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# The feasibility of using remotely piloted aircraft systems (RPAS) for recreational fishing surveys in Western Australia

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# Abbreviations

| | |
|---|---|
| AGL | Above ground level |
| BVLOS | Beyond visual line of sight |
| DPIRD | Department of Primary Industries and Regional Development |
| EVLOS | Extended visual line of sight |
| IMU | Inertial measurement unit |
| IP | Ingress protection |
| LOA | Length overall |
| MSC | Marine Stewardship Council |
| ReOC | Remote Operators Certificate |
| RePL | Remote Pilot’s Licence |
| RFIF | Recreational Fishing Initiatives Fund |
| RGB | Red/green/blue i.e. full-colour |
| RPAS | Remotely piloted aircraft system |
| SEM | Standard error of the mean |
| UAV | Unmanned aerial vehicle |
| VLOS | Visual line of sight |
| VTOL | Vertical take-off and landing |

# Executive Summary

Accurate data on recreational fishing activity are required for the sustainable management of many fisheries resources in Western Australia. As such, recreational fishing surveys play a crucial role in providing estimates of participation, fishing effort and recreational catches. A key part of designing recreational fishing surveys involves the selection of the most suitable survey design and data collection tool to match the desired management objective. Recreational fishing surveys should also incorporate probability-based survey designs to enable data collected from a random sample to be expanded to the whole population.

Across Western Australia, a variety of innovative data collection tools have been successfully incorporated into recreational fishing surveys by the Department of Primary Industries and Regional Development (DPIRD), including remote camera networks with access point creel surveys, thermographic cameras to monitor fishing effort, and laser technology in roving creel surveys. The rapid increase in the use of remotely piloted aircraft systems (RPAS), colloquially known as drones, has afforded researchers a potentially innovative tool for collecting recreational fishing data; however, no study to date has evaluated the suitability of this data collection tool within the context of a recreational fishery.

The main objective of this study was to trial RPAS as a data collection tool to monitor recreational fishing effort in Freycinet Estuary (inner Shark Bay) and Peel-Harvey Estuary. The former fishery has a broad geographic scale in a remote location, while the latter fishery has a smaller geographic scale close to major metropolitan centres, but has a substantial nocturnal component. Collectively, these characteristics enable the utility of RPAS to be examined for a wide range of recreational fishing surveys. In each fishery, RPAS were used to assess the spatial extent of recreational fishing activity and were operated concurrently with conventional recreational fishing surveys, thereby enabling comparisons of the strengths and limitations between the methods. A desired outcome of this study was to assist DPIRD in considering the utility of RPAS for future recreational fishing surveys in addition to documenting some aspects that need to be considered before applying these systems to fisheries research. The Freycinet Estuary component of this publication is one of two reports that highlight the research outcomes of the project "Innovative methods for monitoring recreational fishing in Shark Bay," funded by the Recreational Fishing Initiatives Fund (RFIF).

A DJI Matrice 210 and a DJI Phantom 4 Pro, both multi-rotor RPAS, were used to capture footage of recreational fishing activity along the foreshore of both the Freycinet and Peel-Harvey estuaries. In the Freycinet Estuary, footage was captured over 36 flights on seven days at Tamala and Carrarang Stations in May and July 2018, while footage was captured over 39 flights on six days between January 2018 and February 2019 within the Peel-Harvey Estuary.

The use of these multi-rotor RPAS as a data collection tool had specific strengths and limitations in terms of meeting the objectives of each survey; however, there were benefits and limitations that were common in both situations. Benefits included: access to otherwise out-of-scope areas, high quality recorded footage, the ability to use waypoints to fly reproducible routes, the potential to use the in-built GPS to geo-reference fishing activity and improved

efficiency when moving between some survey areas. Limitations were primarily: the requirement to maintain visual line of sight (VLOS), battery life, weather-related constraints, connectivity issues when flying from a moving platform, reduced efficiency in data collection, no capability to collect catch data, certification requirements and other logistical considerations.

Based on the outcomes of the present study, RPAS are not currently a viable data collection tool that can be cost-effectively incorporated into DPIRD recreational fishing surveys that utilise probability-based survey designs. Additionally, the current legislative requirement to maintain visual line of sight while operating an RPAS means this data collection tool is not suitable for broad-scale applications at which many recreational fisheries operate. The ability to employ extended-visual line of sight (EVLOS), along with fixed-wing RPAS that have larger battery capacity, would be alternatives that could overcome the limitations associated with VLOS requirements and battery life. However, limitations on the weather conditions, particularly wind, in which it could be operated would still impact the probability-based nature of the survey. The use of smaller RPAS, that do not require the same level of certification as larger RPAS, would potentially be suitable for i) recording fishing effort under some small-scale applications (e.g. counts of abalone/shore-based fishers at distinct beaches), or ii) under scenarios where probability-based designs are less of a priority. There would certainly be uses in other areas of fisheries research, monitoring and compliance, in addition to current applications in primary industries.

# 1. Introduction

Recreational fishing is an important pastime in Western Australia, with an estimated 25.6% of the state's population fishing in 2018/19 (DPIRD, 2019) providing substantial economic benefits to the State (McLeod and Lindner, 2018). Determining levels of recreational fishing effort and catch is important for stock assessments, resource allocation and fisheries management, as recreational harvest can be larger than commercial harvest for some species.

Assessing the levels of recreational fishing effort and catch is complex due to the diffuse nature of many fisheries. Fishers can target many species from various platforms (e.g. shore-based, boat-based, charter), from both public (e.g. boat ramps) and private (e.g. canal estate) locations, 24 hours a day, 7 days a week. In contrast to commercial fisheries in Western Australia, there are no requirements for recreational fishers to report catches. Therefore, probability-based surveys play an integral role in collecting representative data from fishers that can be accurately expanded to the population total (Pollock *et al.*, 1994; Ryan *et al.*, 2016). These techniques are tailored to research or management objectives for each survey; however, in all cases, there are benefits and limitations associated with the methods chosen (reviewed in Pollock *et al.*, 1994).

Technological advances often introduce potential new tools for recreational fishing surveys; however, these tools must be adequately evaluated so that researchers can fully understand whether their perceived benefits can be realised and what potential biases will be introduced into the data being collected (Beckmann *et al.*, 2019). This is important because introducing additional bias into survey design, that cannot be accounted for, can result in inaccurate estimates that may not be suitable for sustainable management of fish resources.

The use of remotely piloted aircraft systems (RPAS), also known as unmanned aerial vehicles or drones, has burgeoned in primary industry (Grenzdörffer *et al.*, 2008; Zhang and Kovacs, 2012; Urbahs and Jonaite, 2013), ecological (Jones IV *et al.*, 2006; Anderson and Gaston, 2013; Christie *et al.*, 2016; Jiménez López and Mulero-Pázmány, 2019), and marine science (Hodgson *et al.*, 2013; Fiori *et al.*, 2017; Levy *et al.*, 2018) applications over the last decade. RPAS have also been used to enhance recreational fishing capabilities (Kopaska, 2014; Molloy, 2016), for example, allowing shore-based fishers to dramatically increase the distance from shore that they can fish. Identified benefits include high resolution mapping, the ability to capture footage beyond the visible spectrum, non-invasive survey techniques for marine fauna, improved cost-efficiency over existing techniques, highly replicable flight routes, and improving access to remote or inaccessible locations. However, there are also several limitations including range, logistical considerations when operating over water, regulatory requirements, and battery life.

As the technology improves and costs decrease, RPAS are being considered for assessing spatial and temporal fishing effort; however, no published study to date has used RPAS to collect recreational fishing information. To address this knowledge gap, in 2018/19 the use of RPAS as a data collection method was trialled in two contrasting recreational fisheries: Freycinet Estuary pink snapper fishery and Peel-Harvey Estuary blue-swimmer crab scoop-net fishery. These fisheries were chosen because other on-site recreational fishing survey methods were being used at the same time enabling a direct comparison to be made between RPAS and other more established survey methods.

# 2. Objectives

This publication is one of two reports that highlight the research outcomes of the project "Innovative methods for monitoring recreational fishing in Shark Bay", funded by the Recreational Fishing Initiatives Fund (RFIF Project # 2017/07). The corresponding report is entitled "Integrated survey of boat-based recreational fishing in inner Shark Bay 2018/19" (Taylor *et al.*, 2019).

The aim of this study was to make recommendations for the applicability of RPAS in future recreational fishing surveys and monitoring applications. In order to make recommendations, the overall objectives of this study were to:

i) assess the effectiveness (i.e. ability to collect appropriate data) of RPAS in capturing recreational fishing data in two recreational fisheries, differing in spatial and temporal scales of activity. This was assessed against how well it met the research objectives for each survey (see section 2.1).

ii) assess the efficiency (i.e. benefits and limitations) of using RPAS compared to existing survey methods for each fishery (see section 5).

## 2.1 Freycinet Estuary considerations

Recreational fishing surveys have been conducted in inner Shark Bay since 1998 to provide accurate catch estimates for pink snapper, more recently for Freycinet Estuary in particular (Taylor *et al.*, 2018a). For this area, there is also a need to monitor recreational fishing effort levels to assist in interpreting whether or not activity levels have changed in response to the removal of harvest tags in 2016 (Taylor *et al.*, 2019). Therefore, the following objectives (detailed in Taylor *et al.*, 2019), relevant to the use of RPAS, were to:

i) estimate recreational fishing effort and the spatial distribution of boat- and shore-based fishers in Freycinet Estuary;

ii) establish the most cost-effective and robust method of data collection and analysis for subsequent recreational fishing surveys in Shark Bay.

