Spinner dolphin	Echolocation clicks, whistles, burst pulses	Bazúa-Durán and Au (2002, 2004), Lammers et al. (2003), Lammers et al. (2006), Lammers and Au (2003), Camargo et al. (2006), Rossi-Santos et al. (2008), Benoit-Bird and Au (2009), Baumann-Pickering et al. (2010), Moron et al. (2015), Bonato et al. (2015), Heenehan et al. (2016)
Indo-Pacific bottlenose dolphin	Echolocation clicks, whistles, burst pulses	Ding et al. (1995b), Morisaka et al. (2005), Hawkins and Gartside (2009), Hawkins (2010), Wahlberg et al. (2011), Gridley et al. (2012), Gridley et al. (2014), De Freitas et al. (2015), Ward et al. (2016), Marley et al. (2017a)
Dugong	Chirps, trills, barks	Nair and Lal Mohan (1975), Anderson and Barclay (1995), Ichikawa et al. (2006), Ichikawa et al. (2009), Ichikawa et al. (2011), Ichikawa et al. (2012), Parsons et al. (2013), Tanaka et al. (2017), Tanaka et al. (2021), Tanaka et al. (2023a), Tanaka et al. (2023b), Jiang et al. (2024)

2. Methods

This section describes the data sets analysed, as well as the methods used for calculating ambient sound, detecting marine mammals, and detecting vessels.

2.1. Acoustic Data Acquisition

2.1.1. Field Work and Underwater Acoustic Recorders

The monitoring program required deployment and retrieval of a monitoring station in the Exmouth Gulf, shown in Figure 1. Vessels used for field operations included the 11.8 m long M/V *Optimus* and the 6 m long M/V *Jetfire* from Terrafirma Commercial Marine Services Pty Ltd (TCM).

Underwater sound was recorded with an AMAR Generation 4 in acetal housing (AMAR G4 ACE, JASCO; Figure 5) paired with a 96-cell external battery pack and positioned on a baseplate (Figure 5). The AMAR was fitted with an M36-V35-900 omnidirectional hydrophone (GeoSpectrum Technologies Inc., −165 ± 3 dB re 1 V/µPa sensitivity). The hydrophone was protected by a hydrophone cage, which was covered with a closed-cell foam cover to minimise non-acoustic noise caused by water flowing over the hydrophone transducer; this noise is often referred to as 'flow noise'. The AMAR recorded continuously at 64,000 samples per second for a recording bandwidth of 10 Hz to 32 kHz. The recording channel had 24-bit resolution with a spectral noise floor of 20 dB re 1 µPa^2/Hz and a nominal ceiling of 171 dB re 1 µPa. Acoustic data were stored on 3.5 TB of internal solid-state flash memory during each period. Appendix A.1 describes the calibration procedure.

Figure 5. (Left) Baseplate with Autonomous Multichannel Acoustic Recorder (AMAR), external battery, and hydrophone on the aft platform of the *Optimus*, with ground line (white) and lowering line (red) prepared for deployment in the Exmouth Gulf. (Right) AMAR G4 in acetal housing.

2.1.2. Deployment Locations

The AMAR was deployed at the location shown in Figure 1 and listed in Table 3 between 1 Oct 2023 and 25 Mar 2024 and redeployed from 25 Mar to 16 Sep 2024. Appendix A.2 provides details about the mooring design.

Table 3. Deployment period, location, and water depth of the Autonomous Multichannel Acoustic Recorder (AMAR) for the Exmouth Gulf monitoring program.

Equipment	Latitude	Longitude	Depth (m)	Deployment	Retrieval	Recording duration (days)
AMAR 627 baseplate	-22.215700°S	114.232510°E	15	1 Oct 2023	25 Mar 2024	176
AMAR 629 baseplate	-22.214326°S	114.232512°E	15	25 Mar 2024	16 Sep 2024	175

2.2. Automated Data Analysis

The AMARs collected approximately 5.29 TB of acoustic data during the entirety of this study. All acoustic data were processed with JASCO's PAMlab software suite, which processes acoustic data hundreds of times faster than real time. PAMlab performed automated analysis of total ocean noise and sounds from vessels, and (possible) marine mammal vocalisations. Automated detections are termed 'possible' until validation of the automated detectors has been undertaken for the specific data set to ensure they are working with an appropriate level of accuracy. Once the detectors have been validated and the level of performance is deemed appropriate, the marine mammal detections are assumed to represent actual detections. The following sections describe each type of analysis, and Appendix B provides an overview of the processing algorithms.

2.2.1. Ambient Data Analysis

2.2.1.1. Soundscape and Time Series Analysis

The data collected in the Exmouth Gulf span one-year over the 10–32 000 Hz frequency band. The goal of the total ocean sound analysis is to present this data set in a manner that documents the baseline underwater sound conditions in the southwestern portion of the Exmouth Gulf and allows for a comparison over time and with external factors that affect sound levels such as weather and human activities.

The first stage of the total sound level analysis involves computing the peak sound pressure level (PK) and sound pressure level (SPL) for each minute of data. This reduces the data to a manageable size without compromising its value for characterising the soundscape (ISO 2017b, Ainslie et al. 2018, Martin et al. 2019). SPL analysis was performed by averaging 120 fast-Fourier transforms (FFTs) that each included 1 s of data with a 50 % overlap that use the Hann window to reduce spectral leakage. The 1 min average data were stored as power spectral densities (1 Hz resolution up to 455 Hz and millidecades frequency bands above 455 Hz) and summed over frequency to calculate decidecade band SPL. Appendix B.2 lists the frequencies of the decidecade band levels (Decidecade bands are similar to 1/3-octave-bands).

The millidecade band analysis approach described in Martin et al. (2021) was applied. Millidecades are logarithmically spaced frequency bands but have a bandwidth equal to 1/1000th of a decade. Using millidecades instead of 1 Hz frequency bands reduced the size of the spectral data by a large factor without compromising the usefulness of the data.

The decidecade analysis sums as many frequencies as contained in the recorded bandwidth and reduces them to a manageable set of up to 45 bands that approximate the critical bandwidths of mammal hearing. The decade bands further summarise the sound levels into four frequency bands for manageability. Appendices B.1 and B.2 contain detailed descriptions of the acoustic metrics and decidecade analysis, respectively.

In Section 3, the total sound levels are presented as:

- **Band-level plots**: These strip charts show the averaged received SPL as a function of time within a given frequency band. The total sound levels (across the entire recorded bandwidth from 10–16,000 Hz) and the levels in the decade bands of 8.9–89.1 Hz (Decade A) are shown; 89.1–891.3 Hz (Decade B); 891.3–8,913 Hz (Decade C); and 8,913–16,000 Hz (Decade D), depending on the recording bandwidth. The 8.9–89.1 Hz band is generally associated with fin and blue whales, large shipping vessels, flow and mooring noise, and seismic survey impulses. Sounds within the 89.1–891.3 Hz band are generally associated with the physical environment such as wind and wave conditions but can also include both biological and anthropogenic sources such as minke and humpback whales, fish, smaller vessels, seismic surveys, and pile driving. Sounds above 1000 Hz include high-frequency components of humpback whale sounds, odontocete whistles and echolocation signals, wind- and wave-generated sounds, and sounds from human sources at close range including pile driving, vessels, seismic surveys, and sonars.
- **Long-term Spectral Averages (LTSAs)**: These colour plots show power spectral density levels as a function of time (*x* axis) and frequency (*y* axis). The frequency axis uses a logarithmic scale, which provides equal vertical space for each decade increase in frequency and equally shows the contributions of low- and high-frequency sound sources. The LTSAs are excellent summaries of the temporal and frequency variability in the data.
- **Decidecade box-and-whisker plots**: The ‘boxes’ in these figures represent the middle 50 % of the range of SPL, so that the bottom of the box is the sound level 25th percentile (L_{25}) of the recorded levels, the bar in the middle of the box is the median (L_{50}), and the top of the box is the level that exceeded 75 % of the data (L_{75}). The whiskers indicate the maximum and minimum ranges of the data.
- **Spectral density level percentiles**: While the decidecade box-and-whisker plots represent the histogram of each band’s sound pressure levels, the power spectral density data have too many frequency bins for a similar presentation. Instead, coloured lines represent the L_{eq}, L_5, L_{25}, L_{50}, L_{75}, and L_{95} percentiles of the histograms. Shading underneath these lines indicate the relative probability distribution. It is common to compare the power spectral densities to the results from Wenz (1962), which documented the variability of ambient spectral levels off the US Pacific coast as a function of frequency of measurements for a range of weather, vessel traffic, and geologic conditions (see Figure 2). The Wenz levels are only appropriate for approximate comparisons because those data were collected in deep water, largely before an increase in low-frequency sound levels (Andrew et al. 2011).
- **Tidal rhythm plots**: Similar to the weekly rhythm plots, the decade band SPL are examined in 10 min steps over each tidal cycle. Median values are calculated from the sample of tidal cycles across the recording period and plotted in reference to time at low tide for a full tidal cycle (from low to high to low tide). Plotting the tidal cadences can reveal the influence of tidal currents on sound level measurements.

2.2.2. Vessel Noise Detection

The boat and ship detectors compare sound levels in established frequency range to criteria values. Boats (small vessels) and ships (large vessels) can be distinguished because boats are quieter and emit more sound at higher frequencies than ships. The highest sound level within the minutes flagged as having a vessel present is assigned as the closest point of approach (CPA). The criteria values are outlined in Table 4; criteria names are shown in italics in the description below:

- The background SPL within the frequency range is calculated as a long-term average over the *Background window duration*.
- Each minute's SPL (within the frequency range) must be greater than the background value by the *Shipping to background threshold*.
- Each minute's SPL (within the frequency range) must exceed the total broadband SPL by the *Shipping to RMS Threshold.*
- Each minute's SPL must be greater than the *Minimum broadband SPL.*
- The average number of tonals detected over a *Minimum shipping duration* minute window must be greater than *Minimum number of shipping tonals.*
- The duration of the shipping detection must be greater than *Minimum shipping duration* and less than *Maximum shipping duration.*

Figure 6 illustrates the vessel detection process. Once vessels are detected, an "anthropogenic shoulder" 15 min before and after each detection is defined. These periods did not meet the detector's criteria but contained acoustic energy from the detected vessels and were therefore excluded from the data used to characterise ambient sound (Section 2.2.1).

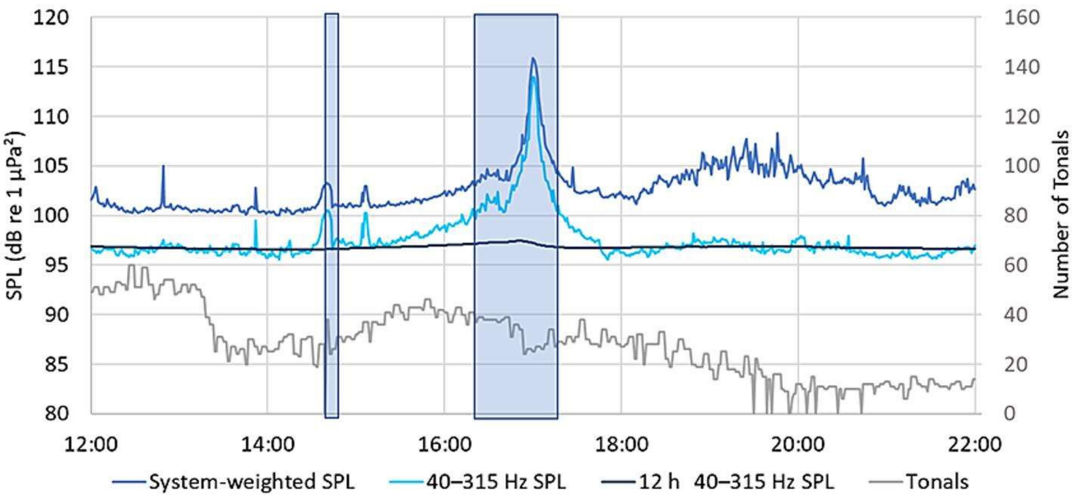


Figure 6. Example of broadband and 40–315 Hz band sound pressure level (SPL), as well as the number of tonals detected per minute as a vessel approached a recorder, stopped, and then departed. The shaded area is the period of shipping detection. Fewer tonals are detected at the ship's closest point of approach (CPA) at 17:00 because of masking by broadband cavitation noise and due to Doppler shift, which affects the tone frequencies.

Table 4. Parameters of the boat and ship detector.

Detector	f_{min} flag (Hz)	f_{max} flag (Hz)	Min. broadband SPL (dB)	Min. # of shipping tonals	Background window duration (min)	Shipping duration (min)		Typical shipping passing duration (min)	Shipping to background threshold (dB)	Shipping to RMS threshold (dB)	Anthropogenic shoulder (min)
						Min.	Max.				
Ship	40	315	105	3	720	5	360	30	3	12	15
Boat	315	2000	95	0.49	720	3	60	10	3	15	15

2.2.3. Marine Mammal Detection Overview

A combination of automated detector-classifiers (referred to as automated detectors) and manual review was used by experienced analysts to determine the presence of sounds produced by marine mammals in the acoustic data. First, a suite of automated detectors was applied to the full data set (see Appendices C.1 and C.2). Second, a subset (1 %) of acoustic data was selected for manual analysis of marine mammal acoustic occurrence. The second six-month subset, representing 179 sound files (44.75 h worth of 15 min sound files sampled at 64 kHz), was selected based on automated detector results via the Automatic Data Selection for Validation (ADSV) algorithm (Kowarski et al. 2021) (see Appendix C.3). Third, manual analysis results were compared to automated detector results to determine automated detector performance (see Appendix C.4). Finally, hourly marine mammal occurrence plots that incorporated manual and automated detections were created (see Section 3.4), and automated detector performance metrics were provided to give a reliable representation of marine mammal presence in the acoustic data. These marine mammal analysis steps are summarised here and detailed in Appendix C. Where automated detector results were unreliable or did not add additional information to species occurrence, only the validated results from manual analysis are presented.

Fish sounds were not targeted by dedicated detectors due to the lack of description of sounds that may be produced by fish in the study area. Fish sounds were manually annotated by analysts in order to provide an index of occurrence at the recorder location.

2.2.3.1. Automated Click Detection

Odontocete clicks are high-frequency impulses ranging from 1 to over 150 kHz (Au et al. 1999, Møhl et al. 2000). An automated click detector to the data was applied to identify clicks from delphinids. This automated detector is based on zero-crossings in the acoustic time series. Zero-crossings are the rapid oscillations of a click's pressure waveform above and below the signal's normal level (e.g., see Figure C-1). Zero-crossing-based features of automatically detected events are then compared to templates of known clicks for classification (see Appendix C.1 for details).

It should be noted that the sampling rate selected for this study (64 kHz, providing a recording bandwidth up to 32 kHz) does not capture the full frequency band of echolocation clicks produced by the odontocetes expected in the Exmouth Gulf. The click detectors used for these species target frequencies 25 kHz and above, leaving a very narrowband band that may not contain enough spectral information for reliable click detection and identification. For this reason, a level of manual analysis is undertaken on each data set to ensure that species are not missed.

2.2.3.2. Automated Tonal Signal Detection

Tonal signals are narrowband, often frequency-modulated, signals produced by many species across a range of taxa (e.g., baleen whale moans, delphinid whistles). They range predominantly between 15 Hz and 20 kHz (Steiner 1981, Berchok et al. 2006, Risch et al. 2007). The automated tonal signal detectors identified continuous contours of elevated energy and classified them against a library of marine mammal signals (see Appendix C.2 for details). JASCO's suite of tonal automated detectors includes those specific to species-specific signals and those that are more generic, capturing signals from potentially more than one species that overlap in spectral characteristics.

2.2.3.3. Automated Detector Validation and Performance Assessment

JASCO's suite of automated detectors are developed, trained, and tested to be as reliable and broadly applicable as possible. However, the performance of marine mammal automated detectors varies across acoustic environments (e.g., Hodge et al. 2015, Širović et al. 2015, Erbs et al. 2017, Delarue et al. 2018). Therefore, automated detector results must always be supplemented by some level of manual review to evaluate automated detector performance. A subset of acoustic files was manually analysed for the presence/absence of marine mammal acoustic signals via spectrogram review in JASCO's PAMlab software. A subset (1 %) of acoustic data was selected via ADSV for manual review (see Appendix C.3).

To determine the performance of the automated detectors per 15 min acoustic files, the automated and manual results (excluding files where an analyst indicated uncertainty in species occurrence) were fed into an algorithm that calculates precision (*P*), recall (*R*), and Matthew's Correlation Coefficient (*MCC*) (see Appendix C.4 for formulas). *P* represents the proportion of files with detections that are true positives. A *P* value of 0.90 means that 90 % of the files with automated detections truly contain the targeted signal, but it does not indicate whether all files containing acoustic signals from the species were identified. *R* represents the proportion of files containing the signal of interest that were identified by the automated detector. An *R* value of 0.90 means that 90 % of files known to contain a target signal had automated detections, but it says nothing about how many files with automated detections were incorrect. An MCC provides an overall measure of performance, and has been argued as the standard metric for assessing binary automated detection (Chicco and Jurman 2023). An MCC of 1.00 indicates perfect performance, i.e., all events were correctly automatically detected, whereas an MCC of 0 indicates the detector did not perform better than random chance. The algorithm determines a per-file automated-detector threshold (the number of automated detections per file at and above which automated detections were considered valid) that maximises the MCC.

For many species, more than one automated detector targeted their vocalisations. In these instances, the performances of all automated detectors were evaluated, and the highest performing detector was used to represent species/vocalisation-type occurrence in Section 3.4. Only automated detections associated with a *P* greater than or equal to 0.75, an *R* greater than or equal to 0.5, and an MCC greater than or equal to 0.4, were considered. When performance metrics fell below minimum requirements, only the validated results were used to describe the acoustic occurrence of a species.

JASCO's Ark software was used to plot the occurrence of each species (both validated and automated, or validated only where appropriate) as time series showing the hourly presence/absence over each day of the recording period. Automated detector performance metrics associated with the results (included in Section 3.4) should be considered when interpreting results.

3. Results

3.1. Soundscape Characterisation

The soundscape analysis results are presented using the following graphic outputs:

1. The long-term spectral average (LTSA) spectrogram and band-level plots (bottom and top panels, respectively, of Figures 7, 9, 13, 16, and 18) provide an overview of the sound variability in time and frequency as well as the presence and level of contributions from different sources. Short-term events appear as vertical stripes on the spectrograms and spikes on the band level plots. Long-term events affect the corresponding band levels over the event period and appear in the spectrograms as horizontal bands of colour.
2. The percentile figures show boxplots by decidecade band and power spectral density by percentile (top and bottom panels, respectively, of Figures 8, 11, 12, 14, 15, 17, and 19) across the recording period. Spikes in the percentiles can be indicative of longer-term trends or major events in specific frequency bands.

The graphics are presented for the full one-year duration of recording (see Figures 7 and 8). In addition, results are presented for two contrasting weeks in October 2023 (humpback whales present; see Figures 9 and 11) and February 2024 (no humpback whales; see Figures 13 and 14) and for specific days within these weeks (see Figures 9 and 12 and Figures 13 and 15, respectively). Soundscape analysis results are also presented for 20 Mar 2024 to highlight a day with weak tidal flow (see Figures 16 and 17).

A few sound sources stand out in the measured soundscape: tidal flow, humpback whale song, snapping shrimp activity, and fish choruses.

- Tidal flow influences sound levels below approximately 100 Hz. Tidal range at the recording site varies between 1.25 and 2.5 m. The variation in flow and its effect on sound levels can be seen by comparing Figures 13 and 16 and is discussed further in Section 3.2.
- Humpback whale song contributed to the soundscape in the 100 Hz to 1 kHz frequency band (see Figures 9 and 11) for about one month from the start of October until the end of October 2023, and again in the last six weeks from August 2024 onwards until the end of the recording period in September 2024. Power spectral density levels increased by approximately 5 dB at 400 Hz when humpback whales were present and singing.
- Snapping shrimp were significant contributors to the soundscape above 500 Hz over almost the entire recording period, with their influence predominantly apparent over 2 kHz (see Figure 7).
- Fish choruses can be seen as horizontal banding patterns in Figures 13 and 16 between approximately 100–1000 Hz and as small peaks in the percentiles of Figure 17. Several types of choruses, presumably from different species, were identified in the data and occurred at different times. In the case of the chorus shown in Figure 17, their peaks occurred usually around midnight (see Figure 16) and cannot yet be attributed to a specific source.

Daily increases in sound levels in the 10–100 Hz range shown in Figure 9 were attributed to thumping sounds (see Figure 10) caused by an unidentified source (likely biological) making contact with the recorder. These sounds occurred consistently from 5 Oct to 18 Nov 2023 (Monitoring period 1) and from 1 Apr to 3 Jun 2024 (Monitoring period 2), from approximately 05:30 to 19:00 local time, during daylight hours, and they are not related to the tidal cycle. The increase in low-frequency noise was consistently associated with a 5–10 dB decrease in sound levels between 2–8 kHz, which is the band where most of the snapping shrimp's energy is concentrated. To further demonstrate the contribution of this thumping sound to the soundscape, analysis of sound levels was performed both including (Table 5) and excluding the period during which these sounds occurred (Figures 18 and 19).

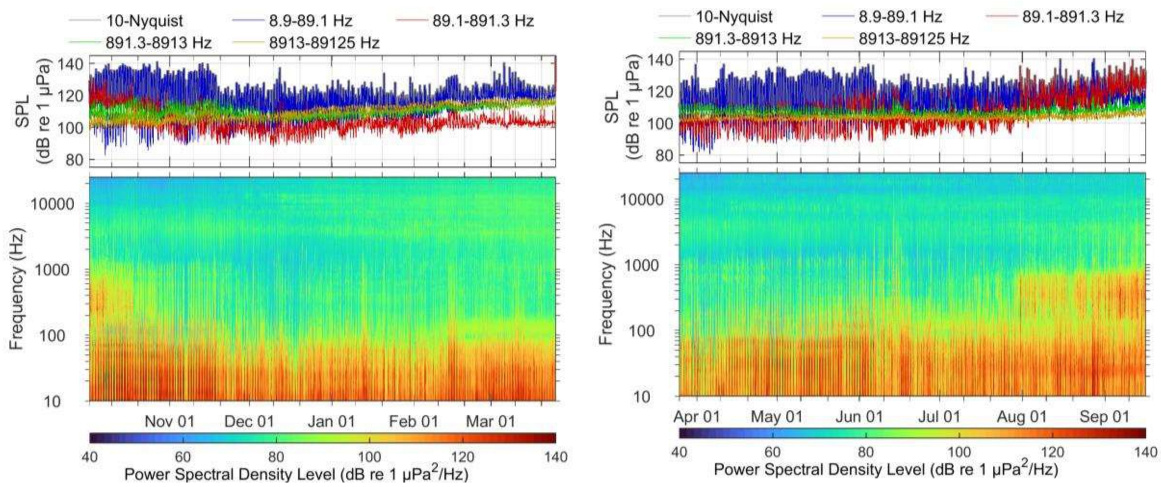


Figure 7. (Top) In-band sound pressure level (SPL) and (bottom) long-term spectral average (LTSA) of the entire recording period (1 Oct 2023 to 16 Sep 2024), for (left) Period 1 and (right) Period 2.

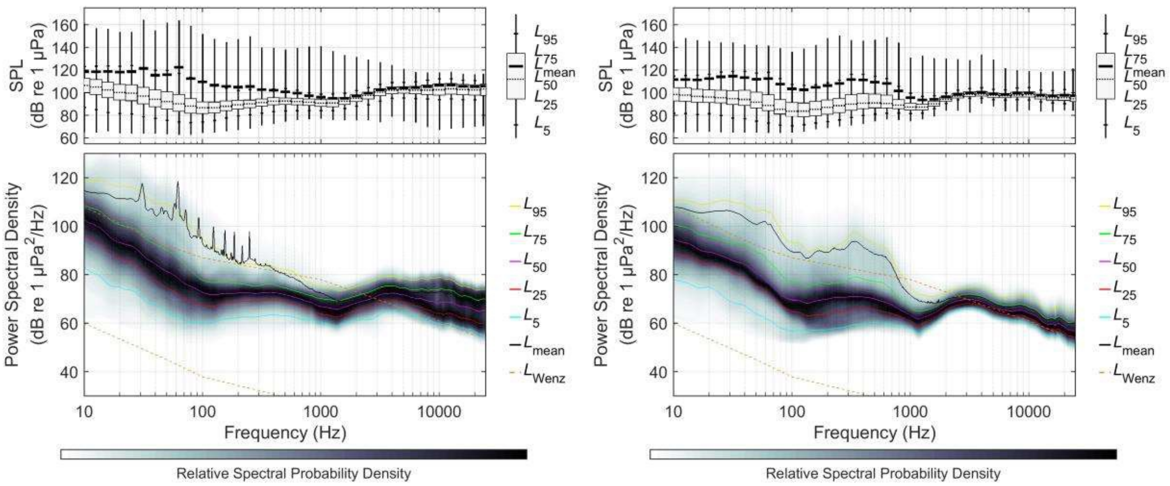


Figure 8. (Top) Percentiles and mean of decidecade band sound pressure level (SPL) and (bottom) percentiles and probability density (grayscale) of 1-min power spectral density levels compared to the limits of prevailing noise (Wenz 1962) for the entire recording period (1 Oct 2023 to 16 Sep 2024) for (left) Period 1 and (right) Period 2.

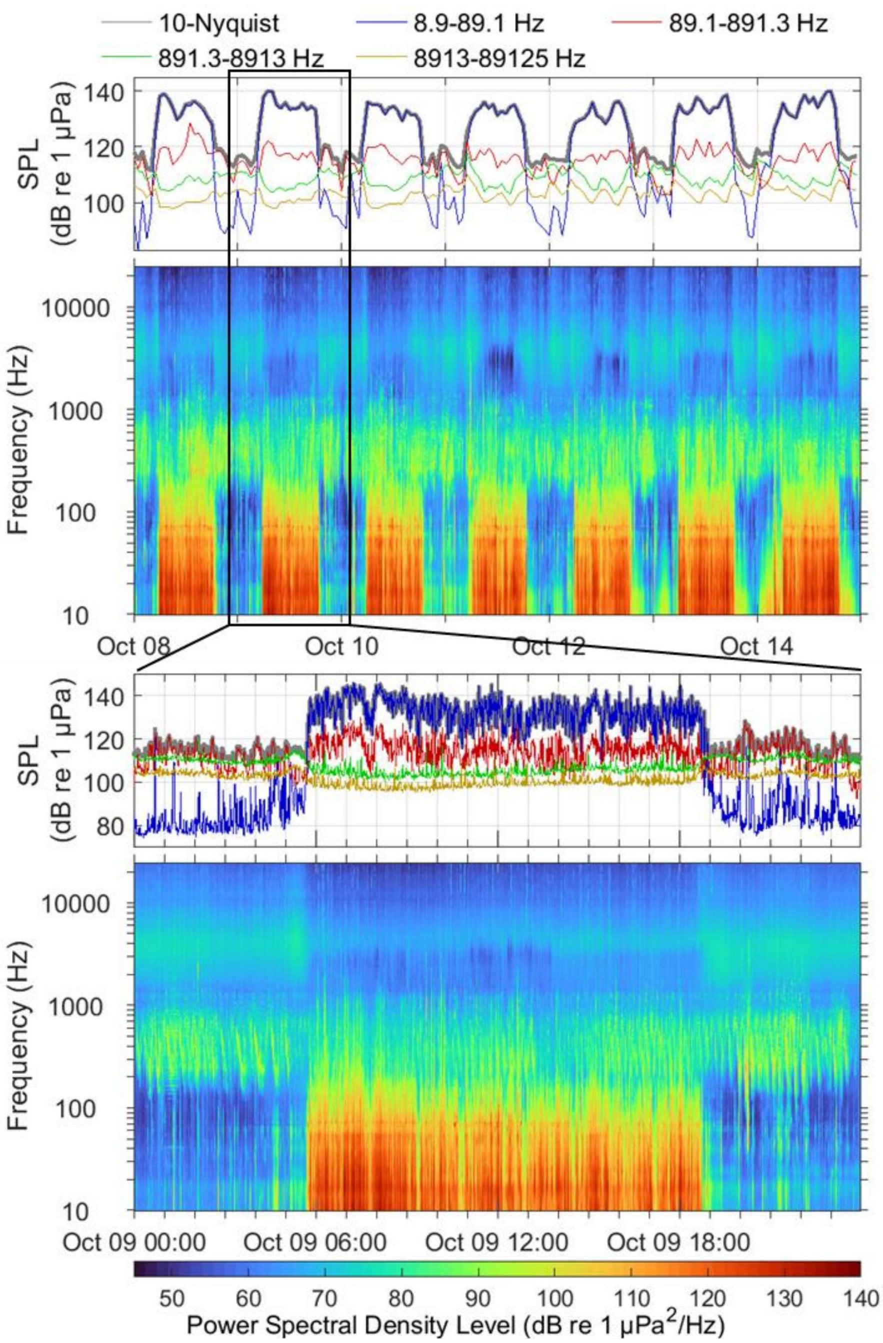


Figure 9. Non-representative week in Oct 2023 showing a yet unidentified diurnal activity (likely of biological origin) dominating the soundscape in the frequency band 10–200 Hz: (top) in-band sound pressure level (SPL) and long-term spectral average (LTSA). (Bottom) blow up LTSA of 9 Oct 2023. Humpback whale song contributed strongly to the soundscape in the frequency band 100 Hz–1 kHz (see also Figure 10).