Preliminary research into the use of RPAS suggested that it would be impractical to fly the entire Freycinet Estuary due to the size of the estuary (site description in section 3.1.1) and the battery life of readily available "off-the-shelf" RPAS. Instead, to address Objective 2.1(i), an RPAS was operated around the shoreline of pastoral stations in Freycinet Estuary in an attempt to determine whether the system would provide an effective and efficient method for identifying camps and people along the shoreline. Aerial surveys using manned fixed-wing aircraft were used to estimate boat-based recreational fishing effort (refer to Taylor *et al.*, 2019) as well as providing counts of camps and people along the shoreline in Freycinet Estuary over the same time period. This report provides a comparison of the two data collection methods (fixed-wing aircraft, multi-rotor RPAS) for shore-based activity in Freycinet Estuary.

## 2.2 Peel-Harvey Estuary considerations

Recent on-site surveys in Peel-Harvey Estuary have been designed to identify areas of high-, medium- and low-intensity recreational scoop-net fishing for blue-swimmer crabs, to address a Marine Stewardship Council (MSC) condition relating to the impacts of recreational scoop-net fishing on habitat and wading birds (Morison *et al.*, 2016, Condition 7). Between March 2018 and April 2019, a modified roving survey was conducted in Peel-Harvey Estuary that enabled the location of recreational scoop-net fishers to be geo-referenced; however, several areas were designated as out-of-scope for the roving survey because it was not possible for staff to access the entire estuary foreshore by car. It was assumed these would be areas with low-activity fishing activity due to their inaccessibility by road for fishers. The relatively small geographic scale of the Peel-Harvey Estuary in comparison to Freycinet Estuary, and the ability to get a boat close to most of the coastline facilitated trialling an RPAS to survey the entire estuary to:

i) determine whether fishers could be observed in the RPAS footage at both night and day; and

ii) assess the assumptions that out-of-scope areas for the shore-based roving survey were low-activity areas.

# 3. Methods

## 3.1 Site description and fishery overview

### 3.1.1 Freycinet Estuary

Freycinet Estuary is a shallow gulf within the semi-enclosed embayment of the Shark Bay Marine Park, approximately 650 km north of Perth in Western Australia covering an area of approx. 1500 $km^2$. It is bounded by Nanga Station to the east, Tamala Station to the south and Carrarang Station to the west (**Figure 1**) which operate as tourist campsites, allowing paying members of the public to camp along the foreshore and access the estuary with towed vessels (Smallwood and Gaughan, 2013). Rubble around limestone islands and a wide variety of seagrass and algal species in close proximity to each other provide habitat for fish and invertebrate species that differ from the rest of Shark Bay (Francesconi and Clayton, 1996). The diversity of marine environments, and associated flora and fauna, resulted in Shark Bay being World Heritage listed in 1991 and National Heritage listed in 2007.

There has been a long history of recreational fishing in Shark Bay with most of the effort targeting pink snapper (*Chrysophrys auratus*: Wise *et al.*, 2012). There are three distinct pink snapper stocks occurring in inner Shark Bay, with each managed to a separate Total Allowable Recreational Catch (TARC): Denham Sound, Eastern Gulf and Freycinet Estuary (**Figure 1**: Johnson *et al.*, 1986; Jackson *et al.*, 2007). There has likewise been a long history of management intervention to recover pink snapper stocks after over-exploitation in the mid-1990s and, due to the discrete populations, different management practices have been applied in Freycinet Estuary compared to Denham Sound and the Eastern Gulf (Jackson and Moran, 2012). The most recent of these changes included the cessation of the harvest tag system in 2016, removing the limit on the number of fish that could be taken in any year. Additional monitoring of recreational catches was therefore required to evaluate whether the specific management arrangements in the inner gulfs were meeting the objective of managing pink snapper catches within the respective TARC, with a particular emphasis on Freycinet Estuary. This was undertaken using a complemented fixed-wing aircraft and boat ramp survey to estimate boat-based recreational fishing effort, along with providing counts of camps and people along the shoreline in Freycinet Estuary, between March 2018 and February 2019 (Taylor *et al.*, 2019). Methodology for the fixed-wing aerial survey is detailed in Appendix 1.

### 3.1.2 Peel-Harvey Estuary

Peel-Harvey Estuary is located approximately 75 km south of Perth, directly adjacent to the City of Mandurah, Western Australia (Figure 2). The estuary covers an approximate area of 136 $km^2$ containing two interconnected lagoons: Peel Inlet (75 $km^2$) and Harvey Estuary (61 $km^2$). Peel Inlet is roughly circular and approximately 10 km in diameter while Harvey Estuary is long and narrow, approximately 20 km long and 2 to 3 km wide (Brearley, 2005). The interconnected basins have a similar mean depth (0.8 m Peel Inlet; 1.0 m Harvey Estuary) with a maximum depth of 2.5 m in each basin (Rogers *et al.*, 2010). The estuary receives water from three tributaries (Serpentine River, Murray River, and Harvey River), and connects to the Indian Ocean through a natural channel (Mandurah Channel) in Peel Inlet and a man-made channel (Dawesville Channel) in Harvey Estuary. The estuary was Ramsar-listed under the International Convention on Wetlands in 1990 (PHCC, 2009).

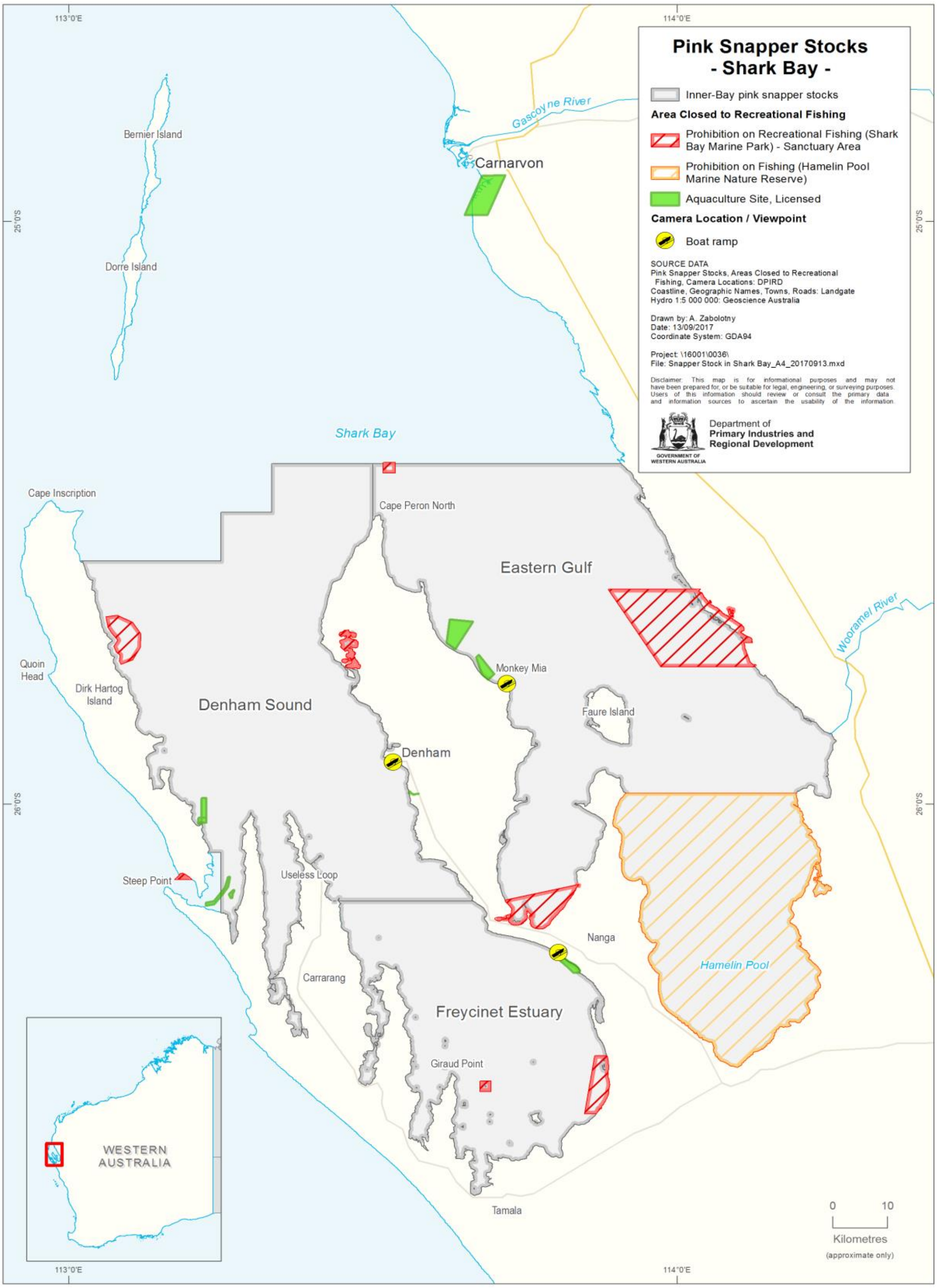


**Figure 1** Map of the Shark Bay region showing the three management zones for separate pink snapper (*Chrysophrys auratus*) stocks. The RPAS were used in the southern part of Freycinet Estuary.


**Figure 2** Map of Peel-Harvey Estuary showing tributaries, inlets and the areas with a depth less than, or equal to, 0.8 m. The RPAS flights covered the majority of these depths.

The estuary supports the largest recreational fishery for blue-swimmer crab (*Portunus armatus*) in the state, and the ease of access and shallow water make it a popular location for scoop-net fishing. In 2016 the Peel-Harvey Estuary blue-swimmer crab and sea mullet (*Mugil cephalus*) fisheries were the first joint commercial-recreational fisheries to be independently assessed as sustainable by the MSC. As part of ongoing accreditation, Condition 7 of the assessment required evidence that the recreational scoop-net sector was “highly unlikely to reduce habitat structure and function to a point where there would be serious or irreversible harm”, particularly in relation to the overlap with habitat for listed threatened bird species (Morison *et al.*, 2016, Table A1.3). A modified roving survey was implemented to collect data on recreational scoop-netting activity (survey details in Appendix 3); however, there were several out-of-scope areas that the survey staff could not access due to inaccessibility by car.

## 3.2 Survey stratification

### 3.2.1 Freycinet Estuary

The Freycinet Estuary survey used a combination of probability-based on-site (access point survey; aerial survey) techniques to assess catch and effort over the entire waterbody between March 2018 and February 2019. As part of the fixed-wing aerial survey, boating activity and fishing camps were counted in real-time throughout the estuary between March and August 2018 (details in Taylor *et al.*, 2019). Twenty-eight days were randomly selected for flights, and were stratified by season (autumn [March to May], winter [June to August]) and day type (weekday, weekend/public holiday; Appendix 1).

In contrast, the RPAS was only used over two short deployments in May and July 2018, to compare its ability to collect data on fishing camps and shore-based fishing activity at Tamala and Carrarang Stations. These periods were selected to coincide with times of expected peak fishing activity during a fishing competition (17/5/18–24/5/18) and school holidays (30/6/18–15/7/18) and scheduled to maximise the data that could be compared to the fixed-wing aerial data. On two days, RPAS surveys were run concurrently with a scheduled fixed-wing survey.

### 3.2.2 Peel-Harvey Estuary

The Peel-Harvey Estuary survey modified traditional roving survey techniques (Pollock *et al.*, 1994) to assess the spatial and temporal distribution of recreational fishing effort to meet MSC audit requirements. A probability-based roving survey was conducted over 35 $km^2$ between March 2018 and April 2019. Sixty-eight days of sampling were scheduled over the 14-month period, stratified by fishing season (high [November to February], medium [March to May], low [June to August], closed [September to October]) and day-type (weekday, weekend/public holiday), with a survey day subset by region (north, east, west) and time of day (a.m., midday, p.m.; Appendix 3). Sampling probability was differently weighted for time of day and fishing season, as scoop-net fishing activity is traditionally higher during the summer months and during twilight periods (Taylor *et al.*, 2018b). Wading activity was recorded and geo-referenced from early morning (05:00) to late evening (23:00) with the use of a compass, laser rangefinder and thermal camera (Desfosses *et al.*, in prep.). Night-time activity is the period between nautical dusk and nautical dawn, as defined in Taylor *et al*. (2018b).

Due to budgetary constraints and the availability of an appropriately qualified pilot, the RPAS component was limited to the period of peak activity (i.e. high fishing season); however, RPAS surveys were scheduled at the same time of day, starting site and travel direction as the shore-based surveys to maintain direct comparison with the roving survey data. Two RPAS surveys were trialled prior to the start of the roving survey in March 2018, and four surveys were conducted during the high fishing season period for the roving survey (Appendix 3). These days were chosen based on the availability of the remote pilot, field staff and vessel for days when the roving on-site survey was also running. Both the roving and the RPAS surveys were limited to the main basins of the estuary: tributaries and entrance channels were excluded.

## 3.3 RPAS logistics

For clarity, RPAS will refer to the entire remotely piloted aircraft system, including the aircraft, batteries, cameras, remote control unit and flight software (**Figure 3**). The aircraft itself will be referred to as 'the drone'.

### 3.3.1 Permits: licences and approvals

The RPAS operations were conducted in accordance with the Civil Aviation Safety Authority (CASA) regulations and standard operating procedures regarding the operation of an included remotely piloted aircraft (CASA, 2018). The pilot was certified with a remote pilot's licence (RePL) and operations were covered under the remote operator's certificate (ReOC) held by Interspacial Aviation Services Pty Ltd. In order to obtain lawful authority to fly over land managed by the Parks and Wildlife Service, all flights were approved under the 'Application to Fly a Remotely Piloted Aircraft (RPA/Drone)' permit. The RPAS was operated from a vessel, therefore no council or shire approvals were required for operations from crown land. Land-owner approval was obtained before conducting operations from privately-owned land.

### 3.3.2 Hardware and Software

A DJI Matrice 210® (hereafter called the "Matrice"), with dual downward-facing gimbals and TB-50 batteries, was used for most flights (Figure 3a); however, when required, a backup RPAS (DJI Phantom 4 Pro®; hereafter called the "Phantom") was used that provided longer flight time (25-30 minutes) per battery, but only one sensor (Figure 3b). The Matrice operated with Zenmuse X4S (4K colour) and Zenmuse XT (thermal) sensors simultaneously, and thus, was suitable for both day and night operations. In contrast, the Phantom was limited to daylight operations as it only had a standard colour (RGB) sensor. Video footage was recorded directly to an internal SD card in high-resolution video.

Manual flight operations (including thermal) with the Matrice used the DJI Pilot flight control software, which was installed on a DJI CrystalSky monitor (Android) supplied with the RPAS. Pre-programmed flight operations with the Matrice were created and flown using the DJI Ground Station Pro flight control software, installed on an Apple iPad Air (iOS). Manual flight operations of the Phantom were undertaken using the DJI GO 4 flight control software, installed and run on an Apple iPad Air (iOS). The configuration and specifications for each RPAS component are outlined in Appendix 5.


**Figure 3** Remotely Piloted Aircraft Systems for a) the DJI Matrice 210, and b) the DJI Phantom 4 Pro. The Matrice 210 shows the aircraft with the XT (left) and X4S (right) lenses mounted on dual downward-facing gimbals, four pairs of TB-50 batteries in two sets of Inspire 2 (IN2CH) charging hubs, a VHF radio, and the Cendence (GL800A) remote controller. The Phantom 4 Pro shows the aircraft with three PH4-5870 batteries in the Phantom 4 charging hub, and the remote controller with an Apple iPad Air for the screen.

### 3.3.3 Flight operations

Before all operations, as part of flight planning approval, the remote pilot performed all required notifications for RPAS operation within each survey area. This involved communication of proposed flight activities with the manned survey flights scheduled within the Freycinet Estuary to ensure operational awareness and to maintain separation at all times during flights. Communication with operational aircraft during RPAS flights was achieved via VHF radio using the appropriate radio frequency for each area (i.e. 126.7 MHz for Freycinet Estuary, 119.1 MHz for Peel Inlet, 120.3 MHz for Harvey Estuary).

The drone was launched and retrieved from the aft deck of the Department of Primary Industries and Regional Development (DPIRD) Regional Services vessels: the *P.V* Edwards (13 m LOA) at the Freycinet Estuary, and the *P.V* Armatus (11.3 m LOA) at the Peel-Harvey Estuary (Appendix 6). Visual line of sight (VLOS) was maintained by tracking the drone with the vessel as it traversed the coast.

For both surveys, the drone flew parallel to the coast at an average altitude of 40 m (range: 15–50 m depending on wind conditions) above ground level (AGL) and an approximate speed of 10 m $s^{-1}$. At Freycinet Estuary, the flights covered the coastline and nearshore areas within 250 m of the coastline. At Peel-Harvey Estuary, the flights were carried out from 100–800 m from the coastline to capture wading activity up to 0.8 m depth. Day-time flight transects in Freycinet Estuary were performed using pre-programmed waypoints, allowing a replicable flight path to be flown between survey days and facilitating comparison between survey periods. At the time that the RPAS surveys were conducted, pre-programmed flight using waypoints was not possible when using the thermal sensor, due to unavailability of the appropriate software from the manufacturer; therefore, all Peel-Harvey Estuary flight transects and evening Freycinet Estuary transects were manually controlled. A random starting location and direction of travel was chosen on each day to reduce bias that can be introduced by starting at the same location and following the same route each day.

Occasionally, flights were cancelled before the end of the scheduled survey due to weather conditions (i.e. wind, rain) that were not conducive to operating the RPAS. There were also delays in the schedule due to initialisation problems on start-up and connectivity issues between the drone and the flight software. Therefore, not all locations in the relevant on-site survey were surveyed in each RPAS survey.

### 3.3.4 Data collection

Footage was recorded from the time the drone was launched until it was retrieved. During most daylight flights, only the RGB sensor was used to maximise battery life, and therefore, flight time. The thermal sensor was used during twilight and night-time operations.