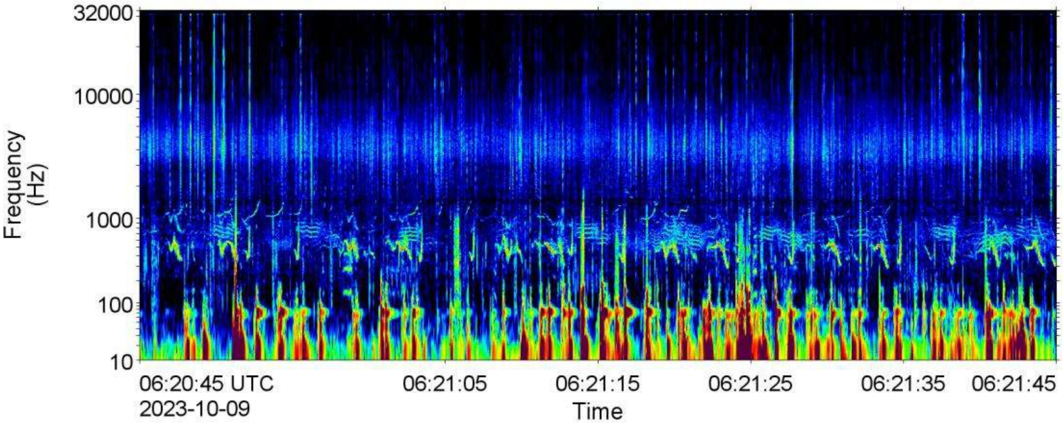


Figure 10. Spectrogram showing low-frequency (<100 Hz) thumping sounds responsible for the daily increases in noise in Figure 9 (2 Hz discrete Fourier Transform (DFT) frequency step, 0.125 s DFT temporal observation window (TOW), 0.03125 s DFT time advance, and Hann window resulting in a 75 % overlap and DFT size (N_{DFT}) of 16384).

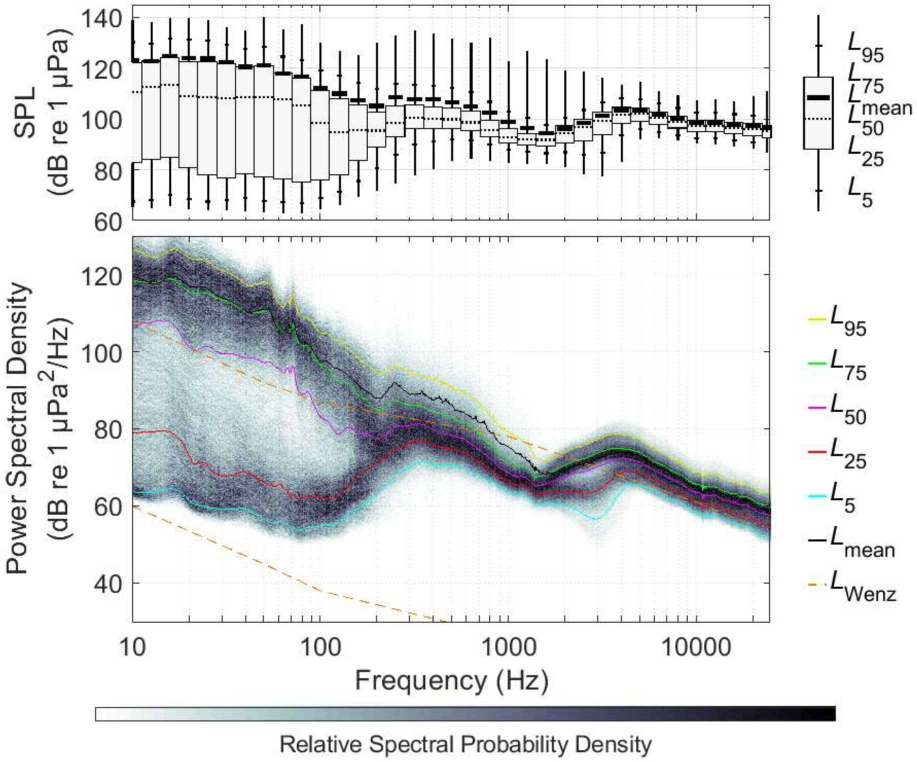


Figure 11. Non-representative week in October 2023: (top) percentiles and mean of decidecade band sound pressure level (SPL) and (bottom) percentiles and probability density (grayscale) of 1-min power spectral density levels compared to the limits of prevailing noise (Wenz 1962) (see also top long-term spectral average (LTSA) in Figure 9).

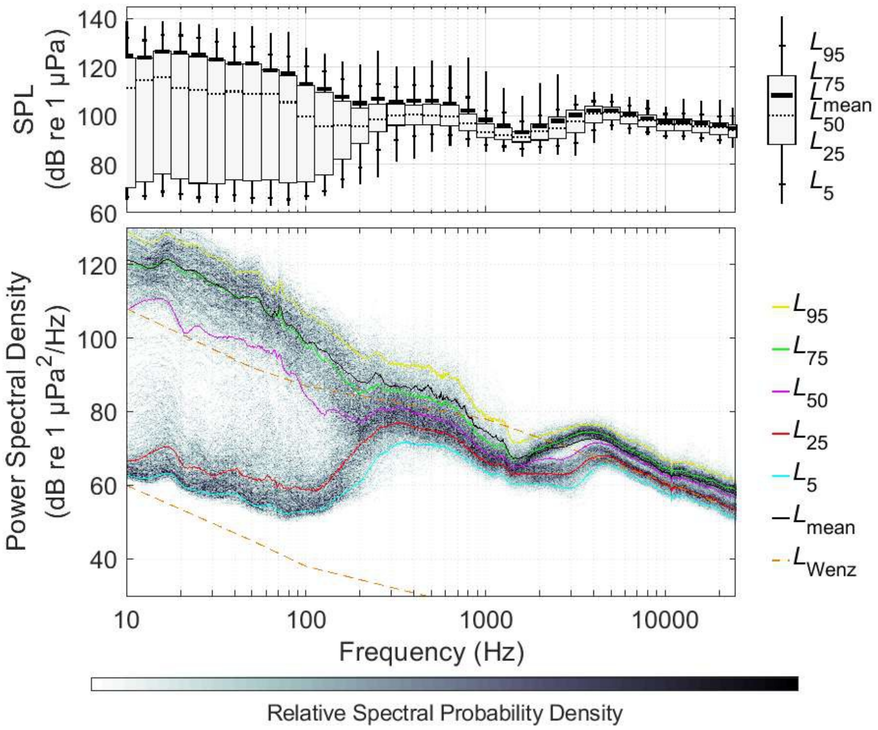


Figure 12. 9 Oct 2023: (top) percentiles and mean of decidecade band sound pressure level (SPL) and (bottom) percentiles and probability density (grayscale) of 1-min power spectral density levels compared to the limits of prevailing noise (Wenz 1962) (see also bottom long-term spectral average (LTSA) in Figure 9).

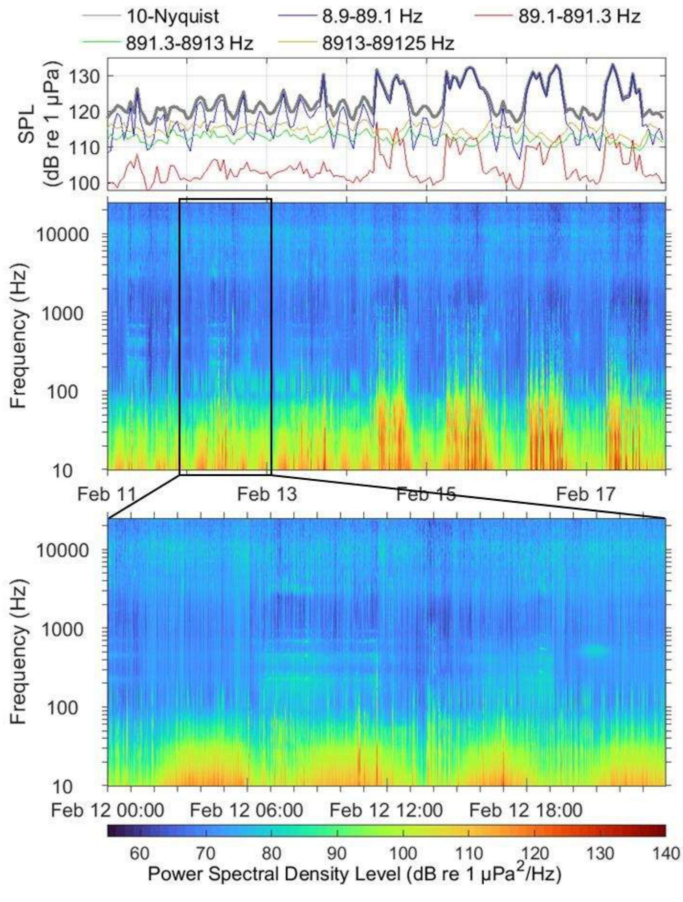


Figure 13. Representative week in February 2024: (top) in-band sound pressure level (SPL) and long-term spectral average (LTSA) of underwater sound, with (bottom) blow up LTSA for 12 Feb 2024, a day with strong tidal flow.

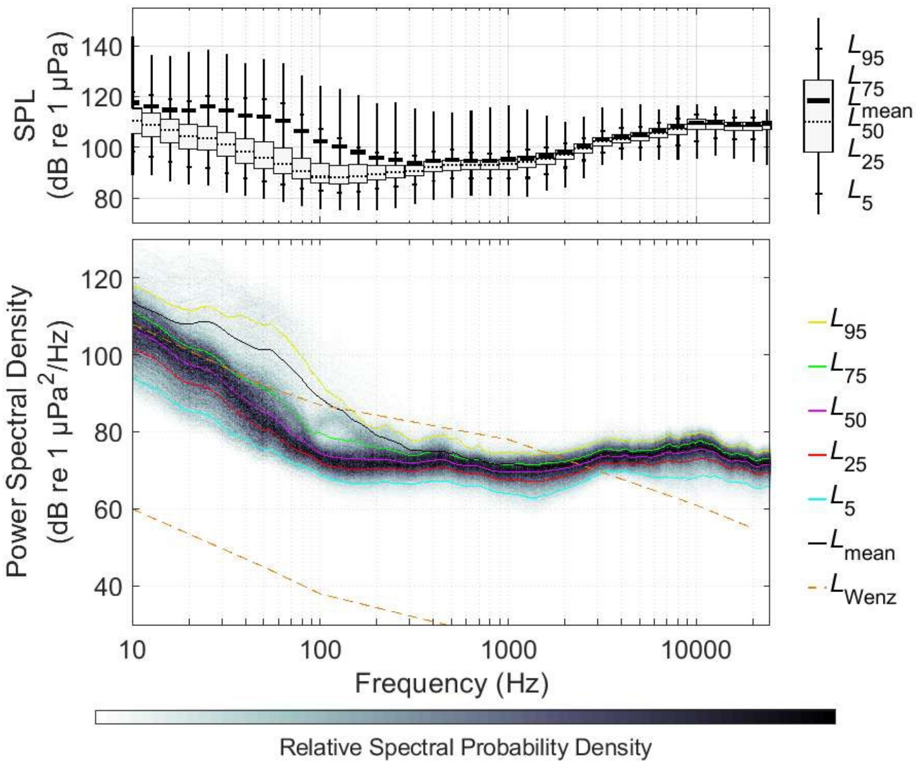


Figure 14. Representative week in February 2024 : (top) percentiles and mean of decidecade band sound pressure level (SPL) and (bottom) percentiles and probability density (grayscale) of 1-min power spectral density levels compared to the limits of prevailing noise (Wenz 1962) (see also top long-term spectral average (LTSA) in Figure 13).

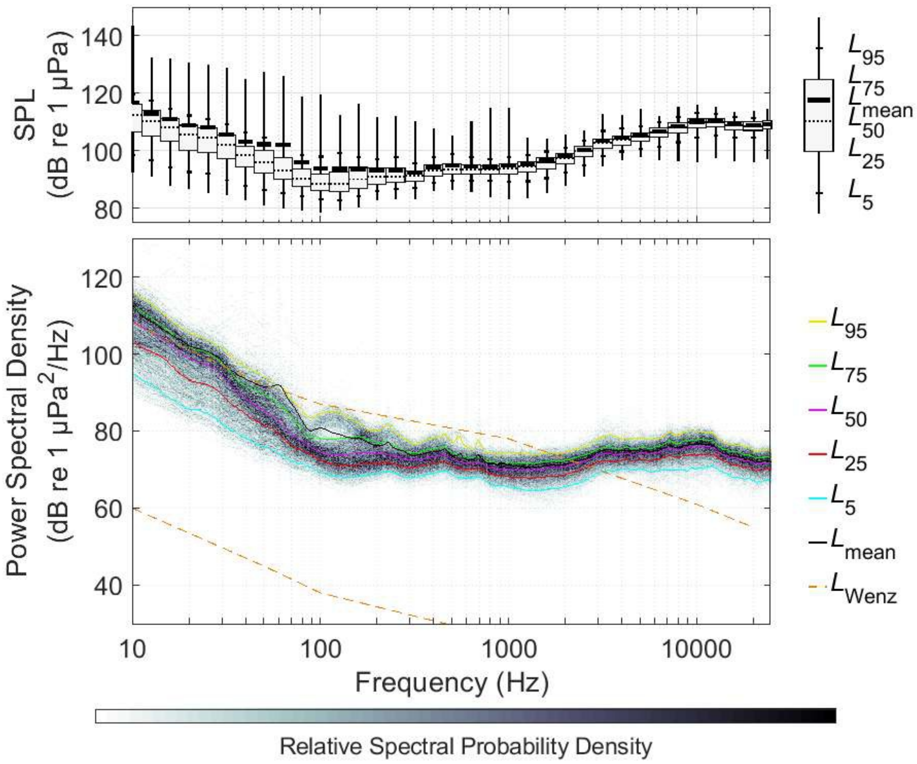


Figure 15. Representative day of 12 Feb 2024: (top) percentiles and mean of decidecade band sound pressure level (SPL) and (bottom) percentiles and probability density (grayscale) of 1-min power spectral density levels compared to the limits of prevailing noise (Wenz 1962) (see also bottom long-term spectral average (LTSA) in Figure 13).

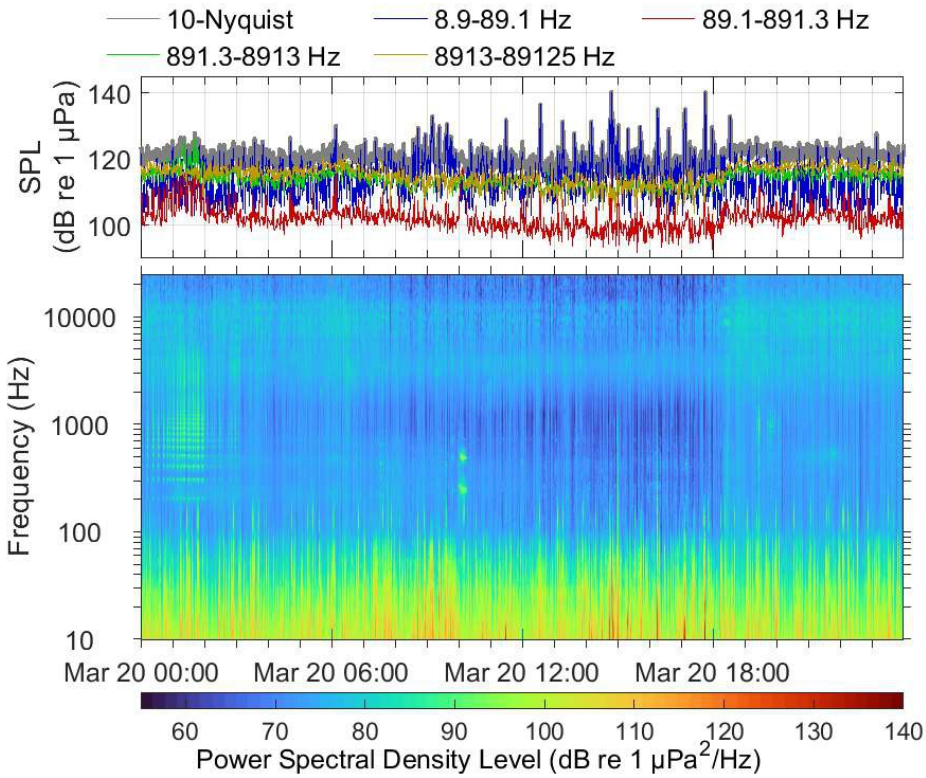


Figure 16. (Top) In-band sound pressure level (SPL) and (bottom) long-term spectral average (LTSA) of underwater sound for 20 Mar 2024, a representative day with weak tidal flow.

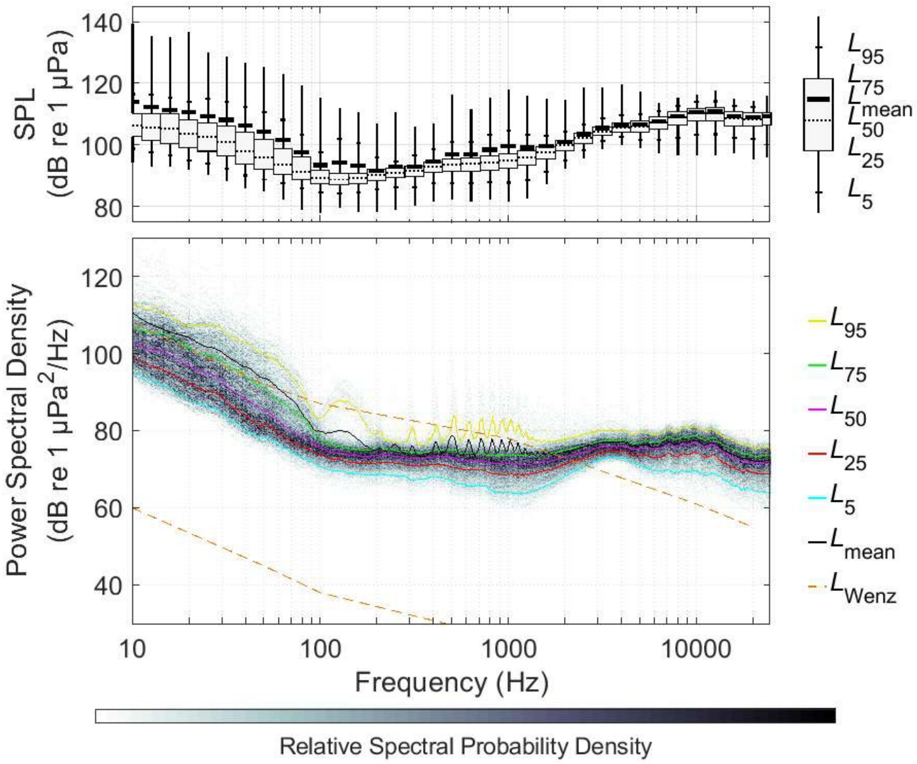


Figure 17. Representative day of 20 Mar 2024: (top) percentiles and mean of decidecade band sound pressure level (SPL) and (bottom) percentiles and probability density (grayscale) of 1-min power spectral density levels compared to the limits of prevailing noise (Wenz 1962) (see also long-term spectral average (LTSA) in Figure 16).

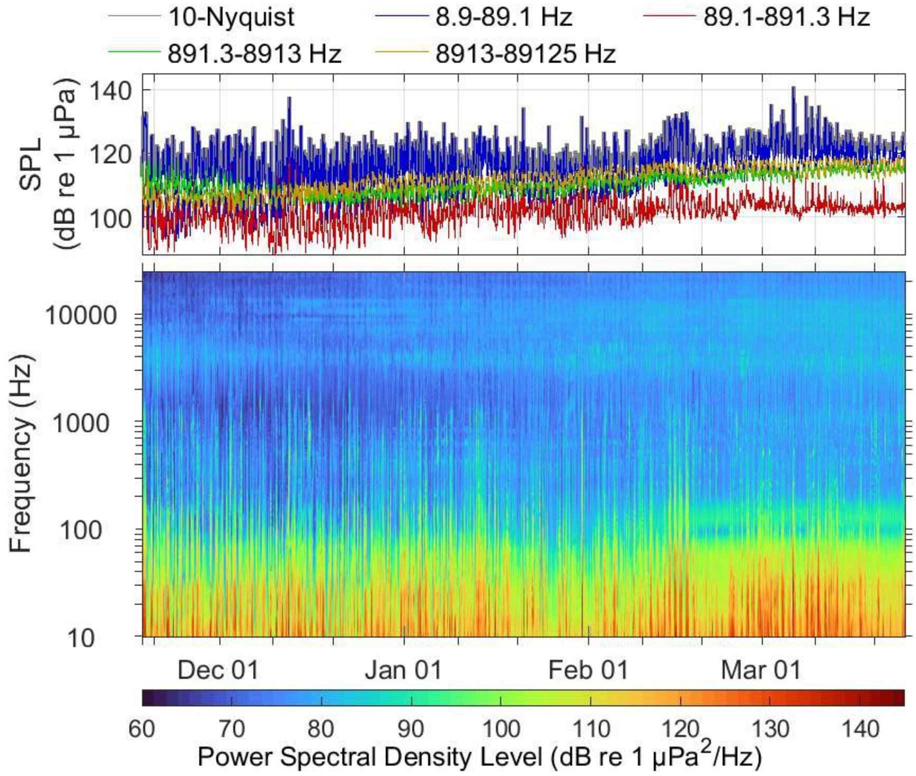


Figure 18. (Top) In-band sound pressure level (SPL) and (bottom) long-term spectral average (LTSA) of the period after the biological interference ends (18 Nov 2023 to 25 Mar 2024).

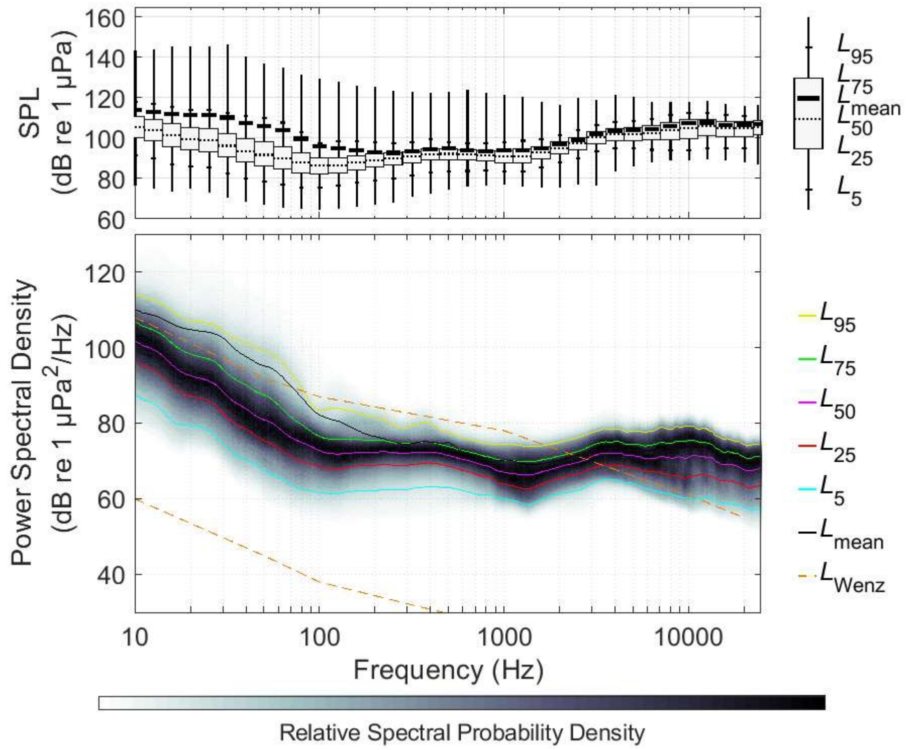


Figure 19. (Top) Percentiles and mean of decidecade band sound pressure level (SPL) and (bottom) percentiles and probability density (grayscale) of 1-min power spectral density levels compared to the limits of prevailing noise (Wenz 1962) for the period after the biological interference ends (18 Nov 2023 to 25 Mar 2024).

Table 5. Statistical analysis of sound levels for the entire recording period (1 Oct 2023 to 16 Sep 2024). Sound pressure level (SPL) units: dB re 1 µPa. For Period 1, levels are shown for the full period as well as the period after the biological interference ends (18 Nov 2023 to 25 Mar 2024). Note that during the latter period the lower levels for the 89.1–891.3 Hz band (which mostly exceeds the frequency of the thumping sounds) are due to humpback whale song now being excluded as well (see Section 3.4.1).

Sound level statistic	Sound level				
	10 to Nyquist	8.9 to 89.1 Hz	89.1 to 891.3 Hz	891.3 to 8913 Hz	8913 to 89125 Hz
Period 1 – Full (Oct 2023 to Mar 2024)					
Minimum	102.8	74.8	84.1	95.1	76.0
L_5	110.2	92.8	92.4	103.0	101.1
L_{25}	114.3	104.9	98.1	107.1	105.3
L_{50}	117.8	111.5	101.3	110.0	110.1
L_{75}	121.5	118.4	105.1	113.1	114.6
L_{95}	132.5	132.3	116.4	116.6	118.4
Maximum	165.0	164.8	153.9	143.5	123.5
Mean	129.1	128.7	114.8	111.9	113.0
Period 1 – After interference (Nov 2023 to Mar 2024)					
Minimum	102.8	83.6	84.1	95.1	96.0
L_5	109.9	96.8	92.1	102.7	102.4
L_{25}	114.0	105.3	97.8	107.0	108.2
L_{50}	117.2	110.6	100.8	110.2	112.5
L_{75}	120.4	116.0	103.6	113.3	115.7
L_{95}	125.2	124.2	108.1	116.6	118.8
Maximum	152.7	152.7	135.2	126.8	123.5
Mean	121.9	120.5	104.2	111.9	114.1
Period 2 (Mar to Sep 2024)					
Minimum	102.8	75.4	84.8	99.9	91.1
L_5	107.0	90.5	89.6	103.0	98.7
L_{25}	109.8	101.3	95.1	104.9	101.4
L_{50}	113.1	106.4	100.5	106.6	103.7
L_{75}	119.0	113.5	110.4	108.6	106.2
L_{95}	129.6	127.7	123.5	111.6	109.5
Maximum	153.9	153.1	153.5	139.8	125.4
Mean	123.9	122.4	118.0	108.1	105.1

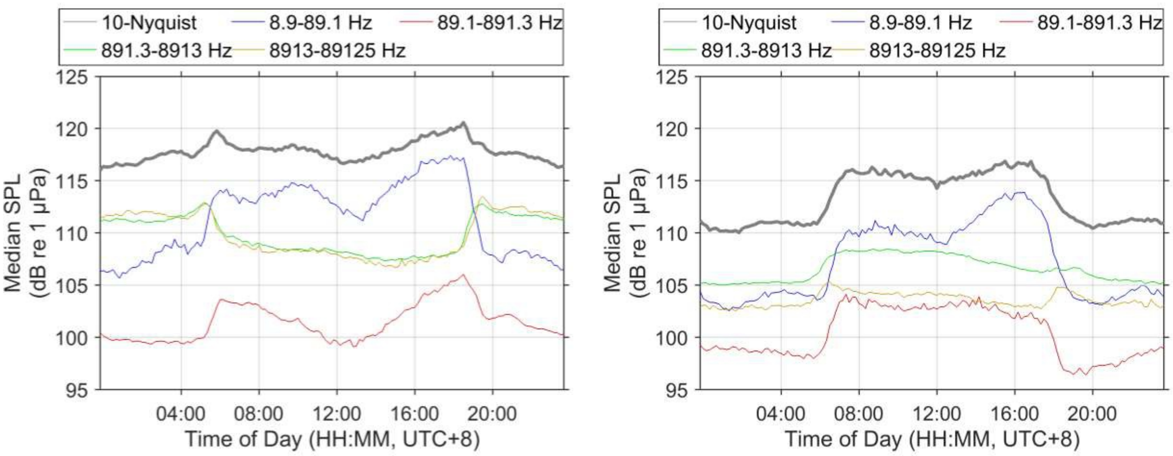


Figure 20. Daily decade band rhythm analysis for the entire recording period (1 Oct 2023 to 16 Sep 2024), for (left) Period 1 and (right) Period 2.