For the Freycinet Estuary survey, the data of interest were camps and people along the shoreline. These were recorded from the footage after the fieldwork had finished, following the same classification used in the concurrent fixed-wing survey (Taylor *et al.*, 2019). For the Peel-Harvey Estuary survey, the data of interest were people below the high-water mark. All wading activity was recorded and classified according to the same categories used in the roving on-site survey (Desfosses *et al*., in prep.). For both surveys, all data were able to be geo-referenced, i.e. assigned a latitude and longitude, based on the GPS co-ordinates of the drone cross-referenced with landmarks and features from satellite images.

# 4. Results

## 4.1 Freycinet Estuary

Thirty-six valid RPAS flights were conducted over seven days between the two survey periods (Table 1): 17 flights over three days in May and 20 flights over four days in July. The average (± standard error of the mean: SEM) survey duration (i.e. excluding travelling/flying to and from the survey site) was 48.8 (± 10.5) minutes per day and 9.5 (± 0.6) minutes per flight, while the average distance surveyed was approximately 26.1 (± 3.9) km per day and 5.1 (± 0.3) km per flight (Table 1). The approximate average area surveyed was 5.5 (± 1.7) $km^2$ per day and 1.0 (± 0.1) $km^2$ per flight.

In comparison, the fixed-wing survey included 28 valid flights over a 6-month survey period: one flight per day (Table 1). The average survey duration and distance surveyed was 113.7 (± 6.3) minutes and approximately 338.4 (± 5.4) km per flight, respectively. This covered the whole area of the Freycinet Estuary.

**Table 1** Comparison of flight statistics and data summaries between the fixed-wing aerial survey at Tamala and Carrarang Stations, and the RPAS aerial survey over the same area. Standard error of the mean is presented in round parentheses. Observed camps and shore-based activity for the whole survey area (i.e. including Nanga Station) are presented in square parentheses.

| | Fixed-wing [a] | RPAS [b] | |
|---|---|---|---|
| | Average per day/flight | Average per day | Average per flight |
| Number of flights | 1 | 5.1 (1.6) | - |
| Flight altitude (m) | 300 | - | 50 |
| Flight speed ($m\ s^{-1}$) | 55.5 | - | 10 |
| Total flight duration (mins) | 150.6 (7.0) | 68.9 (13.8) | 13.4 (0.6) |
| Survey flight duration (mins) | 113.7 (6.3) | 48.8 (10.5) | 9.5 (0.5) |
| Distance surveyed (km) | 338.4 (5.4) [c] | 26.1 (3.9) | 5.1 (0.3) |
| Area surveyed ($km^2$) | ≈1500 | 5.5 (1.7) | 1.0 (0.1) |
| Observed camps | 33.2 (4.3) [33.6 (4.1)] | 29.9 (6.8) | 5.8 (0.9) |
| Observed shore activity | 1.9 (0.8) [6.4 (2.2)] | 6.0 (2.0) | 1.1 (0.4) |

[a] summaries exclude 1 invalid flight which was rescheduled.
[b] summaries exclude 8 invalid flights.
[c] n = 13 for the fixed-wing survey due to incomplete track records from the fixed-wing aircraft.

On average, comparable numbers of camps were observed per day from both the fixed-wing (33.2 ± 4.3) and RPAS (29.9 ± 6.8; Table 1) surveys; however, the statistics for the fixed-wing survey encompass the whole area available to be flown by the RPAS survey (i.e. shoreline areas within Tamala and Carrarang Stations), which the RPAS could not cover in a single day. In contrast, on average the RPAS survey observed more shore-based fishing activity per day (6.0 ± 2.0) than the fixed-wing survey (1.9 ± 0.8).

The higher number of camps observed from the RPAS compared with the aerial surveys was also evident when directly comparing the recorded activity where both methods were surveyed at the same sites and dates (Table 2). The number of camps observed between the two methods was consistent on both days, but the observed shore-based activity is higher for the RPAS method compared to the fixed-wing aerial survey. While these summaries cover the same locations for the dates when the surveys were conducted simultaneously, it should be noted that the surveys were not always conducted at the same time in the same place due to the difference in speed between the survey methods. This could be one explanation for the difference in shore-based activity compared to camp observations. That is, shore-based activity can be dynamic and people are more likely to have moved in the time between the two aircraft passing overhead than camps being set up or packed away. Other explanations could be that inconspicuous activity may have been missed from the fixed-wing aerial survey either due to boating activity being the priority data to be collected or observer inattention (discussed in section 5.1.3).

**Table 2** Comparison of flight statistics and data summaries for campsites and shore-based fishing activity on dates when the RPAS and fixed-wing aerial surveys were conducted on the same day. Observations for the fixed-wing survey are limited to the same areas covered by the RPAS survey

| | 21/5/2018 | | 13/7/2018 | |
|---|---|---|---|---|
| | Aerial | RPAS [a] | Aerial | RPAS [b] |
| Survey flight duration (mins) | 106.5 | 15.0 | 120.2 | 32.2 |
| Total distance surveyed (km) | 333 | 8.2 | 338.4 [c] | 16.4 |
| Total area surveyed ($km^2$) | ≈1500 | 1.1 | ≈1500 | 2.8 |
| Observed camps | 13 | 11 | 23 | 23 |
| Observed shore activity | 0 | 4 | 0 | 1 |

[a] two valid flights for the day

[b] three valid flights for the day

[c] based on the average from 13 flights with recorded GPS tracks

## 4.2 Peel-Harvey Estuary

Thirty-nine valid RPAS flights were conducted over six days (): two days before the shore-based roving survey began, and four days in conjunction with the roving survey (**Error! Reference source not found.**). On average (± SEM), 6.5 (± 0.8) flights were carried out per day, with an average survey duration (i.e. excluding travelling/flying to and from survey sites) of 8.5 (± 0.6) minutes per flight or 55.4 (± 12.8) minutes per day. The average shoreline distance surveyed was approximately 6.0 (± 0.4) km per flight or 38.8 (± 9.3) km per day and the average area surveyed was 3.0 (± 0.3) $km^2$ per flight or 19.3 (± 5.0) $km^2$ per day ().

In comparison, for the high fishing season, between November 2018 and February 2019, 40 shifts were conducted as part of the shore-based roving survey. Since one shift was carried out on each scheduled day, the summary statistics per survey and per day are the same (). The average surveyed shoreline distance was 27.5 (± 0.2) km per day with an average surveyed area of 23.5 (± 0.7) $km^2$ per day.

Therefore, on average, the RPAS survey covered a greater shoreline distance per day while covering a similar, though slightly smaller, area to the shore-based roving survey (). This was due to shore-based survey covering an area up to one kilometre from their location on the shoreline, whereas the RPAS survey generally covered a smaller area (200 to 300 m) that was more aligned to the 0.8 m depth contour. Overlapping standard errors show that the average values for the number of people observed wading (43.2 ± 8.1; 45.3 ± 14.9) and scooping (37.2 ± 7.5; 30.0 ± 12.0) are comparable between the roving and RPAS surveys, respectively.

When considering only the surveys that had a night-time component, there were 14 days surveyed in the high fishing season for the shore-based roving survey compared to 1 day for the RPAS survey. The RPAS survey covered less shoreline distance and area surveyed (18.6 km; 18.0 $km^2$, Table 4) than the average roving survey (27.5 ± 0.2 km; 23.5 ± 0.7 $km^2$). Although the fishery has a substantial night-time component to the scooping activity, the single RPAS flight was only able to be scheduled for an evening that did not fully capture this, recording substantially less wading and scooping activity (wading: 20; scooping: 20) than the average roving survey (wading: 48.9 ± 19.0; scooping: 45.9 ± 17.7, Table 3).

**Table 3** Comparison of statistics and data summaries between the shore-based roving survey during the high season (Nov 2018 to Feb 2019) and the RPAS aerial survey. Standard error of the mean is presented in parentheses.

| | Roving [a] | RPAS [b] | |
|---|---|---|---|
| | Average per day/survey | Average per day | Average per flight |
| Number of flights | | 6.5 (0.8) | |
| Total duration (incl. travel) (mins) | 353.1 (0.7) | 255.2 (30.3) | |
| Survey (at site) duration (mins) | - | 55.4 (12.8) | 8.5 (0.6) |
| Shoreline surveyed (km) | 27.6 (0.1) | 38.8 (9.3) | 6.0 (0.4) |
| Area surveyed ($km^2$) | 23.5 (0.4) | 19.3 (5.0) | 3.0 (0.3) |
| Total wading observed (people) | 43.2 (8.1) | 45.3 (14.9) | 7.0 (1.4) |
| Total scooping observed (people) | 37.2 (7.5) | 30.0 (12.0) | 4.6 (1.1) |
| Night-time wading observed (people) [c] | 48.9 (19.0) [d] | 20 [e] | 20 [e] |
| Night-time scooping observed (people) [c] | 45.9 (17.7) [d] | 20 [e] | 20 [e] |

[a] summaries exclude 1 day where the survey was not completed and not rescheduled.
[b] summaries exclude 3 invalid flights
[c] observations only from surveys with a night-time component.
[d] n = 14
[e] n = 1

When directly comparing the recorded activity at locations surveyed by both methods on the same dates (Table 4), the RPAS survey was able to include large areas that were out-of-scope for the roving survey. This led to more wading and scooping activity being recorded from the RPAS survey than the roving survey for each day, with 19.4% of the activity recorded from the RPAS survey occurring in out-of-scope areas for the shore-based roving survey. On the single day that both methods included a night-time component to the survey, the RPAS survey recorded almost seven-times more wading/scooping activity than the roving survey. There are several possible explanations for this discrepancy. Firstly, the equipment used in the roving on-site survey had a maximum reliable distance of 800 m. Some of the activity observed through the RPAS survey was further than 800 m from the shore, so these people may have been out-of-scope for the roving survey. Secondly, as with the Freycinet Estuary survey, the RPAS survey did not always collect data at the same sites at the same time as the shore-based roving survey due to differences in the time taken to travel between sites and some technical problems that occasionally delayed the RPAS survey. Due to the dynamic nature of the fishery, it is likely that people moved into and out of the survey area in the time between the two methods being carried out.

**Table 4** Comparison of statistics and data summaries between the shore-based roving and RPAS aerial survey methods where the surveys were conducted on the same day. Scooping activity is shown in parentheses.

| | 18/12/18 [a] | | 22/12/18 | | 1/2/19 | | 23/2/19 | |
|---|---|---|---|---|---|---|---|---|
| | Roving | RPAS | Roving | RPAS | Roving | RPAS | Roving | RPAS |
| Number of valid flights | - | 6 | - | 9 | - | 6 | - | 5 |
| Number of roving sites surveyed | 21 | 11 | 21 | 23 | 21 | 16 | 22 | 29 |
| Shoreline surveyed (km) | 26.4 | 18.6 | 26.4 | 46.4 | 28.2 | 31.1 | 28.1 | 38.5 |
| Total area surveyed (km$^2$) | 20.9 | 18.0 | 20.9 | 41.7 | 26.4 | 17.9 | 24.3 | 23.2 |
| Out-of-scope area surveyed (km$^2$) | - | 9.3 | - | 18.1 | - | 5.8 | - | 8.9 |
| Total wading observed | 6 (6) | 29 (29) | 43 (29) | 62 (31) | 18 (13) | 22 (7) | 48 (44) | 104 (84) |
| Wading observed in out-of-scope areas | - | 1 (1) | - | 16 (13) | - | 0 (0) | - | 25 (16) |
| Night-time survey duration (mins) [b] | 151.0 | 32.8 | - | - | - | - | - | - |
| Night-time activity observed [b] | 3 (3) | 20 (20) | - | - | - | - | - | - |

[a] summaries exclude 1 invalid flight

[b] Night-time defined as the time between nautical dusk and nautical dawn

# 5. Discussion

Aerial methods for recreational fishing surveys have traditionally used fixed-wing aircraft, that i) have the capacity to count vessels or fishers over large areas; ii) only collect fishing effort data; and iii) are relatively cost-effective considering the large areas over which data are to be collected (e.g. Smallwood and Gaughan, 2013). The use of multi-rotor RPAS for aerial recreational fishing surveys shows some potential; however, there are several challenges to overcome before they can be recommended for wider application in recreational fishing surveys in Western Australia. Each survey had benefits and limitations that were specific to the conditions experienced; however, there were several that were common to both.

## 5.1 Benefits

Overall, the benefits of the multi-rotor RPAS surveys were that they:

i) allowed previously out-of-scope locations to be included in the survey;

ii) provided high resolution footage at both day and night;

iii) improved the ability to observe imperceptible activity;

iv) had the ability to conduct replicable routes through the use of waypoints;

v) recorded GPS coordinates along the flight path that allowed fishing activity in the footage to be geo-referenced; and

vi) improved efficiency when moving between some survey sites.

### 5.1.1 Out-of-scope areas

Many on-site surveys have areas that are out-of-scope due to logistical constraints, and issues associated with inaccessibility or staff safety. The Peel-Harvey Estuary shore-based roving survey had areas out-of-scope due to the poor condition of tracks and lack of access through private property or crown land. While it was assumed that these were areas of low fishing activity due to their inaccessibility, this discounted the ability of fishers to access the sites by vessel, anchor up and leave the vessel to scoop for blue-swimmer crabs.

The use of the RPAS permitted access to the foreshore of these areas (Appendix 4), allowing us to validate the assumption that these were low activity areas. With the RPAS survey recording less than 20% of activity occurring in these areas that were out-of-scope to the roving on-site survey, the use of the RPAS was able to confirm our assumption that the out-of-scope areas were not high-activity areas.

### 5.1.2 High resolution footage

The footage obtained from both of the surveys was of very high resolution, especially during daylight hours (Figure 4). This facilitated accurate identification of camps and shore-based activity for the Freycinet Estuary survey, and wading activity for the Peel-Harvey Estuary survey.

While the footage taken with the thermal camera during twilight and night was of a lower resolution (640 x 512 pixels for thermal versus 4096 x 2160 pixels for 4K RGB), the image resolution for footage recorded at 40–50 m AGL was sufficient to differentiate and count individual people in the water. However, determining actual activity from thermal footage (or distant RGB footage) was more difficult because it was not always possible to distinguish the gear being used or determine the fisher behaviour (discussed in section 5.2.8). This reduced resolution is due to the lower pixel resolution available in the thermal sensor, and can be improved by flying at a lower altitude during night flights. However, lower flights have the potential to impact on wildlife (e.g. water bird foraging/nesting), change fisher behaviour, and increase the risk of infringing the safe operating distance that must be maintained when operating RPAS around members of the public.

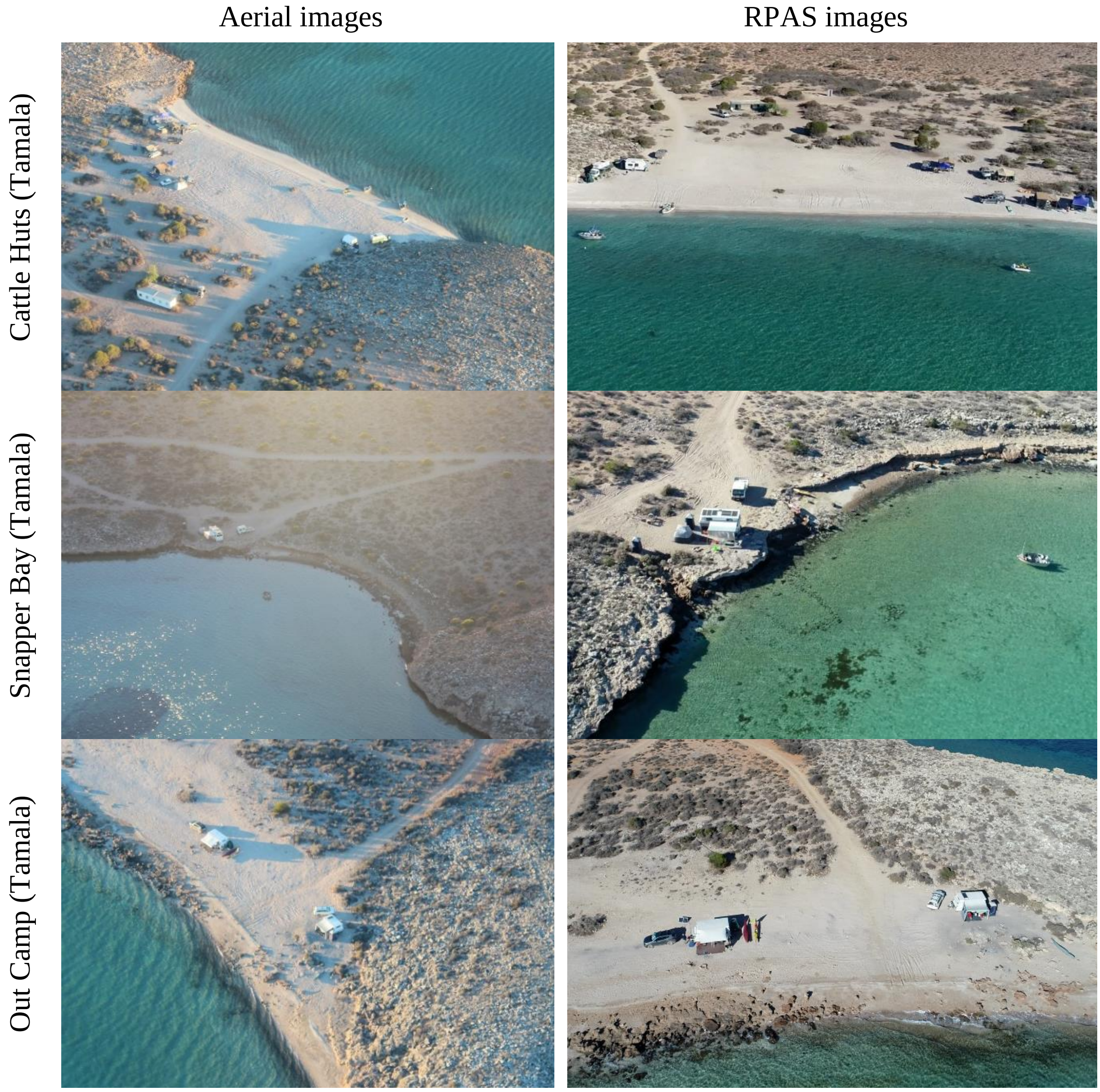


**Figure 4** Comparison of images recorded for the same day (21/5/2018) at three sites in the Freycinet Estuary. Images on the left were recorded from the aerial survey while images on the right were recorded from the RPAS survey.