3.2. Tidal Correlations

Tidal flow in the recording area causes flow noise over the recorder, which is reflected as an increase in sound pressure levels at low frequencies. Figure 21 shows the variation in tidal range during the recording period, with Figure 22 demonstrating the effect of the tidal flow on sound levels. The median SPL over the entire recording period by decade band is presented as a function of time elapsed since high tide. The lowest decade band (10–100 Hz) demonstrates a clear correlation of SPL with tidal flow, with SPL varying by up to 8 dB between slack tide and periods of peak flow. It also demonstrates a slight variation between ebb and flood tide impacts. The other decade bands show minimal variation with stage of tidal cycle.

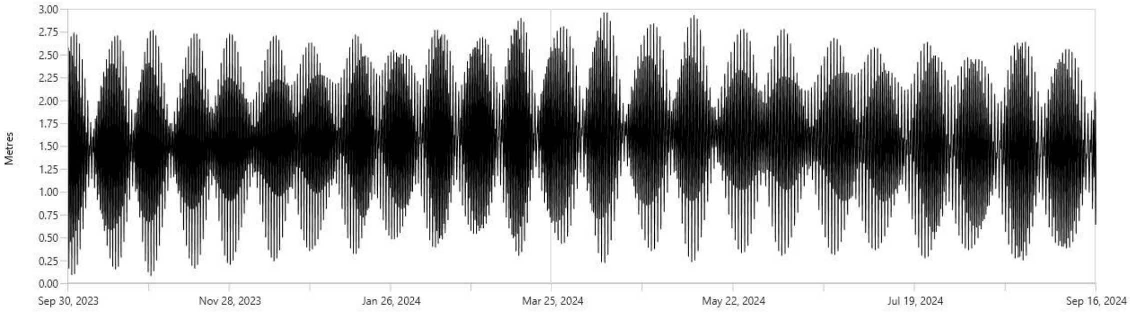


Figure 21. Tidal cadence over the entire recording period.

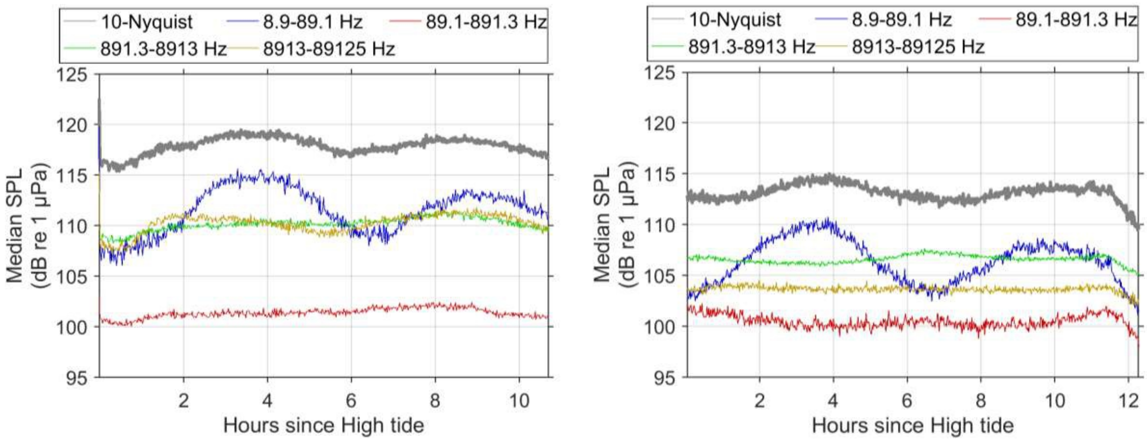


Figure 22. Median sound pressure level (SPL) over the entire recording period relative to time after high tide.

3.3. Vessel Detections

Vessels were detected using the automated detection algorithm described in Section 2.2.2. Detections included a combination of small and large vessels. Detections during Period 1 were clustered over a small number of isolated events, primarily from early October until early December 2023 (Figure 23). During Period 2, increased vessel activity was detected, particularly in June and July 2024. Some detections coincide with the presence of vessels noted in daily spectrograms (Figure 25). Vessels can be detected acoustically over considerable ranges with large vessels often detected at ranges of kilometres to tens of kilometres while small recreational vessels can be detected at ranges of hundreds of metres to kilometres.

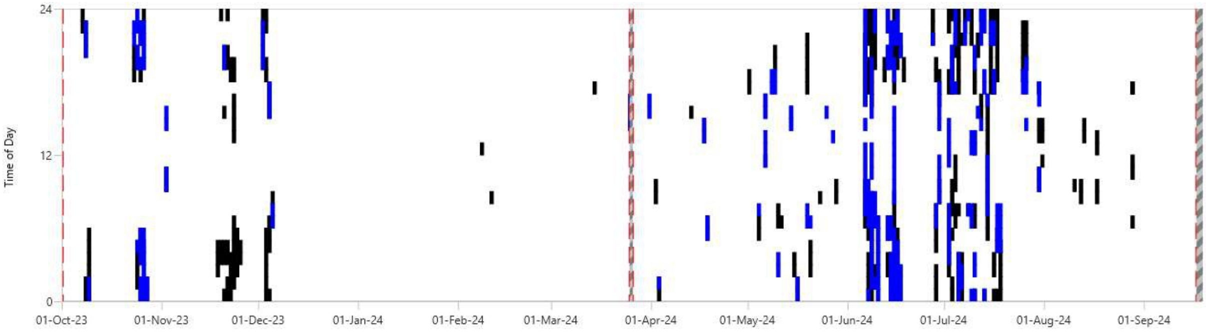


Figure 23. Daily and hourly detections of vessel at the recording location. Black cells represent small vessels. Blue cells represent large vessels (as defined in Section 2.2.2).

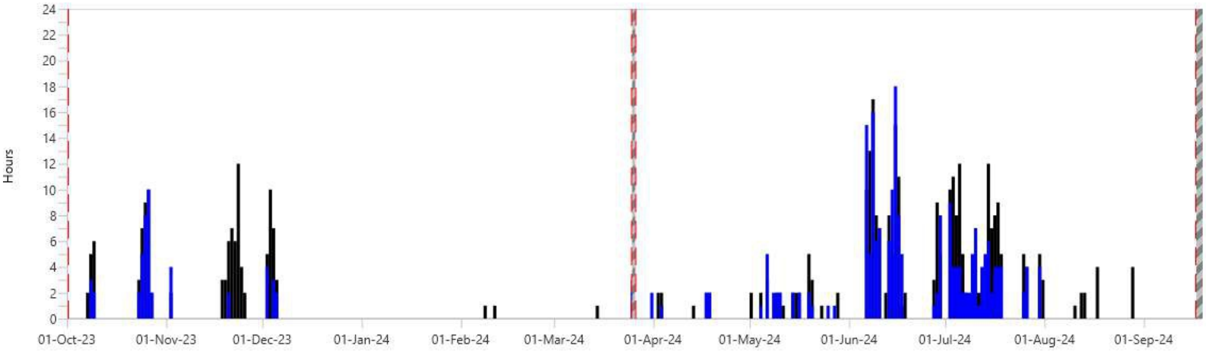


Figure 24. Daily count of hours with vessel detections at the recording location. Black cells represent small vessels. Blue cells represent large vessels (as defined in Section 2.2.2).

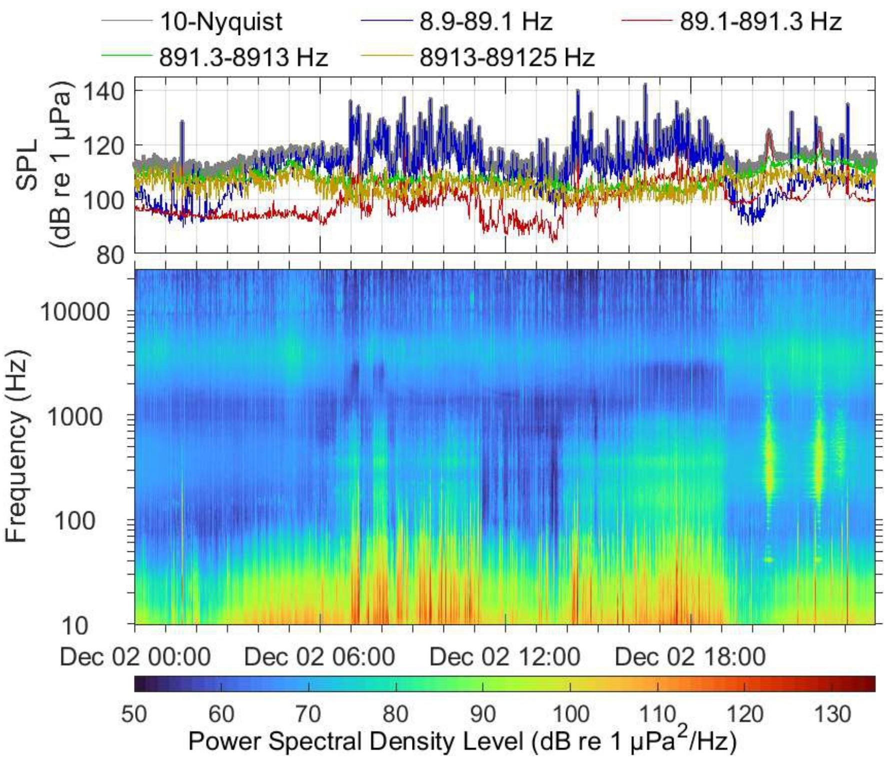


Figure 25. (Top) In-band sound pressure level (SPL) and (bottom) long-term spectral average (LTSA) of underwater sound for 2 Dec 2023. Note the passage of three vessels after 20:00.

3.4. Marine Mammals

The acoustic presence of marine mammals was identified automatically by JASCO's detectors (see Section 2.2.3.3) and validated via the manual review of 1 % of the data set, which represents 179 sound files, or 44.75 h worth of 15-min sound files sampled at 64 kHz. Automated detectors and manual analysts found acoustic signals of humpback whales, dolphins, and fish.

The only vocalisations confidently identified to the species level were those produced by humpback whales. Odontocete clicks and whistles that could be attributed to dolphins were detected. However, neither automated detectors nor manual analysts can currently identify these dolphin clicks to the species level. Fish sounds were manually detected, but no identification to species level is currently feasible.

The automated tonal signal detectors only performed well for humpback whales. While a number of detectors met the defined performance metrics thresholds (see Section 2.2.3.3) for Period 1, the HB.HB detector (Tables 6, C-3, and C-4) was the only one that correctly identified humpback whale sounds at the end of October after the last manual detections (Figure 26) and not beyond without the need to apply temporal restrictions (Table 6). For Period 2, an exclusion period was applied to rule out false detections that were triggered by fish sounds, and this resulted in using the HB.HB detector again (Table 6). The automated click detectors performed poorly due to the large presence of snapping shrimp, which produce impulsive sounds similar to odontocete clicks, resulting in many false positives (over a billion detections in total). In addition, the number of manual detections of dolphin clicks (Figure 29) was too low to assess automated detector performance. The same was true for dolphin whistles.

No signals that may have been produced by dugongs were found in these data.

Table 6. Automated detector performance including the threshold implemented (minimum number of automated detections per file for species to be considered present) and the final automated detector performance values (Final) which represent the performance after threshold restrictions have been applied.

Period	Automated detector	Exclusion period	Per-file threshold	Final [1]						
				P	*R*	*MCC*	TP	FP	FN	TN
1	HB.HB	None	55	1.00	1.00	1.00	39	0	0	147
2	TR.HB.HB	26 Mar to 1 Jul 2024	7	1.00	0.86	0.86	78	0	13	88

[1] *P*: precision. *R*: recall. *MCC*: Matthew's Correlation Coefficient. TP: true positives. FP: false positives. FN: false negatives. TN: true negatives.

3.4.1. Humpback Whales

Humpback whale songs were detected manually from the start of the Period 1 (1 Oct) until 17 Oct 2023 and automatically until 30 Oct 2023 (see Figure 26). During Period 2 recording, humpback whale acoustic occurrence was manually and automatically detected from 11 Jul 2024 through the end of Monitoring Period 2, 16 Sep 2024 (Figure 26). The distinct onset and end in detections is consistent with the expected period of presence based on the annual northbound and southward migration of this population. Figures 27 and 28 show fragments of humpback whale song containing different stereotypical, repetitive song units. Humpback song is a reproductive display that is produced by males of the species. Thus it is important to note that sampling song may introduce a bias in sampling whereby cows and calves are underrepresented. Passive acoustics has however been proven to be an effective monitoring tool for humpback whale populations and where the species is present, they tend to be vocally active.

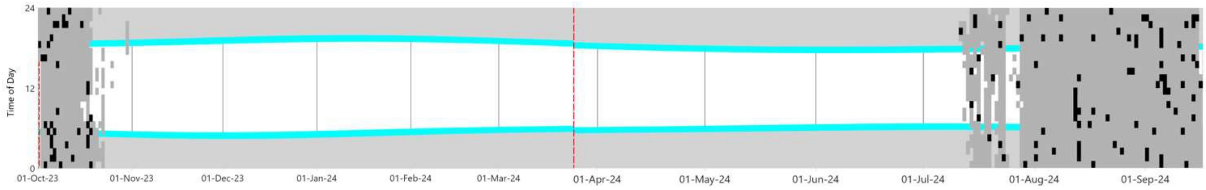


Figure 26. Humpback whales: Daily and hourly occurrence of song recorded in the Exmouth Gulf from 1 Oct 2023 to 16 Sep 2024. Grey cells are automated detections, and black cells are manually validated results. Grey shaded and turquoise areas indicate hours of darkness and nautical twilight, respectively (Ocean Time Series Group 2009). The red dashed line indicates the recorder deployment dates.

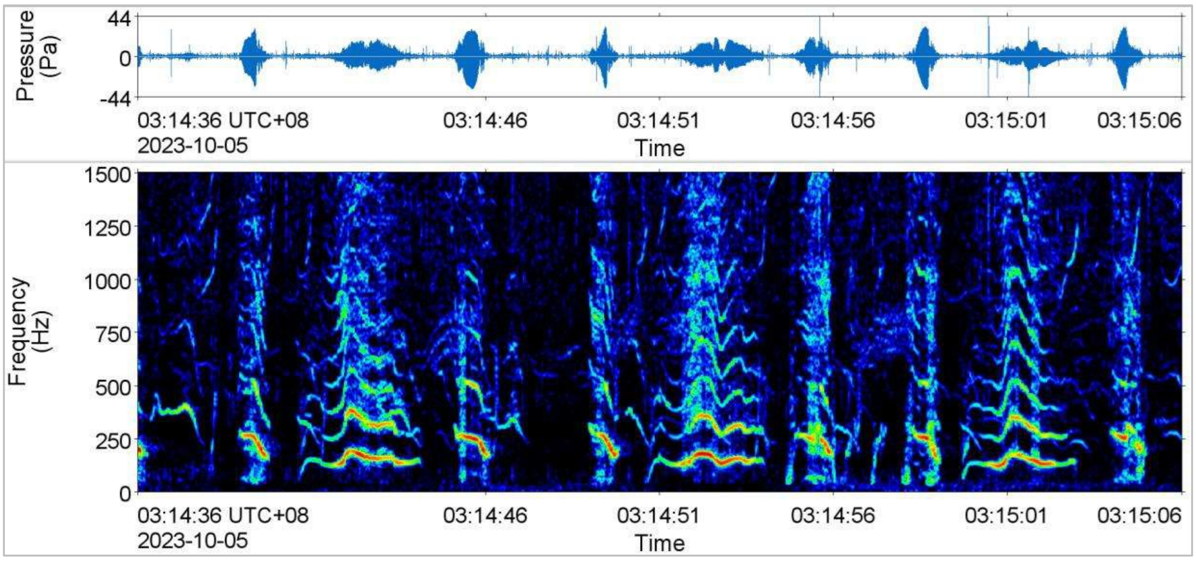


Figure 27. Humpback whales: (Top) waveform and (bottom) spectrogram of humpback whale song, showing different song units (see also Figure 28), recorded in the Exmouth Gulf on 5 Oct 2023 (2 Hz discrete Fourier Transform (DFT) frequency step, 0.125 s DFT temporal observation window (TOW), 0.03125 s DFT time advance and Hann window, resulting in a 75 % overlap and DFT size (N_{DFT}) of 32,768). The spectrogram is 30 s long.

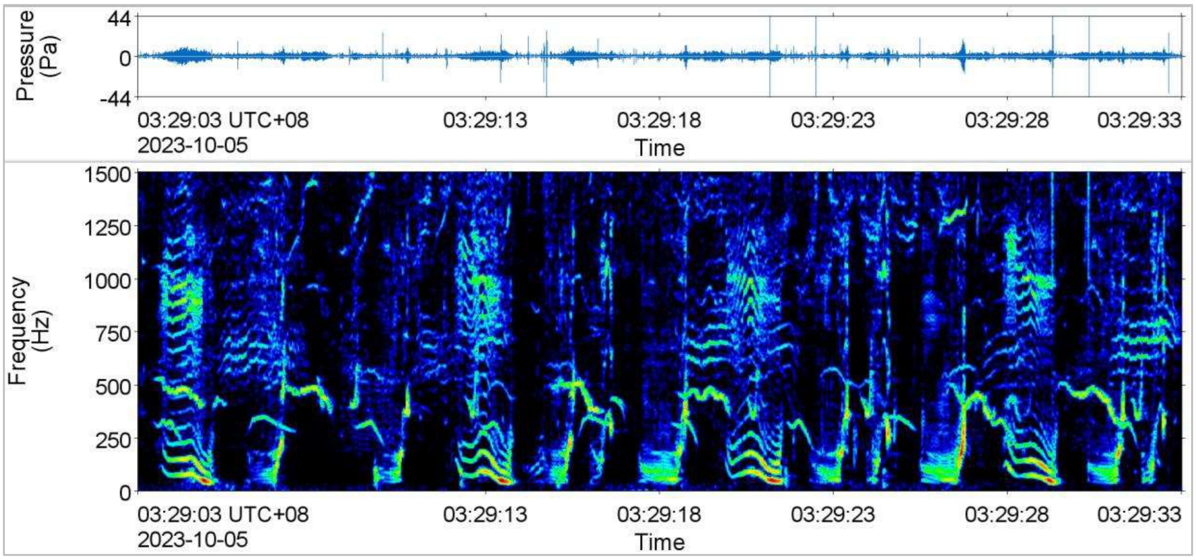


Figure 28. Humpback whales: (Top) waveform and (bottom) spectrogram of humpback whale song, showing different song units (see also Figure 27), recorded in the Exmouth Gulf on 5 Oct 2023 (2 Hz discrete Fourier Transform (DFT) frequency step, 0.125 s DFT temporal observation window (TOW), 0.03125 s DFT time advance and Hann window, resulting in a 75 % overlap and DFT size (N_{DFT}) of 32,768). The spectrogram is 30 s long.

3.4.2. Dolphin Clicks

Dolphin echolocation clicks were manually detected sporadically throughout the data set (Figure 29). Dolphin clicks were rarely detected during Period 1, but detections increased and continued from April to mid-September for the remainder of the recording (Figures 29 and 30).

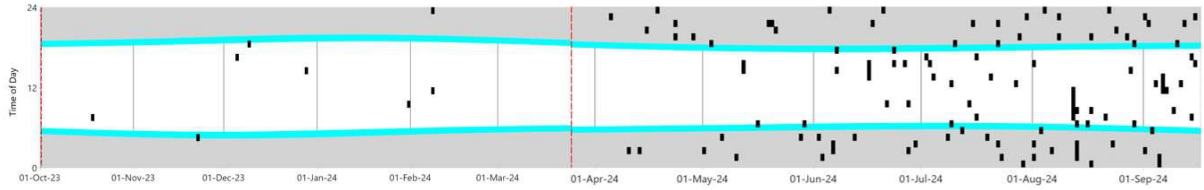


Figure 29. Dolphins: Daily and hourly occurrence of dolphin vocalisations recorded in the Exmouth Gulf from 1 Oct 2023 to 16 Sep 2024. Black cells indicate manual detections of echolocation clicks. Grey shaded and turquoise areas indicate hours of darkness and nautical twilight, respectively (Ocean Time Series Group (2009)). The red dashed line indicates the recorder deployment dates.

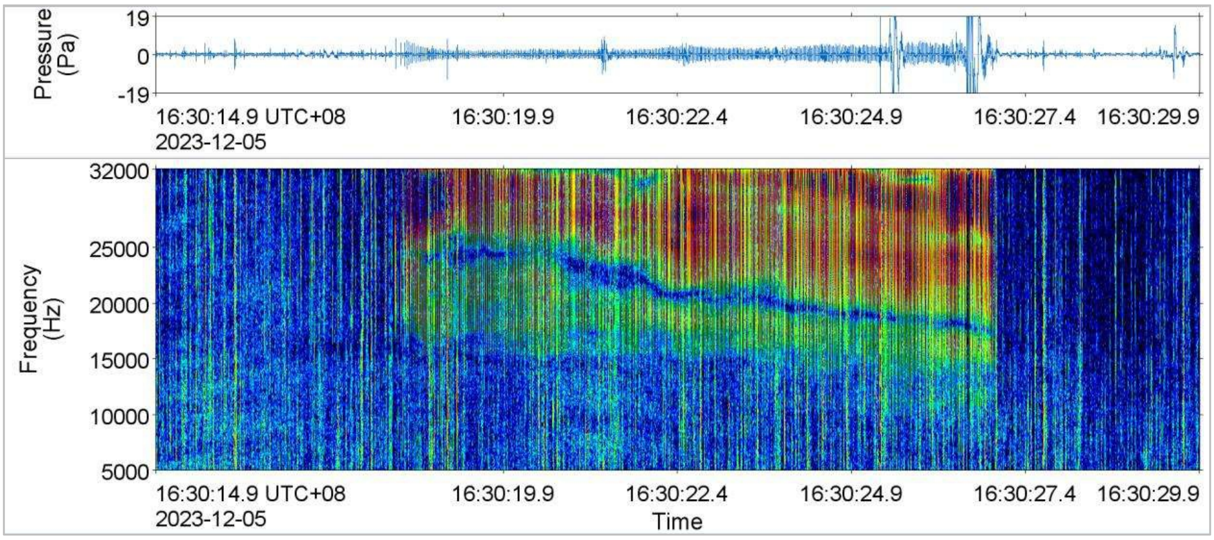


Figure 30. Dolphins: (Top) waveform and (bottom) spectrogram of an echolocation click train recorded in the Exmouth Gulf on 5 Dec 2023 (64 Hz discrete Fourier Transform (DFT) frequency step, 0.01 s DFT temporal observation window (TOW), 0.005 s DFT time advance and Hann window, resulting in a 50 % overlap and DFT size (N_{DFT}) of 1,024). The spectrogram is 15 s long.

3.4.3. Dolphin Whistles

Dolphin whistles were only manually detected twice during Period 1, on 25 Oct 2023 and 1 Nov 2023 (Figure 31). Dolphin whistles (Figure 31) were more common during Period 2 from 18 Apr to 14 Sep 2024 (Figure 32). Overall, dolphin whistles were detected too sporadically to assess any temporal trend.

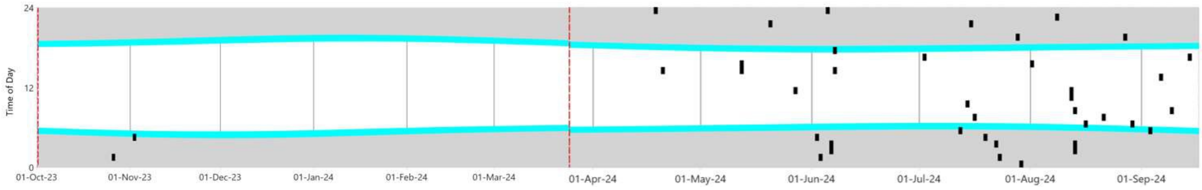


Figure 31. Dolphins: Daily and hourly occurrence of dolphin vocalisations recorded in the Exmouth Gulf from 1 Oct 2023 to 16 Sep 2024. Black cells indicate manual detections of dolphin whistles. Grey shaded and turquoise areas indicate hours of darkness and nautical twilight, respectively (Ocean Time Series Group (2009)). The red dashed line indicates the recorder deployment dates.

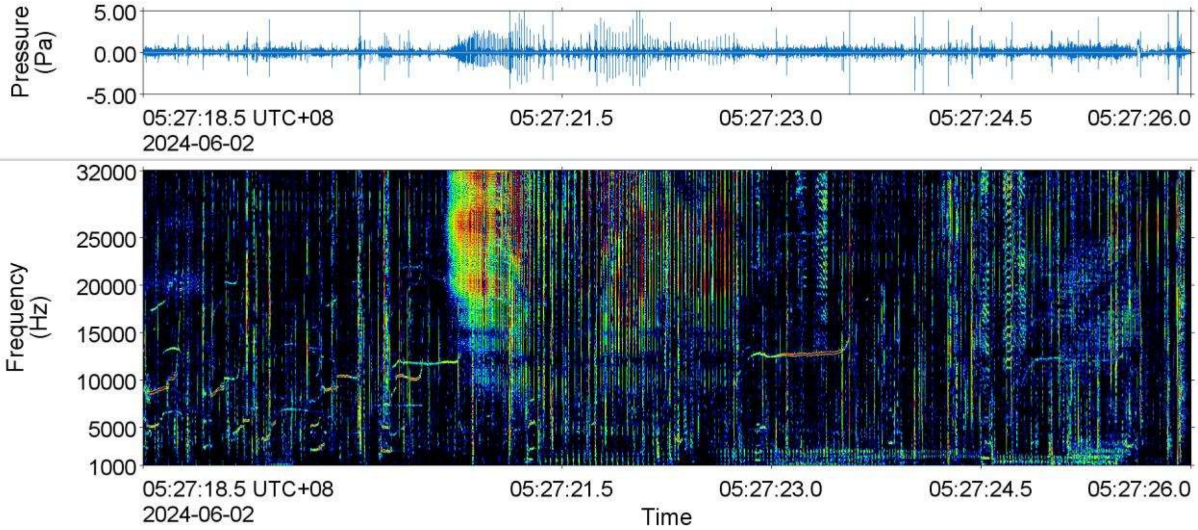


Figure 32. Dolphins: (Top) waveform and (bottom) spectrogram of dolphin whistles and clicks recorded in the Exmouth Gulf on 2 Jun 2024 (4 Hz discrete Fourier Transform (DFT) frequency step, 0.05 s DFT temporal observation window (TOW), 0.01 s DFT time advance and Hann window, resulting in a 80 % overlap and DFT size (N_{DFT}) of 16,384). The spectrogram is 9.5 s long.

3.5. Fish

Vocalisations produced by fish were manually identified in the data (Figure 33). Fish sounds were consistently detected throughout the recording period, with the exception of the first half of October 2023 and late July 2024 to the end of deployment. The latter could have been caused by masking by humpback whale song, which dominated the lower frequency bands during late winter into spring. In addition, because the files for manual review are selected based on the output of automated detectors (many of which triggered on components of humpback whale songs) the files during late summer to early spring may have been biased towards those containing humpback whale sounds, perhaps at the expense of files containing fish sounds.