While it is technically possible to gimbal-mount an image stabilised camera externally on a manned fixed-wing aircraft, a CASA-authorised person must approve the installation as outlined in Australia's Civil Aviation Safety Regulations: Subpart 21.M (CASR, 1998). This was not an option for the third party that carried out the fixed-wing surveys at Freycinet Estuary, so images and footage were recorded from within the aircraft. Since they were not image stabilised to reduce blurring as a result of the motion of the aircraft, the images were harder to interpret and not as defined as those from the RPAS (0).

### 5.1.3 Ability to observe imperceptible activity

Aerial surveys are often used to determine fishing effort over large areas; however, they can be prone to misidentifying or overlooking fishers (discussed in section 5.2.8) due to variations in airplane height or speed, observer fatigue, fisher behaviour, weather conditions, cloud cover, or turbulence affecting video quality (Cook and Jacobson, 1979; Pollock *et al.*, 1994). The primary objective of the aerial survey was to record boat activity to enable subsequent estimation of boat-based fishing effort, with a secondary objective to record camp and shore-based activity. Therefore, only one observer was used in the fixed-wing aircraft; whereas two observers would have been used if shore- and boat-based activity were equally prioritised. While footage was recorded from within the fixed-wing aircraft to prevent missed observations at high activity sites, the footage was blurry and jittery due to the lack of image stabilisation or a gimbal mounted external camera, making observations of people on the shoreline difficult. Even so, having high-quality footage recorded from the RPAS survey was beneficial compared to the direct observations made, or the footage recorded, from inside the fixed-wing aircraft during the Freycinet Estuary survey (0).

While analysing footage requires an extra step in data collection, it improved counts of fishing activity that may have been missed in the aerial survey due to the quality of the footage/images, sightability errors or visibility bias that can be introduced in counts from manned aircraft (reviewed in Colefax *et al.*, 2018). The ability to replay footage when the vision is blurred or there is a fleeting view of fishing activity permits the reader to capture fishing activity that might have been missed at times when an observer is recording activity in real time. This is demonstrated for the Freycinet Estuary survey, where the RPAS survey captured as much shore-based activity in 7 survey days as the fixed-wing aerial survey captured in 28 survey days (Table 1). Having the recorded footage also permits validation of the data by multiple observers or third parties. While the primary applications for RPAS in Colefax *et al*. (2018) relate to marine fauna, it could also apply to fishers in camps or along shorelines, where activity may not always be obvious to an observer in a fixed-wing aircraft.

### 5.1.4 Replicability

The ability to use pre-programmed waypoint flight to produce a replicable route was a substantial advantage in using RPAS to survey the shorelines. In theory, with a replicable route the time at each site and the time spent travelling between sites is consistent, and the camera angle and field of view can be maintained so footage is consistent across survey days. This makes the method more comparable to traditional recreational fishing survey methods, such as the aerial and roving on-site surveys. Replicable footage potentially reduces inconsistencies in analysing the footage, by reducing perception bias and interpretation inconsistencies between staff doing the analysis (discussed in section 5.2.8). However, this was not always possible in reality, as maintaining a consistent camera angle and field of view between repeat transects was not possible due to issues with light refraction from the angle of the sun relative to the sensor on the drone at different times of the day (discussed in section 5.2.9).

### 5.1.5 Geo-referencing

The use of RPAS enabled all observed fishing activity to be geo-referenced within the survey area. While the camera was not at nadir (i.e. downward-facing), the GPS coordinates of the drone, in conjunction with the coordinates from landmarks on the shore, permitted staff analysing the footage to geo-reference fishing activity in both surveys. This was particularly important for the Peel-Harvey Estuary survey, where one of the primary objectives of the shore-based roving survey was to determine the spatial distribution of fishing activity.

Being able to geo-reference fishers facilitated the determination of a footprint for fishing activity, with areas of high, medium and low density fishing able to be quantified. This could then be directly compared with areas anecdotally thought to be susceptible to recreational fishing pressure.

### 5.1.6 Efficiency

Both the Freycinet Estuary and Peel-Harvey Estuary surveys used a vessel to launch, retrieve and track the drone to maintain VLOS. Where the bathymetry was deep enough to allow the vessel to get close to the shoreline in each estuary, it was very efficient to travel from one site to another. This was not always possible with the Peel-Harvey Estuary shore-based survey, as road access does not generally follow the coast and requires travelling a considerable distance from a main road to access each site. This reduced travel time allowed the RPAS to cover more ground in a given timeframe than the Peel-Harvey Estuary shore-based roving survey. However, this efficiency was somewhat negated by the need to retrieve the drone periodically to change the batteries (discussed in section 5.2.3).

## 5.2 Limitations

The overall limitations of using multi-rotor RPAS for the surveys were:

i) number of staff required to operate from a vessel reduced the cost-effectiveness;

ii) operations were limited to VLOS;

iii) limited battery life;

iv) weather constraints on ability to fly;

v) connectivity issues when the pilot was operating from a moving platform;

vi) the method does not allow catch to be estimated;

vii) the certification and oversight required when planning flights;

viii) introduction of visibility, perception and assumption biases; and

ix) other logistical considerations.

### 5.2.1 Cost-effectiveness

Operating from a vessel required 3 to 4 people to collect the data: a skipper, deckhand, remote pilot, and handler (to launch and retrieve the drone). The use of a drone did not provide any extra data or time savings than could have been collected by two staff on a boat with binoculars, a compass and a laser range-finder. Additionally, during high-activity periods, the footage cannot be analysed in real time and must be analysed post-survey, adding extra costs to the survey. However, post-survey analysis could be eliminated if the data being collected by on-site staff were entered directly into an electronic database or there were machine learning algorithms to automatically record activity in the footage. This was not something that we had access to for these surveys.

### 5.2.2 Visual line of sight (VLOS)

Operating within VLOS essentially means that the drone must continually be visible to the operator without the use of optical aids (excluding corrective lenses) (CASA, 2018). Similar legal requirements are not unique to Australia and have been identified as a restriction to using RPAS in other jurisdictions (e.g. Watts *et al.*, 2012; Marris, 2013). In agriculture or forestry applications, the survey site is often privately-owned land, in a fixed location. In contrast, recreational fisheries applications involve flying in a public space over an often-unbounded area. This makes surveying with RPAS a more difficult prospect as the remote pilot can not necessarily operate from a single point and maintain VLOS with the drone. In these surveys, this was overcome through the use of a vessel from which to operate; however, in areas of shallow water (e.g. reef, sand banks, unchartered waters) this would not be as feasible.

In theory, this could be overcome by operating under extended visual line of sight (EVLOS) or beyond visual line of sight (BVLOS) conditions; however, obtaining approval for this type of operation is generally costly, logistically onerous, and not routinely permitted by CASA. In cases when it is permitted, there are logistical constraints that make EVLOS and BVLOS operations infeasible for ongoing routine surveys (CASA, 2018, sec. 5.2.1 & 5.2.2).

### 5.2.3 Battery life

The Matrice, with the camera and battery configuration employed (Appendix 5), had a maximum flying time of 20–22 minutes. However, with the remote pilot's standard operating procedure to return to base with at least 30% battery capacity remaining (CASA, 2018), this flying time was reduced to 16–18 minutes at best. At some sites where the bathymetry did not allow the vessel to get close to the shoreline (e.g. Austin Bay in the Peel-Harvey Estuary, south of Parrot Island in the Freycinet Estuary), the distance between the launch site and the survey site exceeded 0.5 nautical miles. In these instances, footage had to be taken at a distance from the survey site, or the distance consumed the majority of the battery capacity transiting to and from the survey site, leaving very little time to conduct a survey.

The use of dual gimbals underneath the drone decreased the battery life due to the increased current draw, payload and drag. Reducing the configuration to a single RGB lens during the day improved the battery life, with the added benefit of decreasing wind resistance. It was not possible to reduce the configuration at night, as the thermal sensor cannot be used on the Matrice in isolation; therefore, if recording thermal footage, the drone required both sensors to be fitted.

Battery capacity was the primary limiting factor in restricting the operational range and flight time of the drone to approximately 5–-6 linear km and 16–18 minutes. In the Freycinet Estuary survey, this limited the data collection to the immediate foreshore area, missing any boat-based fishing activity that occurred offshore. Whilst longer operational flight times can be achieved with different 'off-the-shelf' RPAS configurations, the best that can currently be expected from a multi-rotor drone is approximately 30–45 minutes. This could be improved markedly by utilising fixed-wing drones or hybrid/petrol-powered motors, where flight times increase to at least 45 minutes for cheaper systems or several hours for considerably more expensive commercial RPAS.

A secondary problem experienced with exhausting a set of batteries within 20 minutes was the speed at which they could be recharged (70–90 minutes to recharge a set of batteries from 30–100% capacity). On a vessel with limited 240V power sources, there were initially problems keeping batteries charged over the duration of a survey day. This was overcome by using five sets of batteries and two sets of the DJI battery chargers, so several sets of batteries could be charged at once.