The recorded fish sounds were diverse and consisted of impulsive sounds, ‘grunts’ (Figure 34), ‘groans’, and ‘honks’ (Figure 35). The opportunistic manual detections are not appropriate to determine any diel cycle often associated with fish sounds in tropical areas.

At least one type of fish sound occurred in the form of chorus that were present on some days between 21:00 and 02:00 local time (Figures 36 and 37). These choruses were alternatively faint and loud, suggesting that the aggregation of fish responsible for them was mobile and occurred at different locations with respect to the recorder during the recording period.

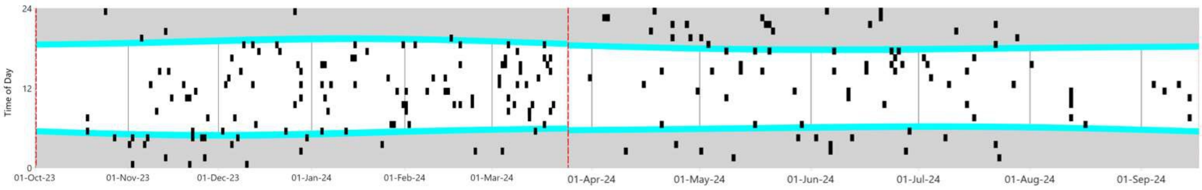


Figure 33. Fish: Daily and hourly occurrence of fish calls recorded in the Exmouth Gulf from 1 Oct 2023 to 16 Sep 2024. Black cells indicate manual detections. Grey shaded and turquoise areas indicate hours of darkness and nautical twilight, respectively (Ocean Time Series Group (2009)). The red dashed line indicates the recorder deployment dates.

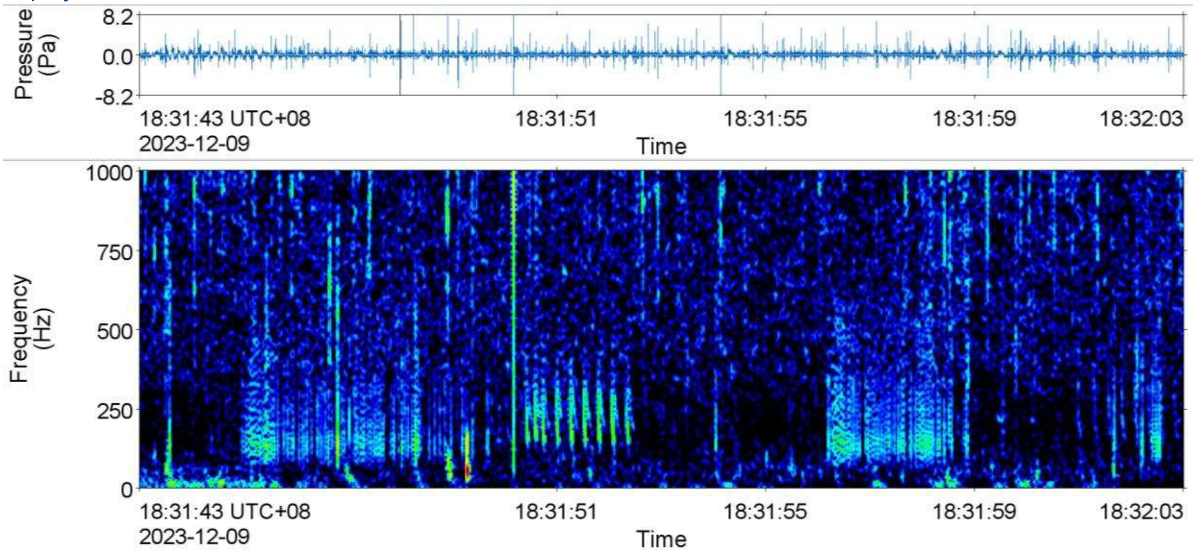


Figure 34. Fish: (Top) waveform and (bottom) spectrogram of fish calls (‘grunts’ and impulsive sounds) at dusk, recorded in the Exmouth Gulf on 9 Dec 2023 (2 Hz discrete Fourier Transform (DFT) frequency step, 0.125 s DFT temporal observation window (TOW), 0.03125 s DFT time advance and Hann window, resulting in a 75 % overlap and DFT size (N_{DFT}) of 32,768). The spectrogram is 20 s long.

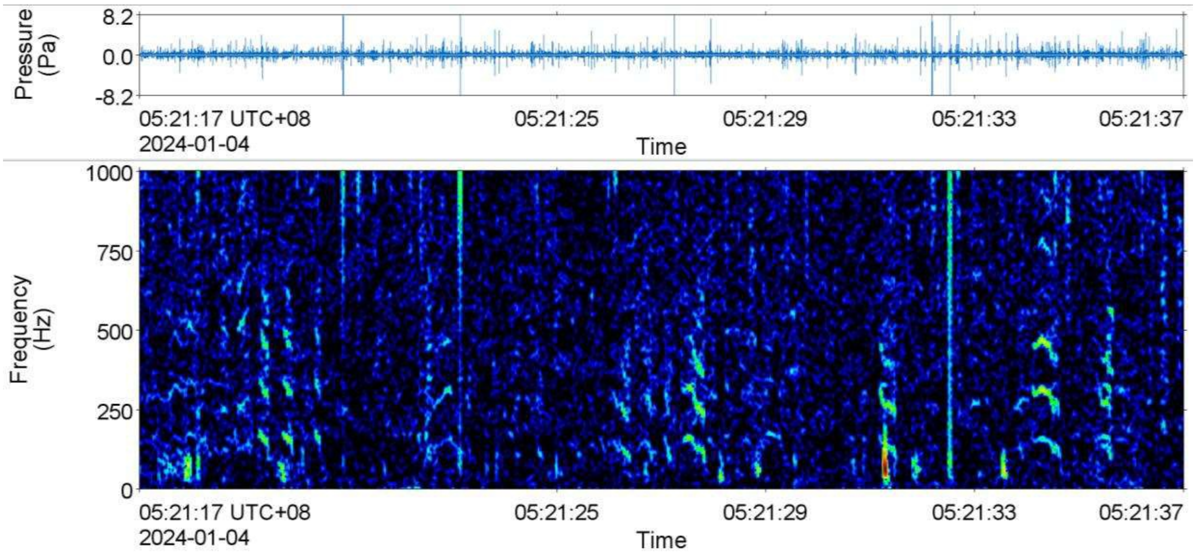


Figure 35. Fish: (Top) waveform and (bottom) spectrogram of fish calls (‘groans’ and ‘honks’) at dawn, recorded in the Exmouth Gulf on 4 Jan 2024 (2 Hz discrete Fourier Transform (DFT) frequency step, 0.125 s DFT temporal observation window (TOW), 0.03125 s DFT time advance and Hann window, resulting in a 75 % overlap and DFT size (N_{DFT}) of 32,768). The spectrogram is 20 s long.

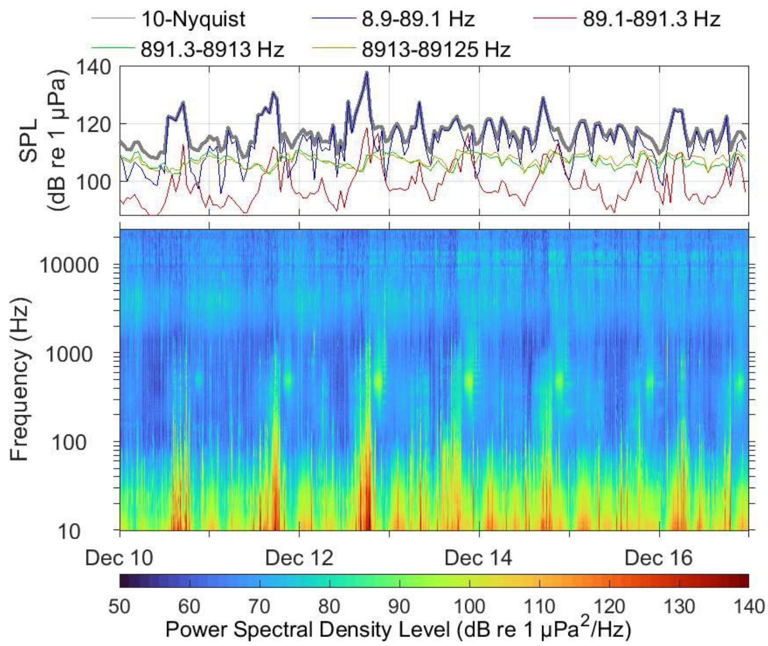


Figure 36. (Top) In-band sound pressure level (SPL) and long-term spectral average (LTSA) of underwater sound for the week of 10 Dec 2023 showing evening fish choruses in the frequency band 300–1000 Hz.

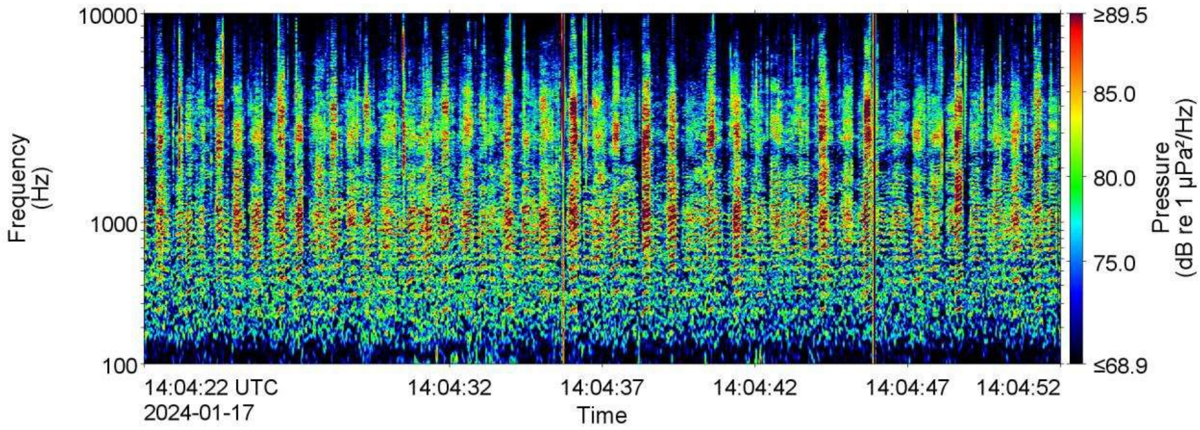


Figure 37. Spectrogram of fish calls present in the form of choruses, recorded in the Exmouth Gulf on 17 Jan 2024 (2 Hz discrete Fourier Transform (DFT) frequency step, 0.125 s DFT temporal observation window (TOW), 0.03125 s DFT time advance and Hann window, resulting in a 75 % overlap and DFT size (N_{DFT}) of 32,768). The spectrogram is 30 s long and the frequency axis is on log scale.

4. Discussion and Conclusion

4.1. Ambient Sound and Vessel Presence

The collected data provide an initial characterisation of the ambient soundscape of the southwestern portion of the Exmouth Gulf across a one-year period. The sound level measurements indicate that the soundscape is primarily influenced by biological sources, including marine mammals, fish, and invertebrates. An unidentified object (likely biological) contacting the recorder caused high levels of low-frequency (<100 Hz) noise that is not part of the soundscape of the area. This was reflected in the analysis of sound levels (Tables 5), which resulted in a significantly lower mean level over the entire frequency band when excluding the period of 'biological interference' (up to 18 Nov 2023). Similarly, sub-100 Hz noise caused by tidal flow was observed in the data. This pseudo-noise is the consequence of the presence of the recorder in the environment and is not part of the soundscape of the area either.

Weather conditions can influence the ambient soundscape primarily due to wind causing waves, which can increase sound levels above 100 Hz (see Figure 2). Over the recording period, this area experienced relatively high winds on many days, which, among other contributions including vessel, mammal, and fish, would cause high sound levels at higher frequencies seen in the percentile figures of Figures 8, 14, and 15. There are two examples of wind speeds over 45 km/h (late December and late January, see Figure 38). These are reflected as slight broadband increases in the spectrogram of Figure 7; however, weather does not appear to be the most substantial soundscape contributor of the study area.

Anthropogenic sources were found to contribute relatively little to the ambient soundscape of the southwestern Gulf. Vessel traffic, which was expected to be the main anthropogenic contributor, was mostly restricted to the northwestern side of the Exmouth Gulf and the approaches to Exmouth (see also Figure 4), with limited traffic passing through the study area. This resulted in only few vessel detections in the data, clustered over a few isolated events.

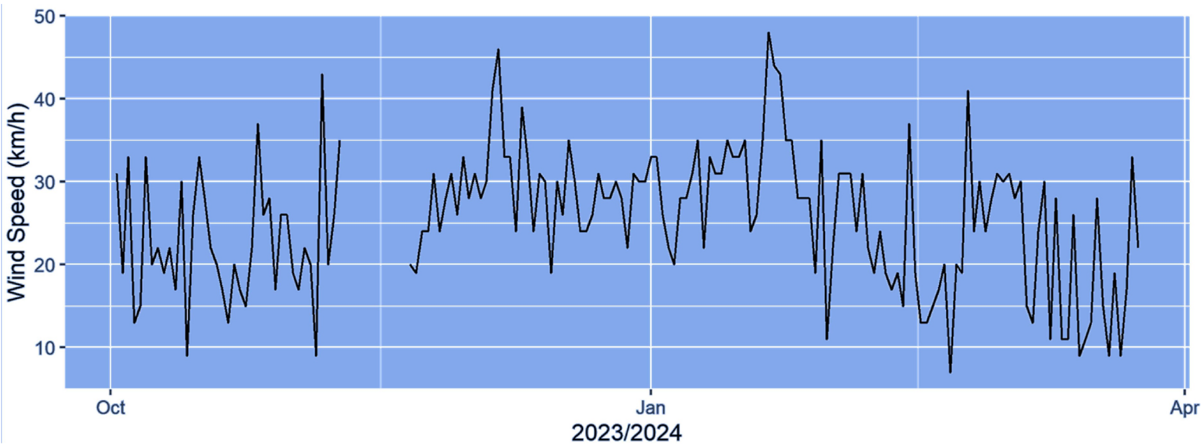


Figure 38. Daily wind speeds at 3 pm at Learmouth. Source: http://www.bom.gov.au/climate.

4.2. Marine Mammals

The acoustic detections of marine mammals presented in this report provide an index of acoustic occurrence for each species. However, while acoustic detection indicates presence of animals and can therefore be used to describe the relative abundance of a species across the study area, an absence of detections does not necessarily indicate absence of animals. There are several factors that influence the detectability of the targeted signals and may thus result in less detections than expected. For instance, an animal may be present but not detected if no individuals were vocalising near the recorder, or if their signals were masked by environmental and/or anthropogenic noise sources, or due to a combination of these factors. Different species will be detectable at different ranges, for example, dolphins may need to be within hundreds of metres to kilometres to be detected, while humpbacks can generally be heard kilometres to tens of kilometres away. In addition, different sound propagation environments and different seasonal effects will impact the detection range of a given signal over time and thus influence the number of detectable signals. Finally, seasonal variations in vocalising behaviour by the species targeted may falsely suggest changes in occurrence. Therefore, the acoustic occurrence of each species across stations is discussed in consideration of environmental, anthropogenic, and/or biological factors that influence the detectability of the targeted acoustic signals.

4.2.1. Humpback Whales

The temporal pattern of humpback whale acoustic detections in these data reflect the known seasonal occurrence of this species in the area. Every year, Southern Hemisphere humpback whales migrate from their high-latitude summer feeding grounds to low-latitude winter breeding grounds. Exmouth Gulf is known to be part of the whales' migratory corridor and of particular biological importance as a resting area for southward migrating mothers and calves (Jenner et al. 2001, Videsen et al. 2017). While the recording period (which started on 1 Oct 2023) covers the period that mother-calf pairs rest in the Exmouth Gulf (Fitzpatrick et al. 2019), social sounds exchanged between mothers and their calves were not detected. This is unsurprising, however, as humpback whale mother-calf pairs are acoustically cryptic, producing vocalisations at very low levels to avoid attracting predators or humpback whale males searching for females to breed with (Videsen et al. 2017). In contrast, song (produced by males) was detected almost continuously from the start of the recording period until the end of October and again starting in mid-July to mid-September suggesting that breeding activities occur in the Gulf as well. The cessation of detections at the end of October is consistent with the expected departure of the whales as they continue to migrate south towards their summer feeding grounds. The onset of detections in mid-July was able to capture the onset of singing and breeding season. This year-long data set suggests that humpbacks reside in the Exmouth Gulf for at least three and half months during the breeding season. It should be noted that given only song was detected these results are biased towards males of the population and cows with calves may stay in the Gulf longer than is indicated by the results of the acoustic monitoring program.

4.2.2. Dolphins

The low number of both dolphin whistles and echolocation clicks was unexpected throughout the Period 1 recording, as various species of dolphin are known to occur in Exmouth Gulf (Table 1) and at least some were expected to make regular use of the area (Fitzpatrick et al. 2019, Sprogis and Parra 2023). It is possible that the acoustic occurrence of echolocation clicks is underestimated because of masking by snapping shrimp sounds. Second, the recording bandwidth provided only limited frequency overlap with the main band of echolocation clicks, which could have limited detection opportunities. Third, detection ranges at the shallow depth of the recorder's location are expected to be short (within hundreds of metres) further reducing detection opportunities. Finally, the shallow depth and location of the recorder deep inside Exmouth Gulf (see Figure 1) may also reduce the spatial overlap between the recorder's detection area for these signals and the main habitat for dolphins, which appears to be along the northwestern coastline of the Gulf (Sprogis and Parra 2023), which could explain the low number of detections. During Period 2, dolphin vocalisations were much more common suggesting that dolphins frequent the Exmouth Gulf mid-April to mid-September.

4.2.3. Other Marine Mammals

Of the species likely to occur in Exmouth Gulf (see Table 1), southern right whales and dugongs were not acoustically detected. In the case of southern right whales, the Exmouth Gulf represents the northernmost recorded boundary of the species' range in Western Australia (Allen and Bejder 2003), and sightings are rare.

In the case of dugongs, which were expected in the Exmouth Gulf during the recording period (Hodgson 2007), the absence of acoustic detections can possibly be attributed to benthic habitat features around the recorder. Dugong presence is strongly associated with seagrass presence; dugongs spend almost three quarters of their time in waters of less than 3 m deep, where seagrass density is usually highest (Chilvers et al. 2004). The recorder was located at 15 m depth and at least 10 km away from areas between 0 and 5 m deep (Figure 1), which is well beyond the expected detection range of dugong vocalisations which is typically tens to hundreds of metres (Tanaka et al. 2023a). Therefore, in addition to the detectability-influencing factors mentioned at the start of Section 4.2, low local density of dugongs near the recorder may have contributed to the absence of detections.

4.3. Fish

Fish were consistent contributors to the soundscape, and the recorded vocalisations were diverse. Almost 800 known species of bony fish inhabit the Exmouth Gulf (Fitzpatrick et al. 2019), and several of these are likely involved in producing the array of sounds detected here. However, descriptions of fish vocalisations for this area are currently unavailable, which made assigning fish sounds to a specific species (or even to a higher taxonomic level) impossible at this time. In addition, due to this lack of published studies on Exmouth Gulf fish sounds, automated detectors for these sounds were not available. The detections presented in this report are, therefore, limited to opportunistic manual detections in files that were selected for manual review of automated marine mammal detections (see Section 2.2.3) and are likely an underrepresentation of the acoustic presence of fish in Exmouth Gulf.

In terms of temporal trends in detections, fish were acoustically present throughout the recording period. The only exception was from the start of recording until mid-October, which can possibly be attributed to masking by humpback whale song. In addition, as the files manually analysed during that period may have been specifically selected for containing humpback whale sounds (see above), the real acoustic presence of fish during the first half of October and again mid-July to mid-September was likely no less than during the rest of the recording period. While the opportunistic nature of manual detection prevented the inference of temporal patterns of vocalisation, such as diel cycles with semi-lunar patterns (Parsons et al. 2016), chorusing was evident from the long-term ambient soundscape representations and occurred at different times of day (see Section 3.5). These various choruses are presumably from different species and may be an indicator of fish biodiversity in the area (Hawkins et al. 2023).

4.4. Conclusions

This report presents a characterisation of the ambient soundscape of the southwestern Exmouth Gulf across a one-year period. The data reveal a soundscape that is primarily influenced by marine fauna, with minor contributions from weather and vessel traffic. The detections of various vocalisation types produced by marine mammals and fish demonstrate the effectiveness of passive acoustic monitoring to infer species presence for vocally active species (for example, seasonal use of the Exmouth Gulf by humpback whales) but also the potential for further refinement (for example, identifying fish chorus source species to utilise chorusing as a biodiversity index).

Acknowledgements

The authors would like the acknowledge the assistance of the JASCO field team (Robert Mills, James Tanner, and Dion Stroot) along with Terrafirma Offshore team (including Daemon Bass) who provided exceptional support, and their professionalism from vessel planning and HAZID process through to implementation in the field was greatly appreciated. Thank you to JASCO's manual analysts that contributed to this work including Allison Richardson and Katie Kowarski.

Glossary of Acoustics Terms

Unless otherwise stated in an entry, these definitions are consistent with ISO 18405 (2017a).

Light blue text indicates related terms that might be in this glossary. Dark blue text indicates clickable links to related terms in this glossary.

1/3-octave

One third of an octave. A 1/3-octave is approximately equal to one decidecade (1/3 oct ≈ 1.003 ddec).

1/3-octave-band

Frequency band whose bandwidth is one 1/3-octave. The bandwidth of a 1/3-octave-band increases with increasing centre frequency.

acoustic noise

Sound that interferes with an acoustic process.

ambient sound

Sound that would be present in the absence of a specified activity (ISO 18405:2017a). It is usually a composite of sound from many sources near and far, e.g., shipping vessels, seismic activity, precipitation, sea ice movement, wave action, and biological activity.

annotation

Within a spectrogram, a labelled selection of a time interval and frequency range as created during manual analysis.

automated detection

The output of an automated detector.

automated detector

An algorithm that includes both the automated detection of a sound of interest (e.g., vessel noise, marine mammal call) based on how it stands out from the background noise, and its automated classification based on similarities to templates in a library of reference signals.

background noise

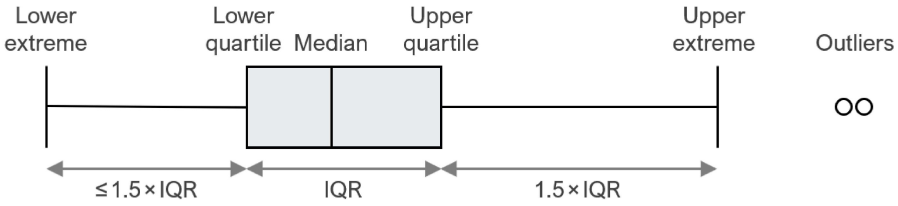
Combination of ambient sound, acoustic self-noise, and, where applicable, sonar reverberation (ISO 18405:2017a) that is detected, measured, or recorded with a signal.

bandwidth

A range within a continuous band of frequencies. Unit: hertz (Hz).

box-and-whisker plot

A statistical data plot that illustrates the centre, spread, and overall range of data as a visual 5-number summary. The box is the interquartile range (IQR), which shows the middle 50 % of the data—from the lower quartile (25th percentile) to the upper quartile (75th percentiles). The line inside the box is the median (50th percentile). The whiskers show the lower and upper extremes excluding outliers, which are data points that fall more than 1.5 × IQR beyond the upper or lower quartiles.



cavitation

A rapid formation and collapse of vapor cavities (i.e., bubbles or voids) in water, most often caused by a rapid change in pressure. Fast-spinning vessel propellers typically cause cavitation, which creates a lot of noise.

cetacean

Member of the order Cetacea. Cetaceans are aquatic mammals and include whales, dolphins, and porpoises.

critical band

The auditory bandwidth within which background noise strongly contributes to masking of a single tone. Unit: hertz (Hz).

decade

Logarithmic frequency interval whose upper bound is ten times larger than its lower bound (ISO 80000-3:2006). For example, one decade up from 1000 Hz is 10,000 Hz, and one decade down is 100 Hz.

decibel (dB)

Unit of level used to express the ratio of one value of a power quantity to another on a logarithmic scale. Especially suited to quantify variables with a large dynamic range.

decidecade

One tenth of a decade. Approximately equal to one third of an octave (1 ddec ≈ 0.3322 oct), and for this reason sometimes referred to as a 1/3-octave.

decidecade band

Frequency band whose bandwidth is one decidecade. The bandwidth of a decidecade band increases with increasing centre frequency.

delphinid

Member of the family of oceanic dolphins (Delphinidae), composed of approximately 35 extant species, including dolphins, porpoises, and killer whales.

Fourier transform, Fourier synthesis

A mathematical technique which, although it has varied applications, is referenced in a physical data acquisition context as a method used in the process of deriving a spectrum estimate from time-series data (or the reverse process, termed the inverse Fourier transform). A computationally efficient numerical algorithm for computing the Fourier transform is known as the fast Fourier transform (FFT).

frequency

The rate of oscillation of a periodic function measured in cycles per unit time. The reciprocal of the period. Unit: hertz (Hz). Symbol: f. 1 Hz is equal to 1 cycle per second.

harmonic

A sinusoidal sound component that has a frequency that is an integer multiple of the frequency of a sound to which it is related. For a sound with a fundamental frequency of f, the harmonics have frequencies of $2f$, $3f$, $4f$, etc.

hertz (Hz)

Unit of frequency defined as one cycle per second. Often expressed in multiples such as kilohertz (1 kHz = 1000 Hz).

hydrophone

An underwater sound pressure transducer. A passive electronic device for recording or listening to underwater sound.

impulsive sound

Qualitative term meaning sounds that are typically transient, brief (less than 1 s), broadband, with rapid rise time and rapid decay. They can occur in repetition or as a single event. Sources of impulsive sound include, among others, explosives, seismic airguns, and impact pile drivers.

level

A measure of a quantity expressed as the logarithm of the ratio of the quantity to a specified reference value of that quantity. For example, a value of sound pressure level with reference to 1 μPa^2 can be written in the form *x* dB re 1 μPa^2.

manual analysis

Human examination of acoustic data via visual review of spectrograms and/or aural inspection of data.

manual detection

The output of manual analysis as recorded in an annotation.

masking

Obscuring of sounds of interest by other sounds at similar frequencies.

median

The 50th percentile of a statistical distribution.

mysticete

Member of the Mysticeti, a suborder of cetaceans. Also known as baleen whales, mysticetes have baleen plates (rather than teeth) that they use to filter food from water (or from sediment as for grey whales). This group includes rorquals (Balaenopteridae, such as blue, fin, humpback, and minke whales), right and bowhead whales (Balaenidae), and grey whales (*Eschrichtius robustus*).

N percent exceedance level

The sound level exceeded *N* % of the time during a specified time interval. See also percentile level.

octave

The interval between a sound and another sound with double or half the frequency. For example, one octave above 200 Hz is 400 Hz, and one octave below 200 Hz is 100 Hz.

odontocete

Member of Odontoceti, a suborder of cetaceans. These whales, dolphins, and porpoises have teeth (rather than baleen plates). Their skulls are mostly asymmetric, an adaptation for their echolocation. This group includes sperm whales, killer whales, belugas, narwhals, dolphins, and porpoises.

peak sound pressure level (PK), zero-to-peak sound pressure level

The level (L_{pk}) of the squared maximum magnitude of the sound pressure (p^2_{pk}) in a stated frequency band and time window. Defined as L_{pk} = $10\log_{10}(p^2_{\mathrm{pk}}/p^2_0)$ = $20\log_{10}(p_{\mathrm{pk}}/p_0)$. Unit: decibel (dB). Reference value (p^2_0) for sound in water: 1 µPa^2.

percentile level

The sound level not exceeded *N* % of the time during a specified time interval. The *N*th percentile level is equal to the (100−*N*) % exceedance level. See also N percent exceedance level.

power spectral density

Generic term, formally defined as power in a unit frequency band. Unit: watt per hertz (W/Hz). The term is sometimes loosely used to refer to the spectral density of other parameters such as squared sound pressure. Ratio of energy spectral density, E_f, to time duration, Δt, in a specified temporal observation window. In equation form, the power spectral density P_f is given by $P_f = E_f/\Delta t$. Power spectral density can be expressed in terms of various field variables (e.g., sound pressure, sound particle displacement).

power spectral density level

The level ($L_{P,f}$) of the power spectral density (P_f) in a stated frequency band and time window. Defined as: $L_{P,f}$ = $10\log_{10}(P_f/P_{f,0})$. Unit: decibel (dB).