Many of the fixed-wing RPAS need a large area for launching and retrieving, making them unsuitable for boat-based applications (Joyce *et al.*, 2019). Using a vertical take-off and landing (VTOL) hybrid aircraft, such as the WingtraOne® (e.g. Clegeur and Hodgson, 2019), would overcome this issue; however, these aircraft are still limited in the wind conditions in which they can take-off, fly and land. This has implications for probability-based sampling designs, particularly in Western Australia where afternoon sea breezes occur along the south east coast during summer (discussed in section 5.2.4).

### 5.2.4 Weather

Weather had a huge impact on the ability of the RPAS to collect survey data. Rain, strong winds and lightning were conditions that restricted, or would have restricted, the use of RPAS for the surveys had they been forecast. While the Matrice has an ingress protection (IP) rating of IP43, the sensors and remote control unit have no IP rating and are not suitable for wet-weather operations. Atmospheric moisture can also severely compromise control uplink and video downlink data transfer due to interference with the relatively low power/high frequency radio communications systems typically employed in RPAS systems. The drone also has a maximum wind resistance rating of 12 m $s^{-1}$; therefore, wet weather and strong wind were the most significantly limiting factors in being able to operate the RPAS.

This has implications for the level of bias that could be introduced to the data as, anecdotally, many shore-based fishers target certain species during windy or stormy conditions (e.g. tailor [*Pomatomus saltatrix*], pink snapper). If the RPAS can only be used to survey recreational fishing activity during fine weather, fishing activity during windy/stormy weather will not be captured, potentially biasing the results.

### 5.2.5 Connectivity

Upon start-up, the drone undertakes multiple internal systems checks prior to activating, not least of which is the initialisation of the inertial measurement unit (IMU). The IMU is crucial to the correct operation and response of the drone during flight, and enables micro-scale adjustments and feedback to changes in the drone’s position and orientation. When the vessel was pitching or rolling, initialisation of the IMU was not possible due to the movement of the vessel interfering with the calibration of the IMU. The drone would not operate in these cases. We managed to mitigate this in moderate seas by slowly steaming with the wind which reduced the pitch and roll of the deck sufficiently to allow the IMU to initialise and operational flights to be performed. It is worth noting that forward movement of the vessel did not adversely affect the IMU initialisation process, so long as the deck was relatively level and steady (i.e. no discernible pitching or rolling).

Problems with the initialisation process were also experienced when the drone was located too close to large ferrous metal objects at start-up. This could be a problem on steel-hulled boats, or boats with large electro-magnetic coils (e.g. the winch on a pot-lifter). This presented issues in early trials of the RPAS but was overcome after moving the drone further away from the interfering objects.

### 5.2.6 Fishing catch

Many fisheries resources have a substantial recreational component to the catch (Cooke and Cowx, 2006; Ryan *et al.*, 2016); therefore, many recreational fishing surveys are designed to provide an estimate of the catch, both retained and released (Pollock *et al.*, 1994). All aerial surveys, both manned and remotely-piloted, provide survey data that can be used to estimate effort; however, these survey methods do not involve interviews with fishers, and therefore do not provide survey data that can be used to estimate catch rate (catch per unit effort), retained harvest, or number of fish released. These are important metrics to inform catch ranges against established tolerance ranges, or the need for management action. The number of released fish can also be an important when catch and release fishing is common, particularly for species with a high level of post-release mortality (e.g. through barotrauma or depredation), which increases fishing mortality.

Where catch data are required, other methods must also be employed. Conceptually, this would involve using the RPAS in a complemented survey, where on-site staff could interview anglers through a roving creel survey or an access point survey.

### 5.2.7 Certification

Under CASA regulation 101.237, operation under certain conditions permit an RPAS to be classified as an excluded RPAS, whereby operations can take place without certain licences and permissions (CASR, 1998). The surveys undertaken in this study predominantly utilised a drone that was heavier than 2 kg and involved night-time operations (outside of Standard Operating Conditions). Therefore, flights could not be operated as an excluded RPAS (0), the operator required a remote pilot’s licence (RePL), and operational flight missions required approval under a RPAS operator’s certificate (ReOC) (CASA, 2018, sec. 3.1.5).

For the purposes of these surveys, the certification of an external organisation (Interspacial Aviation Services Pty Ltd) was used during each operation. While this was suitable for the scope of these initial surveys, if RPAS were to be a regular tool used in recreational fishing surveys, it would be necessary to ensure a consistent and standardised approach to the approval of RPAS operations to maintain replicability between multiple surveys over the long-term.

### 5.2.8 Introduced bias

Several areas of bias were introduced to the survey data as a result of the limited range of flights or the level of detail in the footage. Visibility bias occurs when not all activities in the area are observed and is a recognised characteristic of recreational fishing manned aerial surveys (Pollock *et al.*, 1994). The limited range of the drone meant that only fishing activity along the coastline was in scope and documented, missing any boat-based fishing activity offshore. Perception bias is a component of visibility bias (Marsh and Sinclair, 1989) and occurs when subjects are visible to observers, but are not seen. For all data recorded around the Tamala and Carrarang shorelines, observed shore-based activity from the RPAS survey was more than 3-times greater than that observed from the fixed-wing aerial survey (Table 1). On one of the days when both methods were conducted simultaneously, the fixed-wing aerial survey did not observe any shore-based activity, while the RPAS survey observed 4 people. While this could be primarily due to the fact that recording shore-based activity was a secondary objective for the fixed-wing aerial survey, differences in the speed between the two methods (i.e. fishers arriving on the shoreline in the time between the two aircraft passing overhead), missed observations due to fishers being inconspicuous, or a moment of inattention by the on-board observer are also possible explanations. In any case, counts of shore-based activity from the RPAS footage are likely to be more accurate than counts from the fixed-wing aerial survey, as the quality of the RPAS footage was better than the fixed-wing aerial footage (discussed in section 5.1.3).

Assumption bias occurs when inferences, assumptions or mistaken beliefs are made about people or events due to a tendency to be subjective about the interpretation of the data (Choi and Pak, 2014). The level of detail in some of the night footage during the Peel-Harvey Estuary survey did not allow unambiguous classification of fishing activity (Figure 5). In contrast to on-site surveys, where the staff can watch how fishers are moving or interacting with each other, the few seconds that fishers are on screen in the RPAS footage does not often provide enough information to give an indication of fishing activity, especially if the fishing gear cannot be seen. This leaves the classification of the activity up to the person doing the analysis, which may differ depending on the level of training and experience of the observer.

**Figure 5** Observed activity at 21:51 on 18/12/2018 at Island Point. This was classified as scoop-net fishing due to the time of day, the grouped fishers and floating bin to store the catch.

### 5.2.9 Other logistical considerations

While the primary limitations of the RPAS operations have been listed above, there were several logistical issues that were encountered or have been identified in other marine applications (Joyce *et al.*, 2019) that are relevant to recreational surveys. While these are not necessarily unique to RPAS operations, it is worth outlining them here for future reference.

Flying over water was the main concern in this case, particularly when operating from a moving vessel, and the limited safe landing areas this scenario represents. Under normal operating conditions, the drone will set a 'home point' immediately prior to taking off, to which it will return when the battery level gets too low or there are connectivity problems with the flight controller/software. This serves as an extremely useful fail safe for terrestrial based RPAS operations; however, when operating from a moving platform, this can result in the drone returning to a site that is several kilometres away from the actual retrieval location. While the flight software can create 'dynamic home' locations, this was tied to the current location of the drone and not to the location of the remote controller, meaning that returning the drone to the anticipated retrieval location relied on coordination between the drone operator and the skipper of the vessel. As such, the 'return home' fail safe protocol incorporated into nearly all commercial RPAS is not as dependable a backup when operating from a moving vessel as when operating from a fixed location. As an alternate safety precaution, if the RPAS operator judged the remaining battery capacity insufficient to safely return the drone to the vessel, it would be landed on shore and retrieved manually. This occurred twice during the surveys: once at Freycinet Estuary and once at Peel-Harvey Estuary.

Consideration was also required for flying the drone at an angle that minimised light reflection from the water (e.g. Mount, 2005; Flynn and Chapra, 2014). During the early morning and late afternoon, when the sun is low on the horizon, reflection of the sun on the water surface can make footage unreadable. This can also be a problem for land-based cameras near water or manned aerial surveys. For RPAS operations, this can be minimised by altering the direction of flight, the camera angle or only flying susceptible sites at certain times of the day (Joyce *et al.,* 2019); however, this has implications for the probability-based nature of the survey. Typically, the starting point and direction of travel are randomised for each day so that there is no systematic bias in surveying the same sites at the same time of the day. If the route cannot be randomised, the data may not be representative of daily fishing activity.

During the survey period there were a significant number of software and firmware updates rolled out for the RPAS by the manufacturer. This was ascribed to the occurrence of multiple 'teething' problems/issues in the recently released software associated with cutting edge RPAS technology. As such, it was important to ensure that the RPAS was updated with the most recent software version(s) immediately prior to departure for the field sites to avoid needing to perform updates over mobile networks in remote locations, which were not always available. On at least one occasion, software malfunction whilst in the field curtailed flight operations half way through a day of flying requiring the software to be installed on another device (iPad), and flight paths re-created to enable flight operations to continue. Limited mobile network coverage at remote sites therefore, can complicate efforts to resolve software errors.