As with power spectral density, power spectral density level can be expressed in terms of various field variables (e.g., sound pressure, sound particle displacement). The reference value ($P_{f,0}$) for power spectral density level depends on the nature of the field variable.

power spectral density source level

A property of a sound source equal to the power spectral density level of the sound pressure measured in the far field plus the propagation loss from the acoustic centre of the source to the receiver position. Unit: decibel (dB). Reference value: 1 µPa^2 m^2/Hz.

received level

The level of a given field variable measured (or that would be measured) at a given location.

sound

A time-varying disturbance in the pressure, stress, or material displacement of a medium propagated by local compression and expansion of the medium. In common meaning, a form of energy that propagates through media (e.g., water, air, ground) as pressure waves.

sound pressure

The contribution to total pressure caused by the action of sound (ISO 18405:2017a). Unit: pascal (Pa). Symbol: p.

sound pressure level (SPL), rms sound pressure level

The level (L_p) of the time-mean-square sound pressure (p^2_{rms}) in a stated frequency band and time window: $L_p = 10\log_{10}(p^2_{\mathrm{rms}}/p^2_0) = 20\log_{10}(p_{\mathrm{rms}}/p_0)$, where rms is the abbreviation for root-mean-square. Unit: decibel (dB). Reference value (p^2_0) for sound in water: 1 μPa^2. SPL can also be expressed in terms of the root-mean-square (rms) with a reference value of p_0 = 1 μPa. The two definitions are equivalent.

soundscape

The characterisation of the ambient sound in terms of its spatial, temporal, and frequency attributes, and the types of sources contributing to the sound field (ISO 18405:2017a).

source level (SL)

A property of a sound source equal to the sound pressure level measured in the far field plus the propagation loss from the acoustic centre of the source to the receiver position. Unit: decibel (dB). Reference value: 1 μPa^{2} m^{2}.

spectrogram

A visual representation of acoustic amplitude over time and frequency. A spectrogram's resolution in the time and frequency domains should generally be stated as it determines the information content of the representation.

spectrum

Distribution of acoustic signal content over frequency, where the signal's content is represented by its power, energy, mean-square sound pressure, or sound exposure.

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Appendix A. Recorder Calibration and Mooring Design

A.1. Recorder Calibrations

Each AMAR was calibrated before deployment and upon retrieval (battery life permitting) with a pistonphone type 42AC precision sound source (G.R.A.S. Sound & Vibration A/S; Figure A-1). The pistonphone calibrator produces a constant tone at 250 Hz at a fixed distance from the hydrophone sensor in an airtight space of known volume. The recorded level of the reference tone on the AMAR yields the system gain for the AMAR and hydrophone. To determine absolute sound pressure levels, this gain was applied during data analysis. Typical calibration variance using this method is less than 0.7 dB absolute pressure.

Figure A-1. Split view of a G.R.A.S. 42AC pistonphone calibrator with an M36 hydrophone.

A.2. Mooring Design

Figure A-2 shows the mooring design used for the AMAR with a baseplate with groundline to an anchor weight.

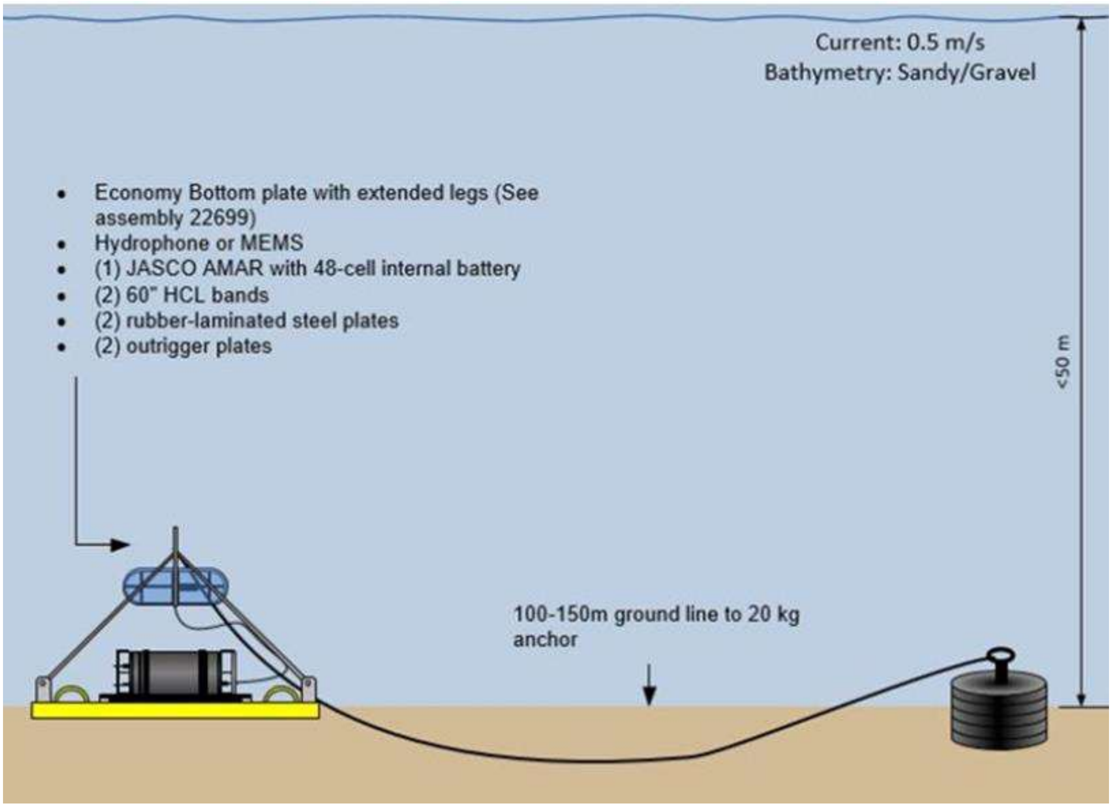

Figure A-2. Mooring design with one Autonomous Multichannel Acoustic Recorder Generation 4 in acetal housing (AMAR G4 ACE) attached to a bottom plate.

Appendix B. Acoustic Data Analysis

The sampled data were processed for ambient sound analysis, vessel noise detection, and detection of all marine mammal vocalisations with JASCO's PAMlab acoustic analysis software suite. The major processing stages are outlined in Figure B-1. The results are calculated in terms of various acoustics metrics, defined in Appendix B.1, and in various frequency bands, defined in Appendix B.2.

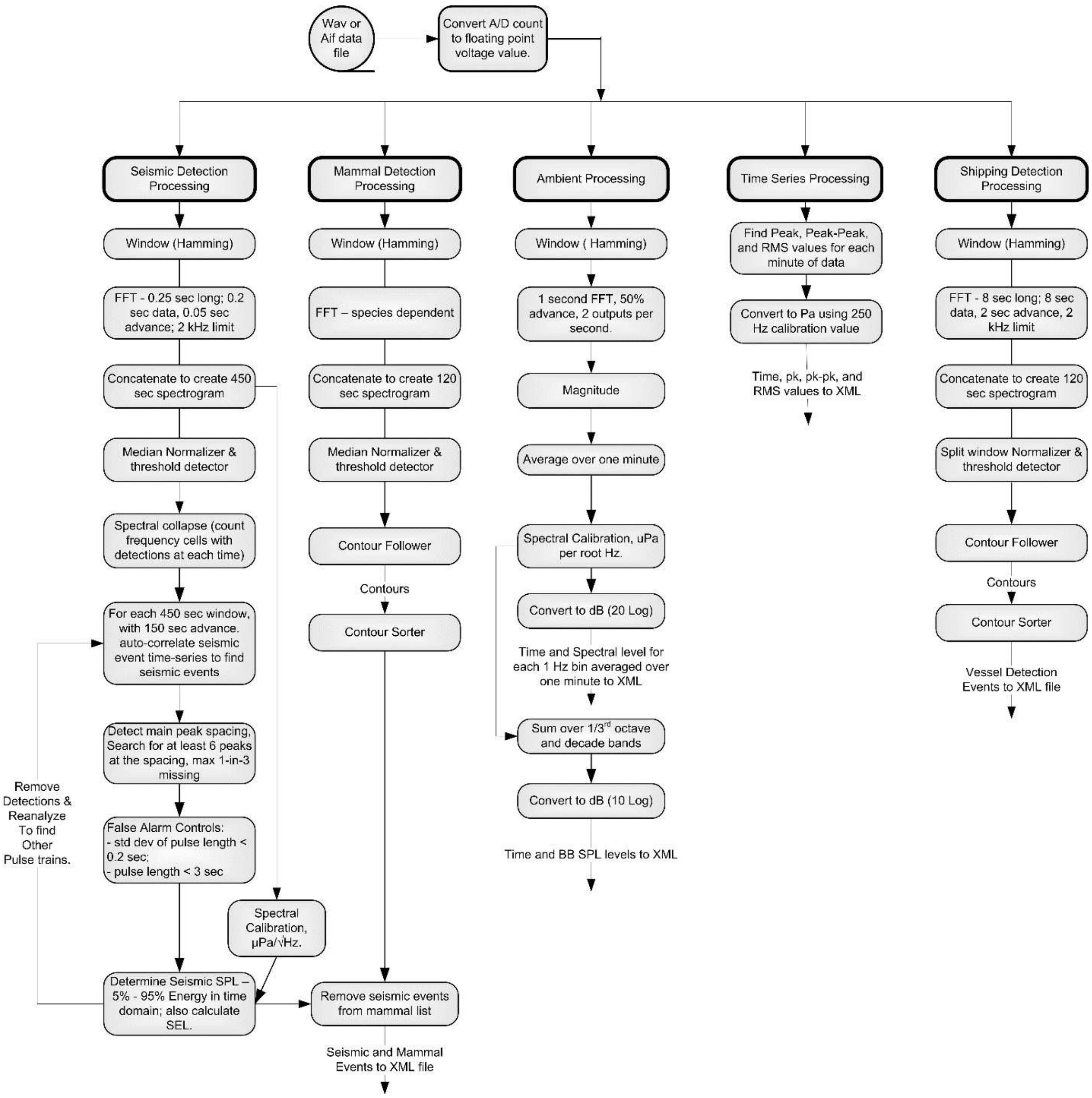

Figure B-1. Major stages of the automated acoustic analysis process performed with JASCO's PAMlab software suite.

B.1. Acoustic Metrics

Underwater sound pressure amplitude is quantified in decibels (dB) relative to a fixed reference pressure of p_0 = 1 μPa. Because the perceived loudness of sound, especially pulsed sound such as from seismic airguns, pile driving, and sonar, is not generally proportional to the instantaneous acoustic pressure, several sound level metrics are commonly used to evaluate sound and its effects on marine life. Here, the specific definitions of relevant metrics used in the accompanying report are provided. Where possible, International Organization for Standardization definitions and symbols for sound metrics are followed (e.g., ISO 18405:2017a, ANSI S1.1-2013).

The zero-to-peak sound pressure, or peak sound pressure (PK or L_{pk}; dB re 1 μPa), is the decibel level of the maximum instantaneous sound pressure in a stated frequency band attained by an acoustic pressure signal, $p(t)$:

$$L_{\text{pk}} = 10\log_{10}\frac{p_{\text{pk}}^2}{p_0^2} = 20\log_{10}\frac{p_{\text{pk}}}{p_0} = 20\log_{10}\frac{\max|p(t)|}{p_0}\,. \tag{B-1}$$

PK is often included as a criterion for assessing whether a sound is potentially injurious; however, because it does not account for the duration of an acoustic event, it is generally a poor indicator of perceived loudness.

The sound pressure level (SPL or L_p; dB re 1 μPa) is the root-mean-square (rms) pressure level in a stated frequency band over a specified time window (T; s):

$$L_p = 10\log_{10}\frac{p_{\text{rms}}^2}{p_0^2} = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)\,dt \Big/ p_0^2\right)\,. \tag{B-2}$$

It is important to note that SPL always refers to an rms pressure level (i.e., a quadratic mean over a time interval) and therefore not instantaneous pressure at a fixed point in time. The SPL can also be defined as the *mean-square* pressure level, given in decibels relative to a reference value of 1 μPa^2 (i.e., in dB re 1 μPa^2). The two definitions of SPL are numerically equivalent, differing only in reference value.

B.2. Decidecade Band Analysis

The distribution of a sound's power with frequency is described by the sound's spectrum. The sound spectrum can be split into a series of adjacent frequency bands. Splitting a spectrum into 1 Hz wide bands, called passbands, yields the power spectral density of the sound. These values directly compare to the Wenz curves, which represent typical deep ocean sound levels (see Figure 2) (Wenz 1962). This splitting of the spectrum into passbands of a constant width of 1 Hz, however, does not represent how animals perceive sound.

Animals perceive exponential increases in frequency rather than linear increases, so analysing a sound spectrum with passbands that increase exponentially in size better approximates real-world scenarios. In underwater acoustics, a spectrum is commonly split into decidecade bands, which are one tenth of a decade wide. A decidecade is sometimes referred to as a "1/3-octave" because one tenth of a decade is approximately equal to one third of an octave. Each decade represents a factor of 10 in sound frequency. Each octave represents a factor of 2 in sound frequency. The centre frequency of the ith decidecade band, $f_c(i)$, is defined as:

$$f_c(i) = 10^{\frac{i}{10}}\ \text{kHz}\,, \tag{B-3}$$

and the low (f_{lo}) and high (f_{hi}) frequency limits of the ith decidecade band are defined as:

$$f_{\mathrm{lo},i} = 10^{\frac{-1}{20}} f_{\mathrm{c}}(i) \text{ and } f_{\mathrm{hi},i} = 10^{\frac{1}{20}} f_{\mathrm{c}}(i)\,. \tag{B-4}$$

The decidecade bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure B-2).

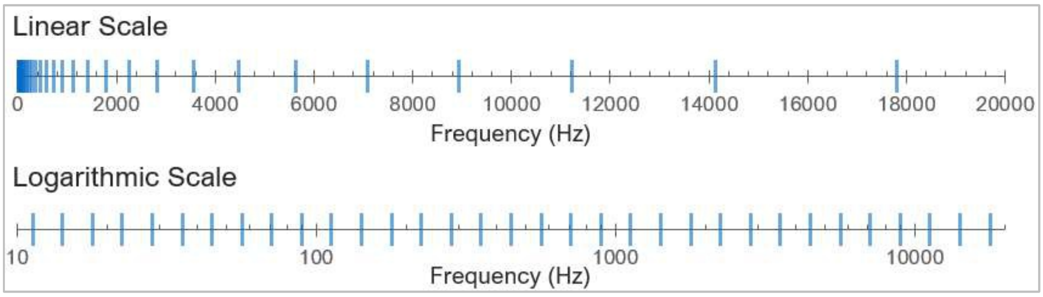

Figure B-2. Decidecade frequency bands (vertical lines) shown on (top) a linear frequency scale and (bottom) a logarithmic scale. On the logarithmic scale, the bands are equally spaced.

The sound pressure level in the ith band ($L_{p,i}$) is computed from the spectrum $S(f)$ between $f_{lo,i}$ and $f_{hi,i}$:

$$L_{p,i} = 10 \log_{10} \int_{f_{\mathrm{lo},i}}^{f_{\mathrm{hi},i}} S(f)\,\mathrm{d}f \;\mathrm{dB}\,. \tag{B-5}$$

Summing the sound pressure level of all the bands yields the broadband sound pressure level:

$$\text{Broadband SPL} = 10 \log_{10} \sum_{i} 10^{\frac{L_{p,i}}{10}} \;\mathrm{dB}\,. \tag{B-6}$$

Figure B-3 shows an example of how the decidecade band sound pressure levels compare to the sound pressure spectral density levels of an ambient sound signal. Because the decidecade bands are wider than 1 Hz, the decidecade band SPL is higher than the spectral levels at higher frequencies. Decidecade band analysis can be applied to continuous and impulsive sound sources. For impulsive sources, the decidecade band SEL is typically reported.

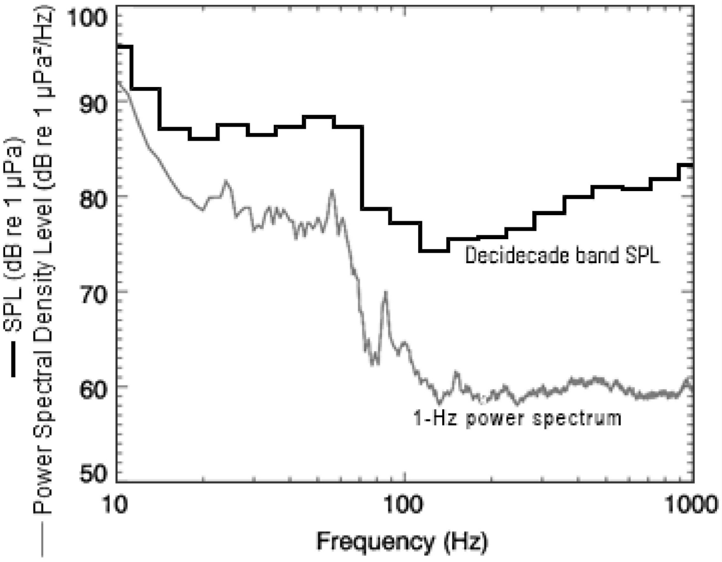

Figure B-3. Sound pressure spectral density levels and the corresponding decidecade band sound pressure levels of example ambient sound shown on a logarithmic frequency scale. Because the decidecade bands are wider with increasing frequency, the decidecade band SPL is higher than the power spectrum, which is based on bands with a constant width of 1 Hz.

Table B-1. Decidecade band centre and limiting frequencies (Hz).

Band	Lower frequency	Nominal centre frequency	Upper frequency	Band	Lower frequency	Nominal centre frequency	Upper frequency
10	8.9	10.0	11.2	28	562	631	708
11	11.2	12.6	14.1	29	708	794	891
12	14.1	15.8	17.8	30	891	1000	1122
13	17.8	20.0	22.4	31	1122	1259	1413
14	22.4	25.1	28.2	32	1413	1585	1778
15	28.2	31.6	35.5	33	1778	1995	2239
16	35.5	39.8	44.7	34	2239	2512	2818
17	44.7	50.1	56.2	35	2818	3162	3548
18	56.2	63.1	70.8	36	3548	3981	4467
19	70.8	79.4	89.1	37	4467	5012	5623
20	89.1	100.0	112.2	38	5623	6310	7079
21	112	126	141	39	7079	7943	8913
22	141	158	178	40	8913	10000	11220
23	178	200	224	41	11220	12589	14125
24	224	251	282	42	14260	16000	17952
25	282	316	355	43	17825	20000	22440
26	355	398	447	44	22281	25000	28050
27	447	501	562	45	28074	31500	32000

Table B-2. Decade band centre and limiting frequencies (Hz).

Decade band	Lower frequency	Nominal centre frequency	Upper frequency
2	10	50	100
3	100	500	1000
4	1,000	5,000	10,000
5	10,000		32,000

Appendix C. Marine Mammal Detection Methodology

C.1. Automated Click Detector for Odontocetes

Figure C-1 shows how an automated click detector/classifier is applied to the data to detect clicks from odontocetes. This detector/classifier is based on the zero-crossings in the acoustic time series. Zero-crossings are the rapid oscillations of a click's pressure waveform above and below the signal's normal level. Clicks are detected by the following steps:

1. The raw data are high-pass filtered to remove all energy below 5, 25 or 50 kHz depending on the species targeted (see Table C-1). This removes most energy from sources other than odontocetes (such as shrimp, vessels, wind, and cetacean tonal calls) yet allows the energy from all marine mammal click types to pass.
2. The filtered samples are summed to create a 0.334 ms rms time series. Most marine mammal clicks have a 0.1–1 ms duration.
3. Possible click events are identified with a split-window normaliser that divides the 'test' bin of the time series by the mean of the 6 'window' bins on either side of the test bin, leaving a 'notch' that is 1-bin wide.
4. A Teager-Kaiser energy detector identifies possible click events.
5. The high-pass filtered data are searched to find the maximum peak signal within 1 ms of the detected peak.
6. The high-pass filtered data are searched backwards and forwards to find the time span when the local data maxima are within 9 dB of the maximum peak. The algorithm allows for two zero-crossings to occur where the local peak is not within 9 dB of the maximum before stopping the search. This defines the time window of the detected click.
7. The classification parameters are extracted. The number of zero crossings within the click, the median time separation between zero crossings, and the slope of the change in time separation between zero-crossings are computed. The slope parameter helps identify beaked whale clicks, because beaked whales can be identified by the increase in frequency (upsweep) of their clicks.
8. The Mahalanobis distance between the extracted classification parameters and the templates of known click types is computed. The covariance matrices for the known click types (computed from thousands of manually identified clicks for each species) are stored in an external file. Each click is classified as a type with the minimum Mahalanobis distance unless none of them are less than the specified distance threshold.

It should be noted that the sampling rate selected for this study (64 kHz, providing a recording bandwidth up to 32 kHz) does not capture the full frequency band of echolocation clicks produced by the odontocetes expected in the Exmouth Gulf. The click detectors used for these species target frequencies 25 kHz and above, leaving a very narrowband band that may not contain enough spectral information for reliable click detection and identification.

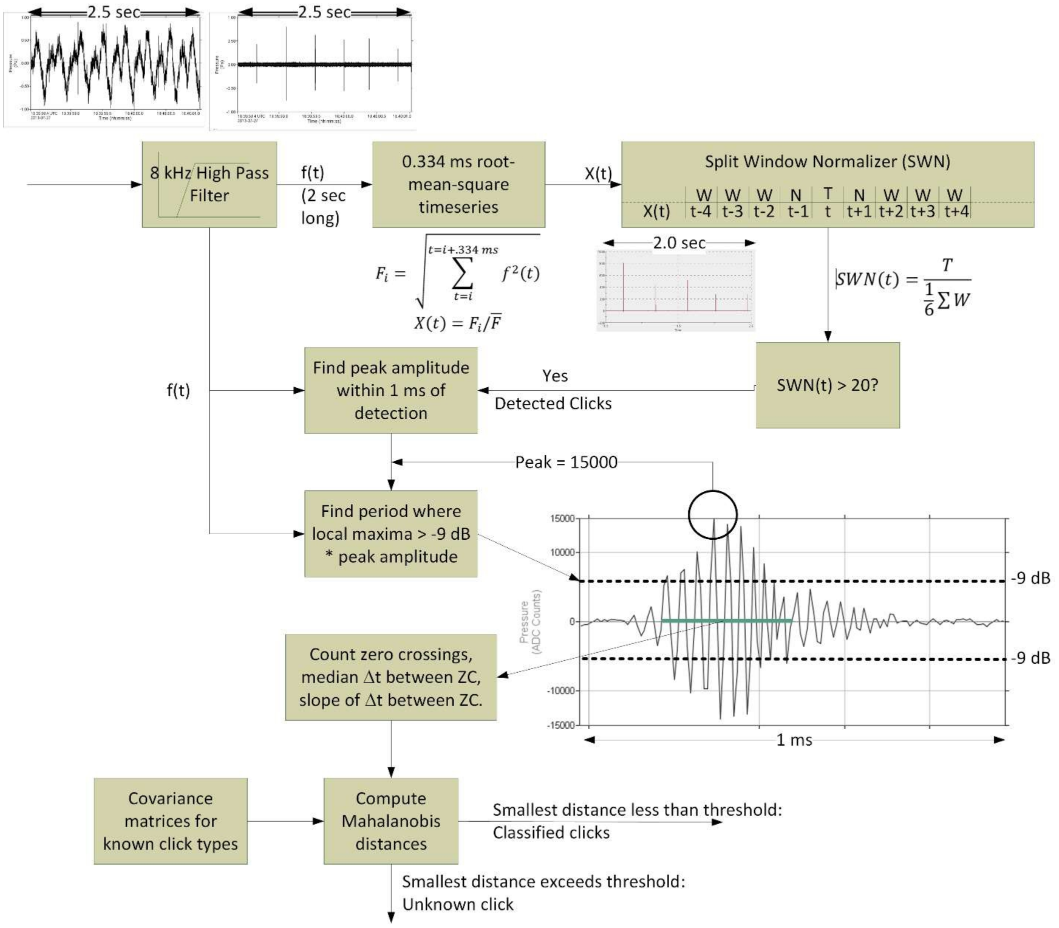

Figure C-1. Flowchart of the automated click detector/classifier process.

Odontocete clicks occur in groups called click trains. Each species has a characteristic inter-click-interval (ICI) and number of clicks per train. The automated click detector includes a second stage that associates individual clicks into trains (Figure C-2). The automated click train detector performs the following steps:

1. Queue clicks for N seconds, where N is twice the maximum number of clicks per train times the maximum ICI.
2. Search for all clicks within the window that have Mahalanobis distances less than 11 for a species of interest (this finds 80 % of all clicks for the species as defined by the template).
3. Create a candidate click train if:
    a. The number of clicks is greater or equal to the minimum number of clicks in a train;
    b. The maximum time between any two clicks is less than 2.5 times the maximum ICI, and
    c. The smallest Mahalanobis distance for all clicks in the candidate train is less than 4.1.
4. Create a new ‘time series’ with a value of 1 at the time of arrival for each click and zero everywhere else (using a ‘time series’ with a bin duration of 0.5 ms).
5. Apply a Hann window to the time series, and then compute the cepstrum.
6. A click train is classified if a peak in the cepstrum with an amplitude greater than five times the standard deviation of the cepstrum occurs at a quefrency between the minimum maximum ICI.
7. For each click related to the previous Ncepstrum, create a new time series and compute ICI. If there is a good match, then extend the click train.
8. Output a species_click_train detection if the click features, total clicks, and mean ICI match the species.

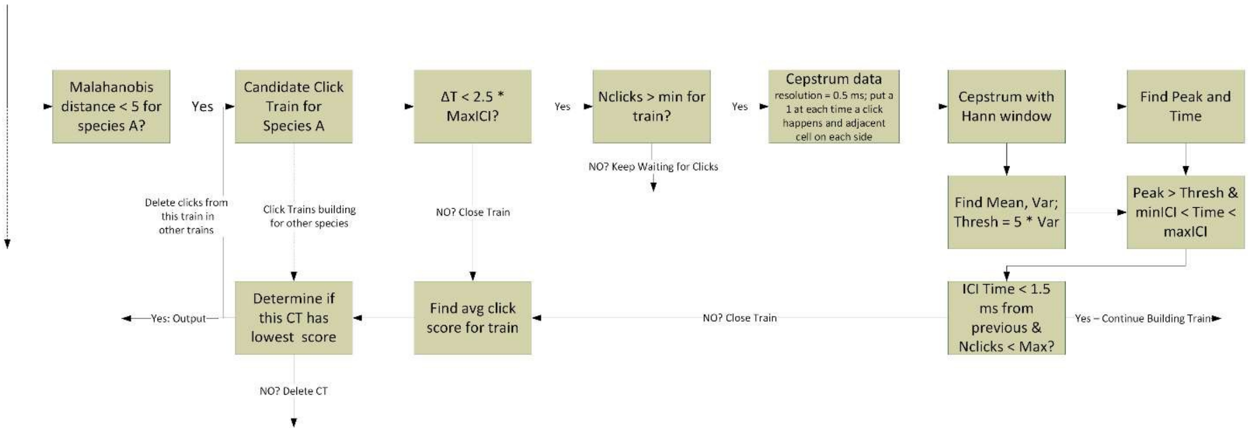

Figure C-2. Flowchart of the click train automated detector/classifier process.

Table C-1. List of automated detectors used to identify clicks produced by odontocetes and the nomenclature used in the detector results that were provided alongside this report.

Detector	Species targeted	Result nomenclature		Comments
		Clicks	Click trains	
DefaultClicks_LF.xml	Sperm whale	SpermWhale:Click	SpermWhale (Click Train)	5 kHz HPF
	Killer whale	KillerWhale:Click	KillerWhale (Click Train)	
spermClicks16kHz.xml	Sperm whale	SpermWhale16:Click16	SpermWhale16 (Click Train)	3 kHz HPF
DefaultClicks_MF.xml	True's or Gervais beaked whale	TBW_GBW:Click	TBW_GBW (Click Train)	25 kHz HPF
	Unidentified beaked whale	CanaryIslands:Click	CanaryIslands (Click Train)	
	Unidentified beaked whale	ScarboroughBW:Click	ScarboroughBW (Click Train)	
	Cuvier's beaked whale	Cuviers:Click	Cuviers (Click Train)	
	Unidentified beaked whale	BW-STP:Click	BW-STP (Click Train)	
	Northern bottlenose whale	NBW:Click	NBW (Click Train)	
	Delphinids	Dolphin:Click	Dolphin (Click Train)	
	Atlantic white-sided dolphin	AWSD_La:Click	AWSD_La (Click Train)	
	Stenella species	StenellaSP:Click	StenellaSP (Click Train)	
	Unidentified dolphin, type A	UDA:Click	UDA (Click Train)	
	Unidentified dolphin, type B	UDB:Click	UDB (Click Train)	
	Risso's dolphin	Rissos_Gg_Short:Click	Rissos_Gg_Short (Click Train)	
		Rissos_Gg_long:Click	Rissos_Gg_long (Click Train)	
	Pilot whale	PilotWhale:Click	PilotWhale (Click Train)	
	Blainville's beaked whale	Blainsvilles:Click	Blainsvilles (Click Train)	
	Beluga	Beluga:Beluga	Beluga (Click Train)	

HPF = high-pass filter

C.2. Automated Tonal Signal Detection

Marine mammal tonal acoustic signals are automatically detected using the contour detection and following algorithm depicted in Figure C-3. The algorithm has the following steps:

1. Create spectrograms of the appropriate resolution for each mammal vocalisation type that were normalised by the median value in each frequency bin for each detection window (Table C-3).
2. Join adjacent bins and create contours via a contour-following algorithm (Figure C-4).
3. Apply a sorting algorithm to determine if the contours match the definition of a marine mammal vocalisation (Table C-4).

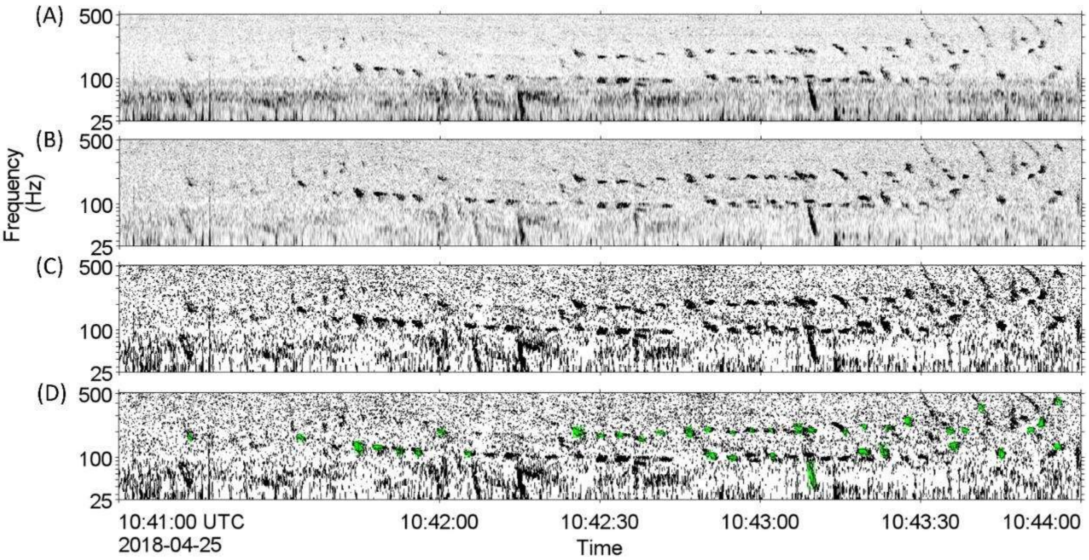

Figure C-3. Illustration of the contour detection process. (A) A spectrogram is generated at the frequency and time resolutions appropriate for the tonal calls of interest. (B) A median normaliser is applied at each frequency. (C) The data are turned into a binary representation by setting all normalised values less than the threshold to 0 and all values greater than the threshold to 1. (D) The regions that are '1' in the binary spectrogram are connected to create contours, which are then sorted to detect signals of interest, shown here as green overlays.

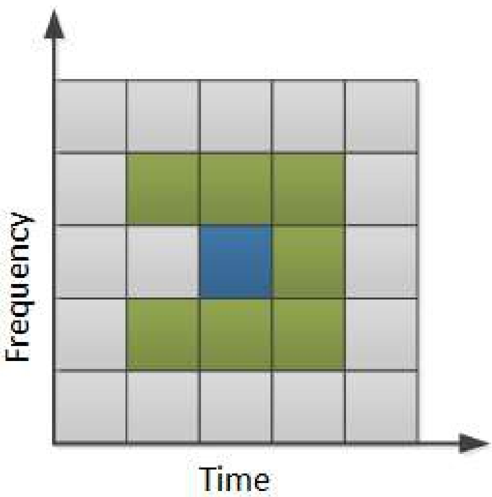

Figure C-4. Illustration of the search area used to connect spectrogram bins. The blue square represents a bin of the binary spectrogram equalling 1, and the green squares represent the potential bins it could be connected to. The algorithm advances from left to right, so grey cells left of the test cell need not be checked.

The tonal signal detector is expanded into a pulse train detector through the following steps:

1. Detect and classify contours as described in Steps 1 and 2 above.
2. A sorting algorithm determines if any series of contours can be assembled into trains that match a pulse train template (Table C-2).

Table C-2. Vocalisation sorter definitions for the tonal pulse train vocalisations ('bioduck') of the Antarctic minke whale, a cetacean species possibly occurring in the area.

Automated detector	Species targeted	Frequency (Hz)	Pulse duration (s)	Inter-pulse interval (s)	Train duration (s)	Train length (# pulses)
Bioduck	Antarctic minke whale	50–500	0.1–1	0.1–1	0.5–10	2–15

Table C-3. Discrete Fourier Transform (DFT) and detection window settings for all automated contour-based detectors used to detect tonal vocalisations of marine mammal species in the data. Values are based on JASCO's experience and empirical evaluation of various data sets. Due to the overlapping characteristics of some species' signals, automated detectors developed for a particular signal (Primary species (signal) targeted), can also effectively detect the signals of other species (Other species (signal) targeted). For some signals, JASCO applies many automated detectors and during manual validation determines which perform best.

Automated detector	Primary species (signal) targeted	Other species (signal) targeted	Discrete Fourier transform			Detection window (s)	Detection threshold
			Frequency step (Hz)	Temporal observation window (s)	Time advance (s)		
ANT_BlueWhale_H25_LT	Antarctic blue whale (Z call)	NA	0.125	2	0.5	50	2
ANT_BlueWhale_H25_HT			0.125	2	0.5	50	3
ANT_BlueWhale_H27			0.125	2	0.5	40	2
AUS_BW_H67	Pygmy blue whale (Song note)	NA	0.125	2	0.5	5	3
AUS_BlueWhale_AH17 AUS_BlueWhale_AH60			0.125	2	0.5	50	2
AUS_BW_AH60_70_lowthresh			0.4	2	0.5	50	2
NZ_BlueWhale_H67			0.125	2	0.5	1200	3
NZ_BlueWhale_IM			0.125	2	0.5	1200	4
AUS_BW_D	Pygmy blue whale (non-song call)	Sei whale (downsweep)	0.4	2	0.5	5	2
NZ_BlueWhale_DS			2	0.2	0.05	5	3
NPac_BlueWhale_D			2	0.25	0.05	10	2
NPac_BlueWhale_D_HT			2	0.25	0.05	10	4
Brydes_DS	Bryde's whale (moan)	NA	2	0.25	0.125	120	3
Brydes_IM_S Brydes_IM_W			0.125	2	0.5	5	4
Bioduck	Antarctic minke whale (bioduck)	NA	2	0.125	0.03125	40	3.5
DMW_StarWars_lowthresh	Dwarf minke whale (Star Wars call)	Humpback (moan)	2	0.125	0.03125	40	2
DMW_StarWars_highthresh			2	0.125	0.03125	40	5
DMW_StarWars_highthresh6			2	0.125	0.03125	40	6
WA_DMW_Boing_Weak WA_DMW_Boing_200harmonic	Dwarf minke whale (boing)	Humpback (moan)	2	0.125	0.03125	40	2
WA_DMW_Boing_Strong			2	0.125	0.03125	40	3
NPac_MW_Boing	Common minke whale (boing)	Humpback (moan)	8	0.125	0.05	7	3
Atl_FinWhale_21	Fin whale (20 Hz pulse)	NA	1	0.2	0.05	5	1.7
Atl_FinWhale_21_HT			1	0.2	0.05	5	3.7
Atl_FinWhale_21.2			1	0.2	0.05	5	4
Atl_FinWhale_21.2_HT			1	0.2	0.05	5	6

NPac_FinWhale_21LSNR			1	0.2	0.05	5	1.7
NPac_FinWhale_21HSNR			1	0.2	0.05	5	5
VLFMoan			2	0.2	0.05	15	4
NPac_FinWhale_17LSNR	Fin whale (18 Hz pulse)		1	0.2	0.05	5	1.7
NPac_FinWhale_17HSNR			1	0.2	0.05	5	5
LFMoan	Humpback whale (moan)	Blue whale (non-song call), right whale (moan), sei whale (downsweep)	2	0.25	0.05	10	3
HB		Right whale (moan), dwarf minke whale (Star Wars call and boing)	4	0.128	0.032	30	3
MFMoanLow			4	0.2	0.05	5	3
MFMoanLow_HT			4	0.2	0.05	5	5
MFMoanHigh		Killer whale (whistle), small dolphin (social call)	8	0.125	0.05	5	3
MFMoanHigh_HT			8	0.125	0.05	5	5
Omura_S1	Omura's whale (moan)	NA	0.25	2	0.25	120	6
Omura_S2			0.5	0.5	0.25	60	4
Omura_W			0.25	2	0.25	120	4
S_RightWhale_25	Right whale (25 Hz spot call)	NA	0.125	2	0.5	120	3
N_RightWhale_Up1	Right whale (upcall)	Humpback (moan)	4	0.128	0.032	8	2.5
SeiWhale_LowThreshold	Sei whale (downsweep)	Blue whale (non-song call)	3.25	0.2	0.035	5	2.5
SeiWhale_MidThreshold			3.25	0.2	0.035	5	5
SeiWhale_HighThreshold			3.25	0.2	0.035	5	5.5
ShortLow	Minke whale (bioduck)	Humpback (grunt), right whale (gunshot), fish (grunt)	7	0.17	0.025	10	3
WhistleHigh_Suppress	Small dolphin (Whistles with energy between 4–20 kHz)	Pilot, killer whale (whistle)	64	0.015	0.005	10	1.5
WhistleHigh_Quiet			64	0.015	0.005	10	1.5
WhistleHigh_Loud			64	0.015	0.005	10	4.5
WhistleLow_Suppress	Pilot, killer whale (Whistles with energy between 1–10 kHz)	Small dolphin (whistle)	8	0.125	0.05	10	1.5
WhistleLow_Quiet			8	0.125	0.05	10	1.5
WhistleLow_Loud			8	0.125	0.05	10	4.5

Table C-4. A sample of vocalisation sorter definitions for the tonal vocalisations of cetacean species expected in the area.

Automated detector	Frequency (Hz)	Duration (s)	Bandwidth (Hz)	Other parameters
ANT_BlueWhale_H25_LT ANT_BlueWhale_H25_HT	13–30	4.00–13.00	NA	f_{min} <28 Hz, MIB <8 Hz
ANT_BlueWhale_H27	10–100	6.00–30.00	>1	f_{min} <100 Hz, MIB <30 Hz, 26< f_{peak} <28
AU_BW_H67	60–70	10.00–30.00	1–10	None
AUS_BlueWhale_AH17	10–100	6.00–60.00	>1	f_{min} <100 Hz, MIB <50 Hz, 17< f_{peak} <18.5
AUS_BlueWhale_AH60	10–100	6.00–60.00	>1	f_{min} <100 Hz, MIB <50 Hz, 59< f_{peak} <60.5
AUS_BW_AH60_70_lowthresh	61–72	6.00–30.00	3.5–10	f_{min} <100 Hz, MIB <50 Hz
NZ_BlueWhale_H67	60–70	10.00–30.00	>10	None
NZ_BlueWhale_IM	15–24	10.00–30.00	1–4	f_{min} <18 Hz
AUS_BW_D	25–150	1.00–7.00	20-120	MIB <80 Hz, −200<SR<−1 Hz/s
NZ_BlueWhale_DS	30–100	0.45–1.00	30-60	f_{min} <18 Hz

NPac_BlueWhale_D NPac_BlueWhale_D_HT	20–100	2.00–10.00	>15	MIB <30 Hz, −15<SR<−5 Hz/s
Brydes_DS	30–200	0.50–3.00	1-80	-150<SR<−5 Hz/s
Brydes_IM_S	10–70	5.00–20.00	8-50	f_{min} <26 Hz
Brydes_IM_W	24–30	2.00–6.00	0.5-4	*None*
DMW_StarWars_lowthresh DMW_StarWars_highthresh DMW_StarWars_highthresh6	45–400	0.40–3.50	100-350	f_{min} <300 Hz
WA_DMW_Boing_Weak	40–1000	0.50–4.50	10-1000	f_{min} <1000 Hz, 100< f_{peak} <500
WA_DMW_Boing_200harmonic	150–300	0.50–4.50	15-40	f_{min} <1000 Hz, −10<SR<10 Hz/s
WA_DMW_Boing_Strong	40–3000	0.50–4.50	20-2960	f_{min} <1000 Hz, 100< f_{peak} <500
NPac_MW_Boing	1100–1700	0.50–4.00	>20	MIB <700 Hz, −10<SR<50 Hz/s
Atl_FinWhale_21 Atl_FinWhale_21_HT	10–40	0.40–3.00	>6	f_{min} <17 Hz, 20< f_{peak} <22 Hz, −100<SR<0 Hz
Atl_FinWhale_21.2 Atl_FinWhale_21.2_HT	8–40	0.30–3.00	>6	f_{min} <17 Hz, −100<SR<0 Hz
NPac_FinWhale_17LSNR NPac_FinWhale_17HSNR	3–50	0.40–3.00	>6	f_{min} <17 Hz, MIB <30 Hz, 16< f_{peak} <19, −100<SR<0 Hz/s
NPac_FinWhale_21LSNR	3–50	0.40–3.00	>6	f_{min} <17 Hz, MIB <20, 20< f_{peak} <23.5, −100<SR<0 Hz/s
NPac_FinWhale_21HSNR	3–50	0.40–3.00	>6	f_{min} <17 Hz, MIB <30, 20< f_{peak} <23.5, −100<SR<0 Hz/s
VLFMoan	10–100	0.30–10.00	>10	f_{min} <40 Hz
MFMoanLow MFMoanLow_HT	100–700	0.50–5.00	>50	f_{min} <450 Hz, MIB <200 Hz
Omura_S1	15–60	5.00–15.00	8-40	f_{min} <26 Hz
Omura_S2	10–60	3.00–15.00	8–40	f_{min} <26 Hz
Omura_W	24–30	2.00–6.00	0.5–4	None
N_RightWhale_Up1	65–260	0.60–1.20	70–195	f_{min} <75 Hz, 30<SR<290 Hz/s
SeiWhale_LowThreshold	20–100	1.00–1.70	30-80	MIB <100 Hz, f_{peak} <50 Hz, −80<SR<−12 Hz/s
SeiWhale_MidThreshold	20–80	1.00–1.70	30–80	MIB <100 Hz, −80<SR<−12 Hz/s
SeiWhale_HighThreshold	20–150	0.50–1.70	19–120	MIB <70 Hz, −100<SR<−6 Hz/s
HB	100–700	0.50–8.00	>50	f_{min} <500 Hz, MIB <200 Hz
MFMoanHigh MFMoanHigh_HT	500–2500	0.50–5.00	>150	f_{min} <1500 Hz, MIB <300 Hz
ShortLow	30–400	0.08–0.60	>25	None
LFMoan	40–250	0.50–10.00	>15	MIB <50 Hz
WhistleHigh_Suppress	4000–12,000	0.30–5.00	>700	MIB <2000 Hz, Suppress detections for SPL >125 dB from 50–1000 Hz
WhistleHigh_Quiet WhistleHigh_Loud	4000–20,000	0.30–5.00	>700	MIB <2000 Hz
WhistleLow_Suppress	1000–10,000	0.80–5.00	>300	f_{min} <5000 Hz, MIB <1000 Hz, MultiComponent = 1, minComponentduration = 0.4 s, Min_BW>50 Hz, Suppress detections for SPL >125 dB from 50–1000 Hz
WhistleLow_Quiet WhistleLow_Loud	1000–10,000	0.80–5.00	>300	f_{min} 5000 Hz, MIB <1000 Hz, MultiComponent = 1, minComponentduration = 0.4 s, Min_BW>50Hz

f = frequency, MIB = median instantaneous bandwidth, SR = sweep rate; HT = high threshold; BW = bandwidth

C.3. Automatic Data Selection for Validation (ADSV)

To standardise the file selection process for the selection of data for manual analysis, JASCO's Automated Data Selection for Validation (ADSV) algorithm was applied. Kowarski et al. (2021) details the ADSV algorithm, and Figure C-5 shows a schematic of the process. ADSV computes the distribution of three descriptors that describe the automated detections in the full data set: Diversity (number of automated detectors triggered per file), Counts (number of automated detections per file for each automated detector), and Temporal Distribution (spread of detections for each automated detector across the recording period). The algorithm removes files from the temporary data set that have the least impact on the distribution of the three descriptors in the full data set. Files are removed until a predetermined data set size (*N*) is reached, at which point the temporary data set becomes the subset to be manually reviewed.

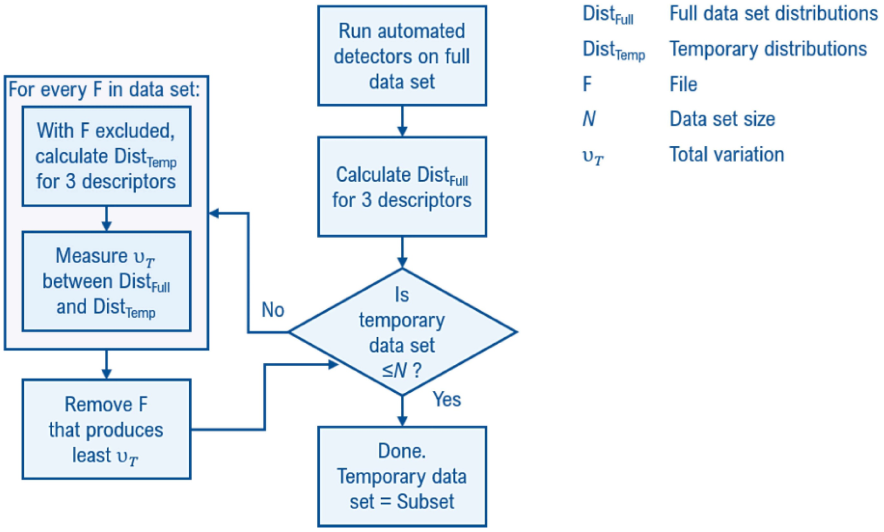

Figure C-5. The Automated Data Selection for Validation (ADSV) process. (source: based on Figure 1 in Kowarski et al. (2021)).

For the present work, an *N* of 1 % was selected, largely due to limited scope for this project and marine mammal analysis. Even with limited manual review, the results presented here can be considered reliable, but some caveats should be considered. It is important to note that with such limited data manually reviewed, very rare species may have been missed or their occurrence underestimated. If the 1 % subset of data manually analysed was not sufficiently large to capture the full range of acoustic environments in the full data set, the resulting automated detector performance metrics may be inaccurate and therefore should be taken as an estimate.

C.4. Automated Detector Performance Calculation and Optimisation

All files selected for manual validation were reviewed by one of two experienced analysts using JASCO's PAMlab software to determine the presence or absence of every species, regardless of whether a species was automatically detected in the 15 min file. Although the automated detectors classify specific signals, the presence/absence of species was validated at the file level, not the detection level. Acoustic signals were only assigned to a species if the analyst was confident in their assessment. When unsure, analysts would consult one another, peer reviewed literature, and other experts in the field. If certainty could not be reached, the file of concern would be classified as possibly containing the species in question or containing an unknown acoustic signal. Next, the validated results were compared to the automated detector results in three phases to refine the results and ensure they accurately represent the occurrence of each species in the study area.

In Phase 1, the human validated versus automated detector results were plotted as time series and critically reviewed to determine when and where automated detections should be excluded. Questionable detections that overlap with the detection period of other species were scrutinised. By restricting detections spatially and/or temporally where appropriate, the reliability of the results can be maximised. No temporal restrictions were necessary for the automated detector results.

In Phase 2, the performance of the automated detectors was calculated and optimised for each species using a threshold, defined as the number of automated detections per file at and above which detections of species were considered valid.

To determine the performance of each automated detector and any necessary thresholds, the automated and validated results (excluding files where an analyst indicated uncertainty in species occurrence) were fed to a maximum likelihood estimation algorithm that maximises the probability of detection and minimises the number of false alarms using the Matthews Correlation Coefficient (MCC):

$$\mathrm{MCC} = \frac{\mathrm{TP} \cdot \mathrm{TN} - \mathrm{FP} \cdot \mathrm{FN}}{\sqrt{(\mathrm{TP}+\mathrm{FP})(\mathrm{TP}+\mathrm{FN})(\mathrm{TN}+\mathrm{FP})(\mathrm{TN}+\mathrm{FN})}}$$

$$P = \frac{\mathrm{TP}}{\mathrm{TP}+\mathrm{FP}}; \quad R = \frac{\mathrm{TP}}{\mathrm{TP}+\mathrm{FN}}$$

where *TP* (true positive) is the number of files in the subset with both manual and automated detections, *FP* (false positive) is the number of files in the subset with automated detections but no manual detections, *FN* (false negatives) is the number of files in the subset with manual detections but no automated detections, and *TN* (true negatives) is the number of files in the subset with neither automated nor manual detections. Automated detector performance was calculated for each species and station.

In Phase 3, detections were further restricted to include only those where *P* was greater than or equal to 0.75, *R* was greater than or equal to 0.50, and *MCC* was greater than or equal to 0.40. When performance metrics fell below minimum requirements, only validated results were used to describe the acoustic occurrence of a species. The occurrence of each species was plotted using JASCO's Ark software as time series showing presence/absence by hour over each day.

The origin and sources of final knowledge gaps used in the prioritisation process

Themes used for grouping knowledge gaps are provided. Numbers in parentheses indicate the source of the original knowledge gap: (1) = Sutton & Shaw 2021 - literature review (including 2021 NTGAC workshop); (2) = Sutton & Shaw 2021 - informed expert opinion; (3) = Sutton & Shaw 2021 - Risk assessment results; (4) = Exmouth Gulf Taskforce.

Theme: Climate change projections for marine and coastal environments (e.g. sea level rise, marine heatwaves, storms and cyclones)
Final gap: What are the specific climate change projections for Exmouth Gulf, and what are the likely effects on key marine and terrestrial ecosystems and taxa?
Original gaps: • More specific climate change projections for Exmouth Gulf, and likely impacts to key marine and terrestrial ecosystems and taxa (1) • Coral trout and impact of tropical storms and cyclones (3) • Dolphins and impact of tropical storms and cyclones (3) • Dugongs and impact of tropical storms and cyclones (3) • Humpback whales and impact of tropical storms and cyclones (3) • Turtles and the impact of tropical storms and cyclones (3) • Mud crabs and impact of tropical storms and cyclones (3) • Sawfish and impact of tropical storms and cyclones (3) • Sea snakes and impact of tropical storms and cyclones (3) • Tuskfish and impact of tropical storms and cyclones (3) • Samphire and the impact of tropical storms and cyclones (3) • Seabirds and shorebirds and impact of tropical storms and cyclones (3) • Water quality and impact of tropical storms and cyclones (3) • Climate change projections for Exmouth Gulf and likely impacts to key marine ecosystems (4)
Final gap: How resilient are benthic habitats and marine fauna to recurring marine heatwaves?
Original gaps: • Coral trout and the impact of marine heatwaves (3) • Mud crabs and impact of marine heatwaves (3) • Tuskfish and impact of marine heatwaves (3) • Dolphins and impact of marine heatwaves (3) • Dugongs and impact of marine heatwaves (3) • Humpback whales and impact of marine heatwaves (3) • Manta rays and impact of marine heatwaves (3) • Marine turtles and impact of marine heatwaves (3) • Sawfish and the impact of marine heatwaves (3) • Sea snakes and impact of marine heatwaves (3) • Sharks and impact of marine heatwaves (3) • Shovelnose rays and impact of marine heatwaves (3) • Seabirds and shorebirds and impact of marine heatwaves (3) • Macroalgae and turf algae and impact of marine heatwaves (3) • Sand and mud habitats/communities and impact of marine heatwaves (3) • Sponges and filter feeders and impact of marine heatwaves (3) • Better understanding of the impact of marine heatwaves on benthic communities and marine fauna (2) • Mangroves and impact of marine heatwaves (3)

Final gap: How will recurring marine heatwaves affect water quality?

Original gaps:

- Water quality and impact of marine heatwaves (3)

Final gap: What are the effects of current and future climate change pressures, such as storms, cyclones, and sea level rise, on the islands of Exmouth Gulf?

Original gaps:

- Islands and the impact of sea level rise (3)
- Islands and the impact of tropical storms/cyclones (3)

Final gap: What will be the effect of sea level rise on benthic habitats and marine and coastal fauna?

Original gaps:

- Reef flats and oyster beds and the impact of sea level rise (3)
- Samphire and the impact of sea level rise (3)
- Blue green algal mats and the impact of sea level rise (3)
- Direct and indirect impacts of increased storms and sea level rise on marine flora and fauna (2)
- Corals and the impact of sea level rise (3)
- Marine turtles and impact of sea level rise (3)
- Seabirds and shorebirds and impact of sea level rise (3)

Theme: Current and future underwater noise effects on marine life (e.g., seismic activity, vessel noise, construction)

Final gap: To what extent is underwater noise currently effecting marine fauna and ecological functions in Exmouth Gulf and how might this change in the future?

Original gaps:

- Better understanding of the impacts of underwater noise on crustaceans, fishes, elasmobranchs and marine mammals (2)
- Dolphins and impact of noise pollution (pile driving, dredging) (3)
- Dolphins and the impact of noise (3)
- Dugongs and impact of noise pollution (vessel) (3)
- Dugongs and the impact of noise (3)
- Humpback whales and impact of noise pollution (pile driving, dredging) (3)
- Humpback whales and the impact of noise (3)
- Manta rays and the impact of noise (3)
- Marine turtles and the impact of noise (3)
- Seabirds and shorebirds and the impact of noise (3)
- Tuskfish and impact of noise pollution (vessel, pile driving, dredging) (3)
- Dolphins and impact of seismic surveys (3)
- Dugongs and impact of seismic surveys (3)
- Humpback whales and impact of seismic surveys (3)
- Mangrove jack and impact of seismic surveys (3)
- Manta rays and impact of seismic surveys (3)
- Marine turtles and impact of seismic surveys (3)
- Red emperor and impact of seismic surveys (3)
- Sawfish and impact of seismic surveys (3)
- Seabirds and shorebirds and impact of seismic surveys (3)
- Seasnakes and impact of seismic surveys (3)
- Sharks and impact of seismic surveys (3)
- Shovelnose rays and impact of seismic surveys (3)
- Trevally and impact of seismic surveys (3)

• Tuskfish and impact of seismic surveys (3) • Whiting and impact of seismic surveys (3) • Better understanding of the impacts of seismic activity on crustaceans, fishes, elasmobranchs and marine mammals (2) • Coral trout and impact of seismic surveys (3) • Mitigating impacts to marine megafauna (noise, infrastructure, ship strike etc) (4)
Final gap: What is the current marine soundscape of Exmouth Gulf, and how could this be predicted to change with further coastal development?
Original gaps: • Understand the current marine soundscape of Exmouth Gulf, the future soundscape based on modelled development activities, and how underwater noise is impacting key taxa and the ecological function of Exmouth Gulf (2) • Mitigating impacts to marine megafauna (noise, infrastructure, ship strike etc)(4)
Theme: Fisheries and fishing effects on important species (e.g., recreational, commercial, charter, bycatch)
Final gap: Is recreational fishing causing significant decline to ecologically and recreationally important species?
Original gaps: • Coral trout and the impact of recreational fishing (3) • Mangrove jack and impact of recreational fishing (3) • Mud crabs and impact of recreational fishing (3) • Red emperor and the impact of recreational fishing (3) • Sharks and impact of recreational fishing (3) • Trevally and impact of recreational fishing (3) • Tuskfish and the impact of recreational fishing (3) • Whiting and impact of recreational fishing (3)
Final gap: What effect has fishing had on elasmobranch and sea snake populations?
Original gaps: • Shovelnose rays and impact of commercial fishing (3) • Sea snakes and impact of commercial fishing (3) • Sawfish and impact of commercial fishing (3)
Theme: Industrial development impacts on coastal and marine environments and recreational activities (e.g., footprints, noise, clearing)
Final gap: What are the possible effects of seawater intake on the surrounding marine environment, and how can we achieve greater certainty about these effects?
Original gaps: • More certainty around the impacts of seawater intake for use by industrial salt facilities (2)
Final gap: How could development footprints on the eastern coastline of Exmouth Gulf affect nutrient flows and, in turn, marine life reliant on these nutrient flows?
Original gaps: • Nutrient flow and the impact of an industrial salt production facility footprint (3) • Description of nutrient sources and flows into Exmouth Gulf (4)
Final gap: How will marine based recreation be affected by future coastal development (e.g., footprints, noise, light)?
Original gaps: • Marine based recreation and the impact of industrial footprint (3) • Marine based recreation and the impact of industrial noise (3)

Theme: Effects of increased boating and shipping (e.g., increased sediments in water column, marine pests, fuel and oil spills, vessel strikes)

Final gap: What is the natural seasonality of suspended sediments in Exmouth Gulf and how will increases in suspended sediments affect water quality, benthic habitats and marine fauna?

Original gaps:

- Reef flats and oyster beds and impact of suspended sediments (3)
- Sand and mud and impact of suspended sediments (3)
- Sponges and filter feeders and impact of suspended sediments (3)
- Water quality and impact of suspended sediments (3)
- Coral trout and impact of suspended sediments (3)
- Mangrove jack and impact of suspended sediments (3)
- Manta rays and impact of suspended sediments (3)
- Red emperor and impact of suspended sediments (3)
- Sawfish and impact of suspended sediments (3)
- Seabirds and shorebirds and impact of suspended sediments (3)
- Sharks and impact of suspended sediments (3)
- Shovelnose rays and impact of suspended sediments (3)
- Trevally and impact of suspended sediments (3)
- Tuskfish and impact of suspended sediments (3)
- Whiting and impact of suspended sediments (3)

Final gap: What introduced marine pests currently exist in Exmouth Gulf and what risks do current and future pests (from shipping or ocean warming) pose to marine life and habitats?

Original gaps:

- Coral and impact of pests (3)
- Macroalgae and turf algae and impact of pests (3)
- Reef flats and oyster beds and impact of pests (3)
- Sand and mud and impact of pests (3)
- Seagrass and impact of pests (3)
- Sponges and filter feeders and impact of pests (3)
- Impacts of potential introduced marine pests and diseases with international shipping on marine fauna and habitats, including coral diseases (2)
- Coral trout and impact of pests (3)
- Mangrove jack and impact of pests (3)
- Manta rays and impact of pests (3)
- Marine turtles and impact of pests (3)
- Mud crabs and impact of pests (3)
- Prawns and impact of pests (3)
- Red emperor and impact of pests (3)
- Sawfish and impact of pests (3)
- Sea snakes and impact of pests (3)
- Sharks and impact of pests (3)
- Shovelnose rays and impact of pests (3)
- Trevally and impact of pests (3)
- Tuskfish and impact of pests (3)
- Whiting and impact of pests (3)

Final gap: What is the occurrence, extent and severity of fuel and oil spills and is this affecting marine and coastal environments?

Original gaps:

- Coral trout and impact of pollution (oil, fuel, antifoul) (3)
- Dolphins and impact of pollution (oil, fuel, antifoul) (3)

• Dugongs and impact of pollution (oil, fuel, antifoul) (3) • Mangrove jack and impact of pollution (oil, fuel, antifoul) (3) • Manta rays and impact of pollution (oil, fuel, antifoul) (3) • Marine turtles and impact of pollution (oil, fuel, antifoul) (3) • Red emperor and impact of pollution (oil, fuel, antifoul) (3) • Sea snakes and impact of pollution (oil, fuel, antifoul) (3) • Sea snakes and the impact of oil/fuel pollution (3) • Sharks and impact of pollution (oil, fuel, antifoul) (3) • Trevally and impact of pollution (oil, fuel, antifoul) (3) • Tuskfish and impact of pollution (oil, fuel, antifoul) (3) • Whiting and impact of pollution (oil, fuel, antifoul) (3) • Seabirds and shorebirds and the impact of oil and fuel spills and antifoul (3) • Sediment quality and the impact of pollution oil and fuel spills and antifoul (3) • Water quality and the impact of pollution oil and fuel spills and antifoul (3) • Samphire and impact of pollution (oil, fuel, antifoul) (3) • Mangroves and impact of pollution (oil, fuel, antifoul) (3)
Final gap: What is the frequency and consequences of vessel strikes on marine megafauna, including on seabirds and shorebirds?
Original gaps: • Extent of vessel strikes occurring to marine fauna currently (2) • Dolphins and the impact of damage (anchoring/diving), incl vessel strikes (3) • Dugongs and the impact of damage (anchoring/diving), incl vessel strikes (3) • Humpback whales and the impact of disturbance (e.g., vessel strikes and harassment) (3) • Humpback whales and impact of vessel strikes (3) • Manta rays and the impact of damage (anchoring/diving), incl vessel strikes (3) • Marine turtles and the impact of damage (anchoring/diving), incl vessel strikes (3) • Sharks and impact of vessel strikes (3) • Sharks and the impact of damage (anchoring/diving), incl vessel strikes (3) • Mitigating impacts to marine megafauna (noise, infrastructure, ship strike etc) (4)
Theme: Use of marine and coastal habitats by threatened and protected species (e.g., seagrasses, sponges, corals, mangroves, samphire, feeding areas, nursery areas)
Final gap: How are megafauna and seabirds/shorebirds using specific benthic habitats and to what extent could these associations be affected by habitat damage and degradation?
Original gaps: • Dugongs and impact of port infrastructure footprint (3) • Marine turtles and impact of port infrastructure footprint (3) • Sawfish and impact of port infrastructure footprint (3) • Sea snakes and impact of port infrastructure footprint (3) • Shovelnose rays and impact of port infrastructure footprint (3) • Seabirds and shorebirds and impact of salt production facility footprints (3) • Seabirds and shorebirds and impact of port infrastructure footprint (3) • Dolphins and the impact of a port infrastructure footprint (incl. channel) (3) • Better understanding of bonefish, dolphins and sawfish in Exmouth Gulf (4)
Final gap: What are the home ranges and habitat uses of sea snakes in Exmouth Gulf?
Original gaps: • Home ranges and habitat use of sea snakes in Exmouth Gulf (1)

Final gap: Where do nursery locations occur for threatened fauna in Exmouth Gulf e.g., sea snakes, sawfishes, shovelnose rays?
Original gaps: • Identification of nursery locations for threatened fauna e.g., sea snakes, sawfishes, shovelnose rays (2) • Better understanding of bonefish, dolphins and sawfish in Exmouth Gulf (4)
Final gap: What is the role of samphire communities in Exmouth Gulf and how are they utilised by other species e.g., migratory shorebirds?
Original gaps: • Better understanding of samphire communities and the reliance on them by other species e.g., the role of samphire for shore birds (in particular migratory birds) (1)
Final gap: Are elasmobranch species utilising Exmouth Gulf and its intertidal habitats seasonally and how reliant are they on these environments?
Original gaps: • Better understanding of the elasmobranch species using Exmouth Gulf, particularly listed species such as sawfish, and species that may be relying on the extensive mangrove habitat, such as shovelnose rays (1) • Better understanding of bonefish, dolphins and sawfish in Exmouth Gulf (4)
Final gap: What is the diversity of coastal dolphin species utilising Exmouth Gulf, and are the populations resident, migratory, or a combination of both?
Original gaps: • Diversity of coastal dolphin species using Exmouth Gulf and whether populations are resident, migratory or a mix of both (1) • Better understanding of bonefish, dolphins and sawfish in Exmouth Gulf (4)
Theme: Pollution and contamination of the marine environment (e.g., PFAS, bitterns, vessel antifouling, light, marine debris)
Final gap: What is the extent of PFAS contamination and what effect does this have on the marine food web?
Original gaps: • Extent of PFAS contamination in groundwater and surface water systems (2) • Karst systems and the impact of contamination (3) • Stygofauna and the impact of contamination (3) • Stygofauna and the impact of contamination (3)
Final gap: What are the effects of bittern discharge on marine fauna and flora, as well as on water and sediment quality?
Original gaps: • Impacts of bitterns discharge on marine fauna, flora and water quality, including spatial and temporal modelling specific to Exmouth Gulf (2) • Coral trout and impact of bitterns discharge from salt production facilities (3) • Mangroves and impact of bitterns discharge from salt production facilities (3) • Marine turtles and impact of bitterns discharge from salt production facilities (3) • Sawfish and impact of bitterns discharge from salt production facilities (3) • Seasnakes and impact of bitterns discharge from salt production facilities (3) • Tuskfish and impact of bitterns discharge from salt production facilities (3) • Whiting and impact of bitterns discharge from salt production facilities (3)
Final gap: What are the effects of copper-based contaminants, such as antifouling agents, on marine life and benthic communities?
Original gaps: • Coral trout and impact of pollution (oil, fuel, antifoul) (3) • Dolphins and impact of pollution (oil, fuel, antifoul) (3)

• Dugongs and impact of pollution (oil, fuel, antifoul) (3) • Mangrove jack and impact of pollution (oil, fuel, antifoul) (3) • Manta rays and impact of pollution (oil, fuel, antifoul) (3) • Marine turtles and impact of pollution (oil, fuel, antifoul) (3) • Red emperor and impact of pollution (oil, fuel, antifoul) (3) • Sea snakes and impact of pollution (oil, fuel, antifoul) (3) • Sea snakes and the impact of oil/fuel pollution (3) • Sharks and impact of pollution (oil, fuel, antifoul) (3) • Trevally and impact of pollution (oil, fuel, antifoul) (3) • Tuskfish and impact of pollution (oil, fuel, antifoul) (3) • Whiting and impact of pollution (oil, fuel, antifoul) (3) • Seabirds and shorebirds and the impact of oil and fuel spills and antifoul (3) • Sediment quality and the impact of pollution oil and fuel spills and antifoul (3) • Water quality and the impact of pollution oil and fuel spills and antifoul (3) • Impacts of copper-based contaminants (2)
Final gap: What are the effects of light pollution on marine fauna (including but not limited to marine turtles)?
Original gaps: • Impacts of light pollution on marine fauna (not just turtles) (2)
Final gap: How widespread is pollution (rubbish) and what effect is this having on marine and coastal fauna?
Original gaps: • Coral trout and the impact of rubbish pollution (3) • Mangrove jack and the impact of rubbish (3) • Manta rays and the impact of rubbish (3) • Turtles and the impact of rubbish (3) • Mud crabs and the impact of rubbish pollution (3) • Prawns and the impact of rubbish pollution (3) • Red emperor and the impact of rubbish pollution (3) • Sawfish and the impact of rubbish pollution (3) • Sea snakes and the impact of rubbish pollution (3) • Sharks and the impact of rubbish pollution (3) • Shovelnose rays and the impact of rubbish pollution (3) • Trevally and the impact of rubbish pollution (3) • Tuskfish and the impact of rubbish pollution (3) • Whiting and the impact of rubbish pollution (3) • Seabirds and shorebirds and the impact of rubbish (3)
Theme: Understanding and maintaining ecosystem health, connectivity, and processes (e.g., nutrient and groundwater flows, spawning and recruitment, land and sea connections, food webs, water and sediment quality)
Final gap: How is Exmouth Gulf influenced by processes and pathways across the land-sea interface (e.g. nutrient sources and flows, groundwater movement)?
Original gaps: • Comprehensive understanding of all nutrient sources into Exmouth Gulf (2) • Better understanding of connectivity across the land/sea interface and between Exmouth Gulf and surrounds, such as Ningaloo Reef (including but not limited to: nutrient sources and flows, biogeochemical dynamics, seed banks, recruitment, larval dispersal, nursery areas) (1) • Extent and locations of groundwater intrusion into Exmouth Gulf (1)

- Description of connectivity across the land/sea and between Exmouth Gulf and surrounds (4)
- Description of nutrient sources and flows into Exmouth Gulf (4)

Final gap: What is the seasonal exchange between the oceanic and Exmouth Gulf waters and how does this influence species recruitment and dispersal?

Original gaps:

- Better understanding of connectivity across the land/sea interface and between Exmouth Gulf and surrounds, such as Ningaloo Reef (including but not limited to: nutrient sources and flows, biogeochemical dynamics, seed banks, recruitment, larval dispersal, nursery areas) (1)
- Description of connectivity across the land/sea and between Exmouth Gulf and surrounds (4)

Final gap: What are the characteristics of food webs in Exmouth Gulf and how do they vary seasonally?

Original gaps:

- Exmouth Gulf food webs (1)

Final gap: What is the quality and characteristics of water and sediments in Exmouth Gulf?

Original gaps:

- Current understanding of water and sediment quality (1)
- Description of water and sediment quality of Exmouth Gulf (4)

Final gap: What are the characteristics of sand and mud flat communities and how do they contribute to sediment health?

Original gaps:

- Sand and mud flat communities and their role in sediment health (1)
- Soft sediment communities, including at depth e.g., 5-10m (2)
- Better understanding of the types of sediments in Exmouth Gulf e.g., grain size, muddy or sandy (2)

Final gap: How will groundwater systems be affected by expansion of mining activities (e.g., limestone, potash, salt)?

Original gaps:

- Groundwater systems and the impact of limestone mining groundwater drawdown (3)
- Groundwater systems and the impact of potash mining footprint (3)

Theme: Disturbance and degradation to marine and coastal values from unmanaged tourism and population growth (e.g., offroad 4WD, anchoring, diving, carrying capacity)

Final gap: To what extent are seabirds and shorebirds being disturbed or injured by human activity (e.g., 4WD)?

Original gaps:

- Seabirds and shorebirds and the impact of disturbance (e.g., vessel strikes and 4WD) and rubbish (3)

Final gap: What is the extent of damage to benthic habitats caused by human activity (e.g., anchoring and diving)?

Original gaps:

- Coral and the impact of damage (anchoring/diving) (3)

Final gap: What is the carrying capacity of people for Exmouth and what are the implications of increasing numbers of people on Exmouth Gulf?

Original gaps:

- Understand the carrying capacity of people in Exmouth Gulf and the impacts of overcapacity on surrounding environment (2)
- Carrying capacity of groundwater and projected sustainability with increasing development (1)

To note:

Sutton and Shaw (2021) included an additional ~200 gaps relating to terrestrial and social values. These were not included in this report's scope of works, nor were they included in the prioritisation of future research for Exmouth Gulf.

Comprehensive intertidal and benthic habitat mapping across the whole Exmouth Gulf was a key knowledge gap noted in Sutton and Shaw (2021). This gap was not initially included in prioritisation of future research for Exmouth Gulf as WAMSI was actively working to address this gap alongside this report. Currently, there are three contemporary benthic habitat maps available (or soon to be) for Exmouth Gulf that were produced for specific statutory, scientific, or management objectives: DBCA (marine park planning), DPIRD (fisheries management) and Gascoyne Gateway Marine Complex (coastal development). The differences in data inputs, classification approaches, and outputs from past, current, or future mapping efforts in Exmouth Gulf should be interpreted in the context of their scientific merit and intended application, not as inconsistencies. A combined benthic habitat map with high confidence is required by DWER and the Taskforce and WAMSI proposes a consolidated map with accompanying confidence and analytical layers. This requires sharing of input data (e.g., ground-truthing data and satellite imagery), modelled outputs and methodology (particularly descriptions of classifications). All of these data sources are not currently available but will be within 12 months. The only contemporary subtidal benthic habitat map that is currently available is from DBCA, and a contemporary intertidal map has been produced by Hickey et al. (2023b and 2023c). Both the benthic habitat map and the intertidal map are included in this report (Figure 25 and Figure 26). It is recommended that DBCA, DPIRD and Gascoyne Gateway Marine Complex are continued to be engaged and that when data becomes available, all data are shared for the purposes of generating 'fit for purpose' maps that illustrate the variability of the benthic system in Exmouth Gulf.

The risk assessment undertaken in Sutton and Shaw (2021) also highlighted 'gaps' relating to the direct impact of coastal development footprints on benthic habitats:

- Coral and impact of port infrastructure footprint (3)
- Macroalgae and turf algae and impact of port infrastructure footprint (3)
- Samphire and impact of salt production facility footprints (3)
- Seagrass and impact of port infrastructure footprint (3)
- Sponges and filter feeders and impact of port infrastructure footprint (3)
- Mangroves and impact of salt production facility footprints (3)

These were not considered to be gaps in knowledge that should be addressed by a research question. Instead, with an understanding of benthic habitat extents from the above benthic and intertidal mapping project, and defined footprint areas for future developments, the area of habit directly impacted by development (i.e. through removal or compaction) could be determined. These 'gaps' would also form part of a risk assessment undertaken by the proponent and assessed by EPA.

Description of the online survey prioritisation approach

The prioritisation of knowledge gaps for Exmouth Gulf followed the same process described in *A Science Plan for Shark Bay (Gathaagudu) developed from comprehensive stakeholder engagement* (Shaw & Sutton, 2022). An online prioritisation survey was selected from several options suggested to the Taskforce executive. It provided an opportunity to gauge priorities from a range of stakeholders in a transparent and cost-effective way.

The online prioritisation survey was developed using the Qualtrics software, which had the following benefits:

- wide dissemination - locally, nationally and internationally
- less time intensive compared to attending an in-person workshop for multiple days
- accessible 24 hours a day, which meant it could be completed during work hours or at home
- open for a lengthy period of time in order to improve participation
- inclusive and could cater to different levels of knowledge, with opt out options
- enabled interrogation of the participant's interest area and/or expertise (category) to better understand the priorities selected

Structure

At the beginning of the survey, participants were provided with introductory information on:

- Why they were receiving the survey
- The purpose of the survey
- The layout of the survey
- Where the knowledge gaps came from
- Closing date and contact information

In order to identify stakeholders and relate survey results to different stakeholder groups, participants were asked to select all the stakeholder categories that applied to them. These included:

- Agriculture
- Ashburton community member
- Exmouth community member
- Fishing
- Government (local, state, Commonwealth)
- Local business
- Management
- Mining
- Research/University
- Tourism
- Traditional Owner
- Visitor to Ashburton region
- Visitor to Exmouth region
- Other (could specify)

Following this question, participants were asked to identify the stakeholder group that **best** described them from the above list. Participants then had the option of identifying their main area of expertise or interest in the Exmouth/ Onslow areas using free text. No other demographic information was requested, although participants were asked to enter their email addresses for the purposes of survey integrity (reduce fake emails/bots) and if they wished to enter the draw to win one of six $50 vouchers for participating in the survey.

The scoring component of the online survey was divided into two parts to allow all stakeholders to participate in the survey, regardless of their level of knowledge of the marine and coastal environments of Exmouth Gulf:

- Part 1 (required): high-level scoring of research themes (Figure 1)
- Part 2 (optional): scoring of detailed knowledge gaps (nested under high-level research themes (Table 1; Figure 2).

For Part 1, participants were asked to rank high-level research themes by 'dragging and dropping' themes into an order from most in need of attention (1) to least in need of attention (9) when considering future research and management in Exmouth Gulf (Figure 1). This was a requirement for all participants before they could proceed to the next steps.

Part 1 (required) - There are nine themes to be prioritised from high to low. This prioritisation will involve a drag and drop ranking process.

To the best of your knowledge, please order the themes below from most in need of attention (1), to least in need of attention (9) when considering future research in Exmouth Gulf?

1 Climate change projections for marine and coastal environments (e.g. sea level rise, marine heatwaves, storms and cyclones)

2 Current and future underwater noise effects on marine life (e.g., seismic activity, vessel noise, construction)

3 Fisheries and fishing effects on important species (e.g., recreational, commercial, charter, bycatch)

4 Use of marine and coastal habitats by threatened and protected species (e.g., seagrasses, sponges, corals, mangroves, samphire, feeding areas, nursery areas)

5 Industrial development impacts on coastal and marine environments and recreational activities (e.g., footprints, noise, clearing)

6 Effects of increased boating and shipping (e.g., increased sediments in water column, marine pests, fuel and oil spills, vessel strikes)

7 Disturbance and degradation to marine and coastal values from unmanaged tourism and population growth (e.g., offroad 4WD, anchoring, diving, carrying capacity)

8 Pollution and contamination of the marine environment (e.g., PFAS, bitterns, vessel antifouling, light, marine debris)

9 Understanding and maintaining ecosystem health, connectivity, and processes (e.g., nutrient and groundwater flows, spawning and recruitment, land and sea connections, food webs, water and sediment quality)

Figure 1 An example of the drag and drop function for ranking high-level research themes from most in need of attention (1) to least in need of attention (9).

Part 2 was designed to understand those detailed knowledge gaps that should be a priority for Exmouth Gulf. This was an optional part of the online survey as it involved another level of scoring complexity and knowledge, and scientific language was often used. Participants were encouraged to continue- on in the survey if they had an interest or felt comfortable with their level of knowledge of the marine environment of Exmouth Gulf. Subject matter experts or researchers were further encouraged to spend the extra time scoring detailed knowledge gaps.

Participants choosing to continue on to Part 2 and score detailed knowledge gaps had the option to score all gaps under all nine high-level research themes (36 detailed knowledge gaps in total), or they could score a subset of gaps and high-level research themes. Participants could exit the survey at any time, but they were encouraged to finish all the scoring for a detailed knowledge gap for the score to be valid. The number of detailed knowledge gaps under each of the nine high-level research themes ranged from 2 - 6. For example, Figure 2 shows an example of the options available for scoring the Ecosystem importance, Interest, Knowledge and Urgency of detailed knowledge gaps under the high-level research theme 'Climate change projections for marine and coastal environment'. Participants were provided the opportunity to revise their scoring before leaving the survey.

Climate change projections for marine and coastal environments

	Ecosystem importance How important do you think this gap is to a healthy ecosystem? 1- not important at all 2- not very important 3- somewhat important 4- moderately important 5- important 6- very important 7- extremely important							**Interest** How important is this gap to your interest in Exmouth Gulf? 1- not important at all 2- not very important 3- moderately important 4- important 5- very important					**Knowledge** How much relevant and existing knowledge are you aware of? 2- very little 3- some 4- significant amounts 5- extensive				**Urgency** Do you think this gap needs to be answered/addressed urgently? 1- not urgent (>20 yrs) 2- long term (>10 yrs) 3- medium term (5-10 yrs) 4- short term (<5 yrs) 5- immediately (<2 yrs)				
	1	2	3	4	5	6	7	1	2	3	4	5	2	3	4	5	1	2	3	4	5
What are the specific climate change projections for Exmouth Gulf, and what are the likely effects on key marine and terrestrial ecosystems and taxa?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
How resilient are benthic habitats and marine fauna to recurring marine heatwaves?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
How will recurring marine heatwaves affect water quality?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
What are the effects of current and future climate change pressures, such as storms, cyclones, and sea level rise, on the islands of Exmouth Gulf?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

Figure 2 An example table for scoring of detailed knowledge gaps under the high-level research theme 'Climate change projections for marine and coastal environments'.

Scoring criteria

Participants were asked to score the detailed knowledge gaps using the four criteria in Table 1: Ecosystem importance, Interest, Knowledge and Urgency. The criteria and scoring were taken from Shaw and Sutton (2022).

To arrive at a final score for a detailed knowledge gap, the following equation was used:

$$\text{Score} = (E+I) \times U \times (6-K)$$

where E = Ecosystem Importance, I = Interest, U = Urgency, and K = Knowledge

Given the Exmouth Gulf marine ecosystem is critical for the survival of fisheries, tourism and livelihoods, Ecosystem Importance was given extra weighting by having a scoring range from 1-7, as opposed to 1-5 for other criteria. Interest was added to Ecosystem Importance, so they were equally influential to the final score. This reflects WAMSI's goal to involve and elevate stakeholders and their varying views in the prioritisation process. Urgency was made a significant influencer of the score by being a multiplier, which was effective in providing a greater separation between scores of knowledge gaps and further highlighting the priorities. Knowledge was also a significant influencer of the score by being a multiplier, given the prioritisation process is being applied to knowledge gaps. As there is not often a situation where absolutely no knowledge is available, the minimum score of '1' (no knowledge) was removed as a scoring option for the criteria Knowledge. The score for Knowledge was subtracted from six to remove the possibility of a 'zero' value in calculations.

Table 1. Criteria for scoring knowledge gaps in the online Exmouth Gulf Research Prioritisation survey.

Criteria	Guidance	Scoring	Numeric
Ecosystem importance: Importance of this issue to a healthy ecosystem	e.g. Scale of the issue, benefits related to the issue	Extremely important Very important Important Moderately important Somewhat important Not very important Not important at all	7 6 5 4 3 2 1
Interest: How important is this issue to your interest in Exmouth Gulf?	e.g. Uniqueness, Indigenous values and culture, community values	Very important Important Moderately important Not very important Not important at all	5 4 3 2 1
Knowledge: How much existing knowledge is available?	e.g. Is it relevant in addressing the specific issue/question? Is it reliable?	Extensive Significant amounts Some Very little	5 4 3 2
Urgency: Does this question need to be answered immediately?	e.g. How vulnerable is the species/habitat? When do decision-makers need the information for management? Is the species/habitat/process currently under threat?	Immediately (< 2 years) Short term (< 5 years) Medium term (5-10 years) Long term (> 10 years) Not urgent (>20 years)	5 4 3 2 1

Survey analyses

In order to prioritise detailed knowledge gaps, the following aspects of the survey results were considered:

1) *Some consistency in participation*. All participants were required to complete Part 1 and rank high-level research themes
2) *Accounting for those detailed knowledge gaps that were not scored*. If a knowledge gap was not scored, this could be due to lack of expertise, lack of time etc., rather than a lack of importance. All detailed knowledge gaps came from a workshop or publication where it was deemed to be important. To account for instances where no scoring occurred, a base score of '1' was assigned

to 'New rank based on overall score' (step B in Figure 3) so that the final score for the detailed knowledge gap did not result in a '0'.

3) *High-level research themes and detailed knowledge gaps should be linked together*. Not all participants would have scored the detailed knowledge gaps. In order for their views to still have an influence on the prioritisation of detailed knowledge gaps, detailed knowledge gaps received 'extra points' in the calculations depending on where the high-level research theme (of which the gap belonged to), was ranked in Part 1. All participants had to complete Part 1

The following steps outline the process taken to arrive at the final scores for each detailed knowledge gap and, in turn, prioritisation of these detailed knowledge gaps (e.g., Figure 3):

1) For each of the 36 detailed knowledge gaps, the numeric scores for each criterion (E, I, U, K) were averaged, as the sample size (number of participants scoring) for each detailed knowledge gap differed
2) The equation (E+I) x U x (6-K) was used to obtain scores for each detailed knowledge gap, based off the averaged values for each criterion
3) Detailed knowledge gaps were sorted based on scores from high to low
4) Based on this sort from high to low, a new ordered rank was applied from 36 (high) to 1 (low), as there were 36 questions (noting some questions may have been assigned the same rank if they had the same score from (2))
5) The summed ranks for high-level research themes from 1 to 9 were divided by the number of participants to obtain an average rank for each high-level research theme
6) 'Extra points' were then added to the ordered rank values of detailed knowledge gaps based on high-level research themes. This was an addition rather than a multiplication so that Part 1 did not have an overriding influence on the prioritisation of detailed knowledge gaps
7) Detailed knowledge gaps were then sorted again, from high to low, to obtain the prioritised list. An overall prioritised list was obtained as well as individual stakeholder group prioritised lists.

a

Theme	Gap	Overall score = (E+I) x U x (6-K)
A	Gap 1	100
B	Gap 2	120
B	Gap 3	110
C	Gap 4	90
D	Gap 5	75

Theme	Ave rank score	Theme rank order	Reverse rank order
B	2.5	1	4
C	3	2	3
D	4	3	2
A	4.5	4	1

b

Theme	Gap	Overall score = (E+I) x U x (6-K)	New rank based on overall score
B	Gap 2	120	5
B	Gap 3	110	4
A	Gap 1	100	3
C	Gap 4	90	2
D	Gap 5	75	1

c

Theme	Gap	Overall score = (E+I) x U x (6-K)	New rank based on overall score	Added points from ranked themes
B	Gap 2	120	5	9 (5+4)
B	Gap 3	110	4	8 (4+4)
A	Gap 1	100	3	4 (3+1)
C	Gap 4	90	2	5 (2+3)
D	Gap 5	75	1	3 (1+2)

d

Theme	Gap	Overall score = (E+I) x U x (6-K)	New rank based on overall score	Added points from ranked themes	PRIORITY LIST
B	Gap 2	120	5	9	1
B	Gap 3	110	4	8	2
C	Gap 4	90	2	5	3
A	Gap 1	100	3	4	4
D	Gap 5	75	1	3	5

Figure 3 Example of the numeric process and steps used to prioritise knowledge gaps.

Prioritised knowledge gaps for Exmouth Gulf based on Exmouth Gulf Research Prioritisation survey

THEME	GAP	PRIORITY
Industrial development impacts on coastal and marine environments and recreational activities	How could development footprints on the eastern coastline of Exmouth Gulf affect nutrient flow and, in turn, marine life reliant on these nutrient flows?	1
Understanding and maintaining ecosystem health, connectivity, and processes	How will groundwater systems be affected by expansion of mining activities (e.g., limestone, potash, salt)?	2
Understanding and maintaining ecosystem health, connectivity, and processes	How is Exmouth Gulf influenced by processes and pathways across the land-sea interface (e.g. nutrient sources and flows, groundwater movement)?	3
Use of marine and coastal habitats by threatened and protected species	Where do nursery locations occur for threatened fauna in Exmouth Gulf e.g., sea snakes, sawfishes, shovelnose rays?	4
Disturbance and degradation to marine and coastal values from unmanaged tourism and population	What is the carrying capacity of people for Exmouth and what are the implications of increasing numbers of people on Exmouth Gulf?	5
Use of marine and coastal habitats by threatened and protected species	How are megafauna and seabirds/shorebirds using specific benthic habitats and to what extent could these associations be affected by habitat damage and degradation?	5
Pollution and contamination of the marine environment	What are the effects of bittern discharge on marine fauna and flora, as well as on water and sediment quality?	6
Climate change projections for marine and coastal environments	How resilient are benthic habitats and marine fauna to recurring marine heatwaves?	7
Effects of increased boating and shipping	What introduced marine pests currently exist in Exmouth Gulf and what risks do current and future pests (from shipping or ocean warming) pose to marine life and habitats?	8
Pollution and contamination of the marine environment	What is the extent of PFAS contamination and what effect does this have on the marine food web?	8
Use of marine and coastal habitats by threatened and protected species	Are elasmobranch species utilising Exmouth Gulf and its intertidal habitats seasonally and how reliant are they on these environments?	8
Understanding and maintaining ecosystem health, connectivity, and processes	What is the seasonal exchange between the oceanic and Exmouth Gulf waters and how does this influence species recruitment and dispersal?	9

THEME	GAP	PRIORITY
Understanding and maintaining ecosystem health, connectivity, and processes	What are the characteristics of food webs in Exmouth Gulf and how do they vary seasonally?	10
Pollution and contamination of the marine environment	What are the effects of copper-based contaminants, such as antifouling agents, on marine life and benthic communities?	11
Climate change projections for marine and coastal environments	What are the specific climate change projections for Exmouth Gulf, and what are the likely effects on key marine and terrestrial ecosystems and taxa?	12
Current and future underwater noise effects on marine life	What is the current marine soundscape of Exmouth Gulf, and how could this be predicted to change with further coastal development?	13
Effects of increased boating and shipping	What is the occurrence, extent and severity of fuel and oil spills and is this affecting marine and coastal environments?	14
Use of marine and coastal habitats by threatened and protected species	What is the role of samphire communities in Exmouth Gulf and how are they utilised by other species e.g., migratory shorebirds?	15
Disturbance and degradation to marine and coastal values from unmanaged tourism and population	To what extent are seabirds and shorebirds being disturbed or injured by human activity (e.g., 4WD)?	16
Understanding and maintaining ecosystem health, connectivity, and processes	What are the characteristics of sand and mud flat communities and how do they contribute to sediment health?	16
Industrial development impacts on coastal and marine environments and recreational activities	What are the possible effects of seawater intake on the surrounding marine environment, and how can we achieve greater certainty about these effects?	17
Understanding and maintaining ecosystem health, connectivity, and processes	What is the quality and characteristics of water and sediments in Exmouth Gulf?	17
Current and future underwater noise effects on marine life	To what extent is underwater noise currently effecting marine fauna and ecological functions in Exmouth Gulf and how might this change in the future?	18
Disturbance and degradation to marine and coastal values from unmanaged tourism and population	What is the extent of damage to benthic habitats caused by human activity (e.g., anchoring and diving)?	18
Effects of increased boating and shipping	What is the frequency and consequences of vessel strikes on marine megafauna, including on seabirds and shorebirds?	19

THEME	GAP	PRIORITY
Fisheries and fishing effects on important species	Is recreational fishing causing significant decline to ecologically and recreationally important species?	20
Climate change projections for marine and coastal environments	How will recurring marine heatwaves affect water quality?	21
Pollution and contamination of the marine environment	How widespread is pollution (rubbish) and what effect is this having on marine and coastal fauna?	21
Use of marine and coastal habitats by threatened and protected species	What are the home ranges and habitat uses of sea snakes in Exmouth Gulf?	21
Climate change projections for marine and coastal environments	What will be the effect of sea level rise on benthic habitats and marine and coastal fauna?	22
Effects of increased boating and shipping	What is the natural seasonality of suspended sediments in Exmouth Gulf and how will increases in suspended sediments affect water quality, benthic habitats and marine fauna?	22
Climate change projections for marine and coastal environments	What are the effects of current and future climate change pressures, such as storms, cyclones, and sea level rise, on the islands of Exmouth Gulf?	23
Industrial development impacts on coastal and marine environments and recreational activities	How will marine based recreation be affected by future coastal development (e.g., footprints, noise, light)?	23
Pollution and contamination of the marine environment	What are the effects of light pollution on marine fauna (including but not limited to marine turtles)?	24
Fisheries and fishing effects on important species	What effect has fishing had on elasmobranch and sea snake populations?	25
Use of marine and coastal habitats by threatened and protected species	What is the diversity of coastal dolphin species utilising Exmouth Gulf, and are the populations resident, migratory, or a combination of	25

Breakdown of estimated costs for recommended projects in Exmouth Gulf

	Seasonal SST forecasts and marine heatwave predictions for Exmouth Gulf*	Species distribution and ecological niche modelling to predict climate change impacts	Seasonal food web modelling	Multi-species habitat modelling	Scenario modelling of carrying capacity (people) for Exmouth Gulf	Groundwater mapping, monitoring and modelling	Forecasting future effects of bitterns discharge in Exmouth Gulf	Assessing future likelihood scenarios of marine pest establishment (climate change and vessels)	Effects of contaminants on marine food webs	Comprehensive soundscape mapping and modelling future changes based on anthropogenic sources*	Nutrient/ biogeochemical monitoring and modelling *	Larval dispersal and connectivity modelling
Timeframe (yrs)	1	3	3	3	2	3	1.5	1.5	3	2	3.5	3
Data set purchases	$ 10,000	$5,000	NA	$5,000	NA	$5,000	NA	$5,000	NA	NA	NA	NA
Seasonal field data collection/monitoring	NA	$448,000	$80,000	$440,000		$96,000	NA	NA	$48,000	$300,000	$ 680,400#	$80,000
Equipment	NA	$200,000	$20,000	$200,000	NA	$100,000	NA	NA	$20,000	$150,000	$300,000	$20,000
Lab analyses	NA	$50,000	$80,000	NA	NA	$200,000	NA	NA	$80,000		$300,000	$250,000
Modelling/GIS Software/Tools	In-kind	In-kind	In-kind	In-kind	In-kind	In-kind	In-kind	In-kind	In-kind	In-kind	In-kind	In-kind
Salaries	$240,000	$720,000	$720,000	$720,000	$480,000	$720,000	$180,000	$180,000	$720,000	$270,000	$840,000	$720,000
Data management and reporting	$20,000	$20,000	$20,000	$20,000	$20,000	$20,000	$20,000	$20,000	$20,000	$20,000	$40,000	$20,000
Travel/logistics	NA	$168,000	$120,000	$120,000	NA	$120,000	NA	NA	$120,000	$30,000	$761,400	$120,000
Est. cost	$270,000	$1,611,000	$1,040,000	$1,505,000	$500,000	$1,261,000	$200,000	$205,000	$1,008,000	$770,000	$2,921,800	$1,210,000
Rounded to the nearest $100k	**$300,000**	**$1,700,000**	**$1,100,000**	**$1,500,000**	**$500,000**	**$1,300,000**	**$200,000**	**$200,000**	**$1,000,000**	**$800,000**	**$3,000,000**	**$1,300,000**
Considerations	Satellite imagery	Satellite tags Drones Satellite imagery Genetic/eDNA samples	Fatty acids, stable isotopes, gut content analysis	Satellite tags Aerial surveys Drones Satellite imagery		Satellite imagery Side-scan sonar		Satellite imagery	WQ/toxicant sensors	Acoustic recorders Moorings, releases, batteries	WQ/nutrient sensors	plankton nets
Est. # successful ^ trips	NA	8	8	8	NA	8	NA	NA	8	5	18	8

* Cost estimates provided/reviewed by subject matter experts

^ Pending no weather or logistical issues

tripled based on expert feedback

Note: Costings for 'Elasmobranch populations and habitat use' is provided in Appendix 9.12. Costings for 'Comprehensive subtidal and intertidal benthic habitat mapping' is primarily related to data collation and modelling/mapping building upon currently underway projects.

	Est. cost	Comments
Salaries		
Academic	$120,000.00/pa	Salary costings are based on full time, full project length
Travel/logistics		
Flights to Exmouth	500/pers	Assume 3 ppl per trip
Group accommodation	600/night	
Field work		
Boat based	$500/day	
Drone based	NA- equipment cost	
Aerial based	$5,000/day	
Land based (car)	$100/day	
Lab analyses		
Stable isotopes/fatty acids, eDNA, water and sediment quality, tissue samples, plankton samples	$100-$500/sample	

Biogeochemical model scoping meeting

Biogeochemical model scoping meeting

Date: 29 Jan 2025

Jenny Shaw (WAMSI), Alicia Sutton (WAMSI), Tony Arangio (WAMSI), Ryan Lowe (UWA), Matt Hipsey (UWA), Kathryn McMahon (ECU), Kay Davis (Australian Institute of Marine Science), Glenn Hyndes (ECU)

There are five components to consider for an Exmouth Gulf wide biogeochemical model:

1. Ocean dynamics and upwelling – need to resolve this for the whole Gulf
   - Some of this is done already
   - Department of Jobs, Tourism, Science and Innovation and the National Collaborative Research Infrastructure Strategy have funded two water quality and current buoys for 3 years (surface and bottom measurement, currents, salinity, temp, waves), real time. Administered through IMOS. Details of the project to be determined and there could be scope to add on additional sensors if there was funding, or take additional measurement when they are serviced by a field crew every 3-6 months. Likely to be June when they go in. Ryan and Mike Cuttler running the program
2. Benthic fluxes – sediment water interactions, light sensitivity
   - CS = $150-200k for 12 cores/incubations
3. Tidal creek flows and contribution
   - Close to having a good dataset here (from Mardie work)
4. In situ pelagic metabolism e.g., nutrient cycling/ phytoplankton productivity, flux rates and recycling
5. Groundwater seepage
   - Benthic chambers, radon/radium tracing, benthic O2, can look at concentrations along larger spatial gradients and target some areas for longer term. Reasonably cheap. Radon detectors ~$7 a piece – simple kit.
   - There are people keen to do the work e.g., ECU (Pere Masqué) has measured groundwater discharge into EG – high resolution spatial study and site specific over tidal cycles. Not published and would require some funds to work the data up. Nutrient and metals were look at here.

A biogeochemical model is the first piece of the puzzle and can be used as a framework that can feed into other models and studies and be improved continuously e.g., food web modelling, marine heatwaves predictions. Agreement that this is absolutely a project that needs to be prioritised given Exmouth Gulf is a unique location with little understanding that's under a lot of pressure from development. Can be hard to make policy decisions when there are so many gaps in knowledge.

Costings

- 3 years for 1 modeller = $500k - which is for the expertise/salary. Approx %10 of this is spent on the modelling software itself
- $3mil would deliver a reasonable model and provide funds to address the above five components, and a considerable portion of this would go towards field work costs
- The dynamics not predictable in the EG system – need to survey certain events to get confidence in the model. So would need to consider having reactive field teams in place
- Nutrient sensors (nitrate and phosphate) could be used to look at nutrient transfer. They are expensive ($40k) and need regular checking (~2 weeks depending on use). Not sure how they would go with in a high salinity environment

- Remote sensing and imagery costs need to be considered

Timeframe

- 3 year program at a minimum
- Time may be pushed out if trying to capture extreme events e.g., cyclones, so need to consider a time buffer to deal with episodic events that may or may not come.
- Need good temporal and spatial coverage
- Incredibly unpredictable system based on experience with the WAMSI Mardi program

Opportunities for collaboration

- Australian Institute of Marine Science may be able to take additional samples when servicing equipment or sampling in Exmouth Gulf
- IMOS sometimes undertakes event-based sampling that could be leveraged upon
- New IMOS administered wave buoys going into Exmouth Gulf in ~June which could be considered for additional measurements

Considerations

- Ideally, if the wave buoys detect upwelling in Exmouth Gulf then need to be ready to go out and sample to see what the upwelling consists of
- Tricky to define boundary conditions e.g., what is the vertical profile of boundary conditions
- Need to design a new model mesh to cover the whole gulf and creeks
- Mardie project results are useful but limited temporally – only two time periods
- Need to factor in remoteness, scale, unpredictability
- Turbidity is a strong gradient and factor in the system
- Consider undertaking data collection first, then ramp that down as the modelling team ramps up
- Can use Cockburn Sound Integrated Ecosystem Model architecture so not designing from scratch

Potential research scopes to contribute to knowledge gaps on sawfish and other elasmobranchs in Exmouth Gulf

Potential research scopes to contribute to knowledge gaps on sawfish and other elasmobranchs in Exmouth Gulf

Recommendations compiled by Karissa Lear[1], Rebecca Bateman-John[1,2], Sallyann Gudge[3], Kimberley Kliska[3], and Caitlin Taylor[3]

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[2]Fin Focus Research

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Limited directed research on elasmobranchs has been conducted within Exmouth Gulf specifically, and as a result there are many research gaps on sawfish and other threatened elasmobranchs in Exmouth Gulf. Some of the most pertinent knowledge gaps include:

Sawfish

- Adult sawfish ecology, including habitat preferences, migration/residency patterns, depth preferences, diet, population size
- Juvenile sawfish nursery areas, survival rates, diet

Other elasmobranchs

- Life history parameters (growth rates, reproductive rates, size/age at maturity) of most rays and small sharks found in Exmouth Gulf
- Wedgefish (globally threatened with refuges in NW Australia including Exmouth Gulf): Habitat use (especially for juveniles and males which are not found in nearshore areas), reproductive behaviour/periodicity, pupping and/or nursery areas
- Post-release mortality from trawl and recreational (both boat- and shore-based) fisheries
- Recreational fishing effort for elasmobranchs within Exmouth Gulf including retention rates

Various research projects on sawfish and other elasmobranchs have been underway in the Exmouth Gulf for many years, with some continuing in present day (section 1.1). Several other future projects are recommended to fill pertinent data gaps in the immediate future (section 1.2). Approximate budgets for these projects have been estimated, however, final budgets will depend on the institution and researchers undertaking the project and what components are included.

Ongoing research **in Exmouth Gulf**

Exmouth Gulf elasmobranch surveys [$360,000 annually]

Very little of Exmouth Gulf has been scientifically surveyed for elasmobranchs, and most Gulf-wide surveys for other fauna (e.g. marine mammals) are unsuitable for identification of elasmobranch species. Thus, the current knowledge on which species are common throughout different areas of Exmouth Gulf and whether 'hotspots' for certain species of interest (e.g. sawfishes) exist is lacking. This information can be gained through regimented physical (e.g. netting, fishing), and visual (e.g. BRUVS, boat observations, and drone) surveys throughout the region. Extended acoustic tracking of sawfishes and other species of interest caught during these surveys (see 1.1.2) would provide additional information on their spatial ecology. Surveys across a seasonal scale are advisable to capture seasonal variation in species assemblages and abundance. A multi-year project is also advisable to capture potential differences in recruitment rates of sawfish and other species between years.

Murdoch University and DBCA have an ongoing project conducting netting and drone surveys for elasmobranchs across the eastern and southern Gulf, with 1.5 years of the project funded to date but limited future funding in hand. Estimated annual funds required for twice-yearly surveys (two 10-day field trips) are approximated at **$360,000 per year**, which includes liveaboard vessel time, researcher, manager, and Traditional Owner salaries, food and logistical support for remote fieldwork, and sampling equipment. An initial 2-3 year survey period is recommended, with subsequent annual monitoring. Collaboration with local managers including DBCA is necessary and could potentially help to reduce costs.

Acoustic tracking in Exmouth Gulf/Ningaloo Reef [$80,000 annually]

Acoustic tracking provides information on residency and space use of targeted species, including habitat use and home range sizes within Exmouth Gulf and levels of connectivity between Exmouth Gulf, Ningaloo Reef, and the Pilbara. Several acoustic tracking projects on elasmobranchs led by different institutions are in progress within the Exmouth/Ningaloo region, which has resulted in several species in the area currently carrying active long-term (5-10 year) acoustic transmitters. These include adult lemon and tiger sharks, adult female bottlenose wedgefish, and some juvenile-subadult green sawfish. Additional projects (e.g. 1.1.1) can incorporate acoustic tagging into fieldwork to increase the number of tracked individuals/species in the region.

Several groups (including DBCA, CSIRO, Murdoch University, Australian Institute of Marine Science, DPIRD, IMOS) have contributed to deploying and/or maintaining an array of acoustic receivers within Exmouth Gulf as well as across Ningaloo and various areas of the Pilbara coastline. A robust receiver network is essential to providing good quality spatial data, however, start-up costs of installing an array can be substantial, and the array(s) need regular maintenance: receivers need to be downloaded and checked for function at least twice per year, and batteries changed at least once per year. Additionally, over time it is inevitable that some receivers and/or mooring equipment will need maintenance or replacement.

Project funding: Tagging costs are assumed covered by other projects, but there is currently limited funding for servicing the existing acoustic receivers, including the cost of batteries and receiver maintenance, as well as salary and boat time for servicing. Assuming an array of 25 receivers already in hand in the Exmouth Gulf/Ningaloo region from collaborating institutions, servicing costs per year (including researcher time, vessel time, batteries, and receiver/mooring maintenance costs, are approximated at **$80,000 annually**. Additional receivers will help to increase coverage, with each additional receiver costing $2,700 plus a $1,000 mooring as a start-up cost.

Future additional identified elasmobranch priority projects

Assessment of sawfish reporting data from the EGPMF [$12,000]

There is currently no knowledge of adult sawfish habitat use within the Exmouth Gulf or elsewhere in the region. The Exmouth Gulf Prawn Managed Fishery (EGPMF) occasionally catches adult sawfish, and records data on sawfish bycatch potentially including information on species, location/time of capture, and approximate size. However, these data are not publicly available. Access to sawfish bycatch data from the EGPMF followed by time to analyse the data, particularly in relation to recently conducted benthic habitat mapping, would be extremely beneficial to understanding 1) which sawfish species (especially adults) are found where in the Exmouth Gulf including seasonal changes in distribution, 2) habitat preference and potential hotspots for adult sawfish, and 3) whether modelling resulting from goals 1 and 2 could help predict sawfish presence in certain areas in order to the EGPMF to avoid future sawfish captures.

As an initial step, fishery bycatch data can be examined to summarise available spatial and habitat data, and recommendations put forth for more detailed future data collection by the fishery, along with updated species ID guides to enhance the quality of fishery data collection. **Estimated time cost: $12,000.**

Subsequently, depending on the quality of existing data and number of records, more detailed habitat mapping could be conducted to predict potential hotspots of adult sawfish use.

Collaborative work between fishers and researchers to acquire significant data on cryptic elasmobranch species [$800,000]

There are many shark and ray species caught by the EGPMF as bycatch which could be used to collect much-needed information including habitat use, life history, and survivability data for specific species. This is particularly relevant for adult sawfish, which are sometimes caught by trawls within Exmouth Gulf but extremely difficult for researchers to target due to their offshore habitat use and rarity.

Deploying tags on bycaught species of interest (e.g. sawfish, wedgefish) as well as taking genetic samples and dissecting dead individuals of a variety of species could help provide an abundance of information important to sustainable management of elasmobranchs in the region. Such a project would likely require the full-time commitment of 1-2 researchers for 2-3 years potentially alongside a PhD student, travel costs for researchers, equipment costs for tags and dissection equipment, and sample processing costs for genetics and vertebrae (for age and growth). Extremely rough estimates of such costs for a 3-year project are approximated at **$800,000**. The components of this project are explained in more detail in the following sections, all of which have the major costs included in the estimated $800,000 budget.

Long-term tracking of adult sawfish

Because they are so rare and nothing is known about their adult habitat use, it is extremely difficult and time-consuming for researchers to target adult sawfish for tagging studies or other research. However, understanding where sawfish go as adults is crucial to their conservation. Deploying long term tags (e.g. 10-year acoustic tags or pop-up satellite archival tags (PSATs)) on adult sawfish caught in the EGPMF would provide a plethora of highly useful information on adult habitat use.

As above in 1.2.1, collecting more information on sawfish captured in fisheries (e.g. sex and genetic samples as well as photos to confirm species ID), would also be extremely beneficial.

Wedgefish in the trawls

Wedgefish, alongside sawfish and giant guitarfish, are one of the most threatened marine fish families globally. Australian species have a similar story to sawfish, where many were historically distributed across the Indo-Pacific but Australia (because of comparatively low commercial fishing pressure) now offers the last (or one of the last) remaining ‘lifeboat’ habitats in the world. The most common species in the Exmouth Gulf is the bottlenose wedgefish

Rhynchobatus australiae, which is globally Critically Endangered, but is not listed under the EPBC Act in Australia.

Very little is known about wedgefish biology/ecology in general, including in Australia. This includes no knowledge about pupping or reproductive locations and very little knowledge about juvenile/ neonate habitat use. Adult female wedgefish are sighted in nearshore areas and some have been tagged during recent research with long-term acoustic transmitters, but adult males are rarely sighted. Collecting capture data from wedgefish caught in the EGPMF and other trawl fisheries in the Pilbara region, including a photo, location, sex, and length, would be extremely beneficial. Tagging/tracking juvenile wedgefish caught in trawl fisheries could also provide significant information about juvenile habitat use.

Life history information on local small shark and ray species

For most ray species in the region as well as many sharks (particularly smaller species), almost nothing is known about basic biological information such as growth rates, age/size at maturity, longevity, litter size, and reproductive periodicity. Knowledge on these biological parameters is necessary to making accurate assessments of the threat level exerted by fisheries or other sources of mortality. Gaining much of this biological information info requires dissection of animals and therefore lethal sampling, however, this could also be done on individuals that are caught within the trawl fisheries, many of which likely already die in the capture process or when released due to very high shark depredation on fauna released from trawl boats.

Either by the EGPMF fishers collecting and delivering samples of individuals dead at vessel, or by researchers being present on the trawl boats (with the additional benefit of then being able to identify to species, size, and sex, all elasmobranchs caught including those released alive), dissections of all dead individuals from the trawl fishery could be performed. This would provide necessary life history information specific to the region, including size and age at maturity, growth curves, and litter size (noting that predominantly small individuals are caught in the trawl fisheries due to bycatch reduction devices, and therefore only some of these parameters may be available for species reaching large sizes as adults).

Funding: Most of the budget for this project component would consist of time (salary) for 1-2 researchers for fishing and dissection time, as well as analysis and reporting. Travel costs, and small costs for dissection and sampling equipment would be needed. Age estimates can be read from sectioned vertebrae, requiring additional time and some minor equipment costs.

Genetics of elasmobranchs in Exmouth region: species confirmation and population size assessment

As an additional project component, it would also be extremely beneficial to collect genetic samples from sharks/rays in the Exmouth region to 1) confirm species ID on a few species that are not easily morphologically identified, and 2) use kinship methods to estimate population size of sharks/rays in Exmouth Gulf, as well as providing material for future investigation of connectivity with other areas. These samples could be collected from elasmobranchs caught in the EGPMF, and/or by targeted fishing efforts.

Additionally, collecting high-quality genetic samples (e.g. through blood sampling) for elasmobranchs in Exmouth Gulf would help to provide a robust genetic catalogue for species present in the region. This would be extremely beneficial for further genetic research including eDNA assay which rely on matching collected data to published genetic signatures. Unfortunately, due to substantial taxonomic revisions and difficult morphological identification in many families, existing genetic databases are often not sufficient for modern eDNA or other genetic research.

Post-release mortality of sawfish, wedgefish, other threatened species in recreational and trawl fisheries

We know very little about post-release survival rates of sawfish (and most other species) which are caught in commercial or recreational fisheries and then released alive; the stress of capture can cause extensive physiological upset and lead to mortality (usually within a day) of animals that are released alive, even in those that appear fine at the time of release. This is especially true in trawl fisheries which tend to cause injury to animals caught within the trawl, for large species that are brought out of the water on capture (common in trawl fisheries and recreational beach fishing), and for species that show high fight responses when caught (such as wedgefish and hammerheads). To accurately assess the impact of fisheries on a species, it is necessary to understand how many animals released alive are likely to suffer delayed mortality as well.

Post-release mortality can be assessed via a variety of tagging methods, including via accelerometers or PSATs. Each have distinct benefits and limitations, including cost, ease of attachment and detail of returned data. Ideally, a minimum of 10-20 individuals (or more) is needed to obtain robust estimates of post-release mortality, although even a few tags would provide other valuable information. Depending on catch rates of sawfish or the target species within the EGPMF, it could take several years to achieve robust samples sizes, however, sampling could also be supplemented with captures from the Pilbara Fish Trawl which tends to catch greater numbers of sawfish, or with other species of interest that are more commonly caught. Post-release mortality rates of recreationally caught elasmobranchs would also be extremely beneficial in determining fishing pressures of Exmouth Gulf populations. In general, very little is known about post-release mortality rates of sharks caught by recreational fishermen, especially beach fishers, compared to commercial captures.

Funding: Time costs would depend on whether fishers are attaching tags themselves, or whether the target is recreational vs commercial captures, etc. Tagging costs would run at about $2500 per single-use tag for PSATs, or ~$1000 for a reuseable tag for accelerometers, plus boat time for tag recovery.

Species ID guides [$150,000]

At present, there are no publicly available comprehensive shark or ray guides for the Exmouth region. Creating ID guides based on local information of what species are present in the region and their local habitat use and other parameters would be extremely beneficial for future research and management in the region. Region-specific guides also have the potential to increase local knowledge and excitement about elasmobranchs, and to help fishers and other ocean users correctly identify and report threatened species. Estimated costs to create detailed, accurate, region-specific guides for sharks and rays are approximated at $150,000 to cover creation time for the guides, editing, marketing, and distribution.

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