### 5.2.10 Site-specific considerations

Site-specific limitations must also be considered, including restrictions if operating close to aerodromes and controlled airspace. Approvals for RPAS operations vary between jurisdictions, and limitations may be placed on operations around certain wildlife activity (e.g. nesting/foraging seabirds). While this does not necessarily prevent data being collected at all times or locations, it does have the potential to impact the probability-based nature of a survey.

Flying in public spaces also has the potential for the perception of invasion of privacy or 'big brother' oversight. While this can be mitigated by public engagement before and during the survey, not all members of the public will necessarily be supportive.

## 6. Conclusions and recommendations

Remotely piloted aircraft systems (RPAS) are a rapidly emerging technology that are increasingly being used for a broad range of spatial analysis applications in primary industries. However, under current CASA regulations, the use of RPAS for probability-based recreational fishing surveys in Western Australia is not feasible when compared to other survey methods already in use. The primary reasons for this are:

i) the inability to fly in all weather conditions introduces a major source of bias and precludes probability-based sampling;

ii) requirements to maintain visual line of sight (VLOS) make it an impractical method for broad-scale areas;

iii) following the drone with a vehicle or vessel to maintain VLOS requires more staff and is more expensive than conducting a survey using current roving survey techniques;

iv) limited battery life results in inefficiencies, especially when there is a long distance to fly between the launch/retrieval site and the survey site.

It is important to note that these recommendations are only applicable to probability-based recreational fishing surveys in Western Australia under current RPAS regulations. Areas with less of a wind-dominated climate may not have the same issues trying to operate RPAS at randomly scheduled times of the day.

If the technology improved enough that aircraft could track each other through transponders, and regulations were changed so maintaining VLOS was not required, the use of RPAS could also become much more feasible. Extended visual line of sight operations could be carried out with two remote pilots, with each handing over the flight controls to the other as the drone tracked down the coast. This would involve the same number of people that run a conventional roving survey, improving the cost-effectiveness of the operations.

Furthermore, the use of a different drone, with longer battery life would also make RPAS more feasible, especially if the requirement to maintain VLOS was relaxed. Fixed-wing drones with vertical take-off and landing (VTOL) capabilities (e.g. WingtraOne) have been used from vessels for marine mammal monitoring in Western Australia (Clegeur and Hodgson, 2019). These drones can combine the limited launch and retrieval area requirements of multi-rotor drones with longer flight times of fixed-wing drones; however, there would still be the issue of only being able to take-off and land in conditions where the wind speed does not exceed 8 m $s^{-1}$ (≈15.6 knots).

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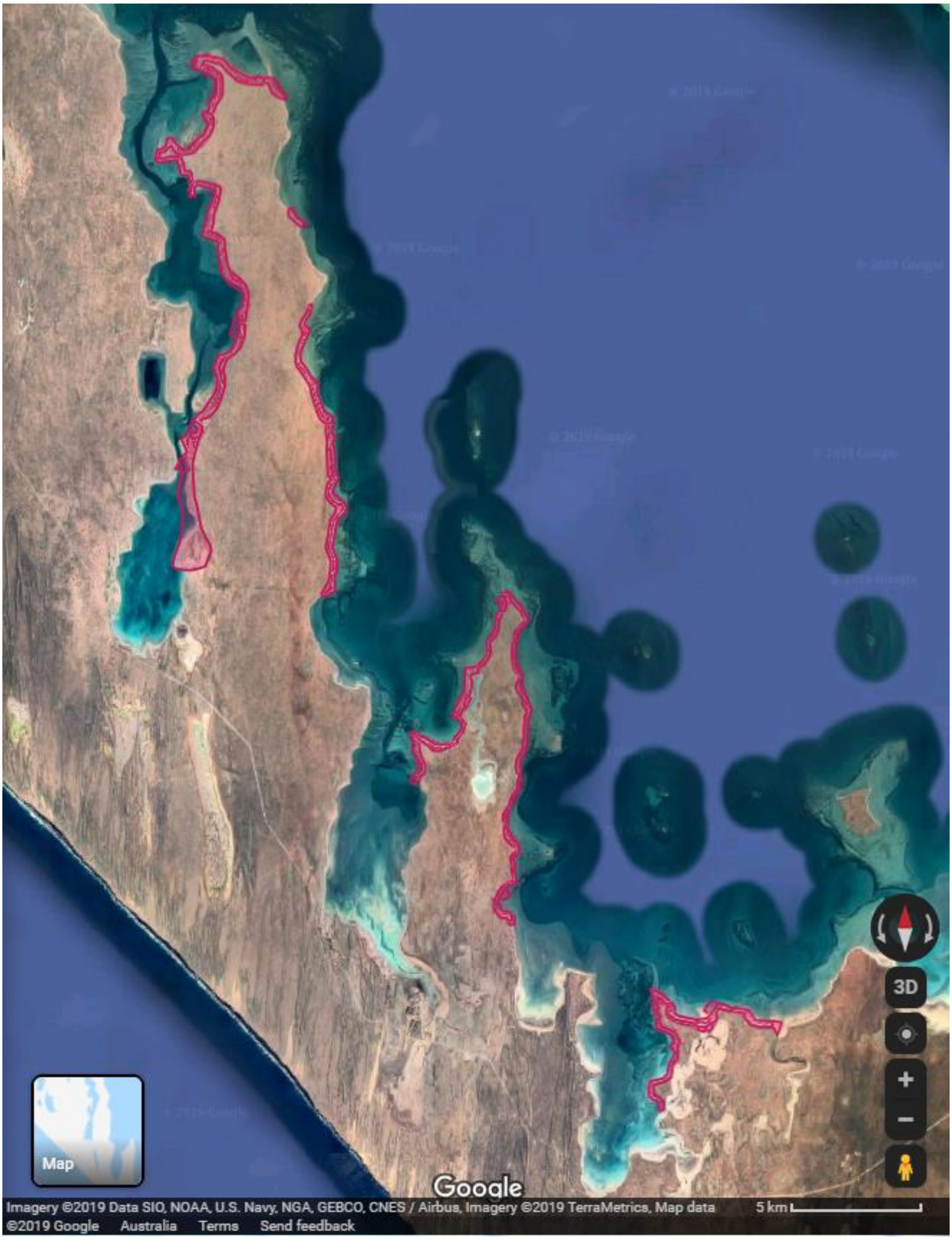
# Appendix 1. Freycinet Estuary survey design components

| | | Fixed-wing aerial survey | | RPAS survey |
|---|---|---|---|---|
| **Persons in scope** | **Residency status** | All | | All |
| | **Age** | All | | All |
| **Activities in scope** | **Platform** | Boat<br>Shore | | Shore |
| | **Fishing methods** | All boat-based methods<br>All shore-based methods | | All shore-based methods |
| **Temporal scope** | **Dates** | 01/03/2018 to 31/08/2018 | | 19/05/2018 to 21/05/2018<br>10/07/2018 to 13/07/2018 |
| | **Time of day** | 08:00 to 16:59 | | 08:00 to 16:59 |
| **Spatial scope** | | Entire Freycinet Estuary | | Shoreline at Tamala and Carrarang Stations |
| **Area to survey** | | ≈1508 km$^2$ | | ≈21 km$^2$ |
| **Sampling frame** | | Spatio-temporal | | Spatio-temporal |
| **Strata** | **Season** | Autumn: March to May<br>Winter: June to August | | Autumn: May<br>Winter: July |
| | **Day type** | Weekday<br>Weekend/Public Holiday | | Weekday<br>Weekend/Public Holiday |
| **Primary sampling unit** | **Fishing day** | 28: random sample | | 7: targeted sample |
| **Secondary sampling unit** | **Time of day** | 07:00 – 08:59<br>09:00 – 10:59<br>11:00 – 12:59<br>13:00 – 14:59<br>15:00 – 16:59 | | Not applicable |
| **Selection probability** | **Season** | Autumn<br>Winter | 0.50<br>0.50 | Not applicable (targeted dates) |
| | **Day type** | Weekday<br>Weekend/PH | 0.64<br>0.36 | Not applicable (targeted dates) |
| | **Time of day** | 07:00 – 08:59<br>09:00 – 10:59<br>11:00 – 12:59<br>13:00 – 14:59<br>15:00 – 16:59 | 0.20<br>0.30<br>0.20<br>0.20<br>0.10 | Not applicable (whole day sampled) |
| **Starting location** | | Random selection: 8 sites | | Random selection: 8 sites |
| **Travel direction** | | Random selection:<br>Clockwise/anticlockwise | | Random selection:<br>Clockwise/anticlockwise |
| **Data collection method** | **Aircraft** | Cessna 172 RG | | DJI Matrice 210 |
| | **Altitude** | 304.8 m (1000 ft) | | 50 m (164 ft) |
| | **Cruising speed** | 51.4 m s$^{-1}$ (100 knots) | | 10.3 m s$^{-1}$ (20 knots) |
| | **Camera** | iPad Pro (10.5’: 4K 30 fps) | | X4S (4K 60 fps) |
| | **Data entry** | iPad Pro (10.5’) | | Filemaker database |

## **Appendix 2.** RPAS areas surveyed for Freycinet Estuary




RPAS survey areas (maroon shading) for all flights carried out along shorelines at Tamala and Carrarang Stations in Freycinet Estuary.

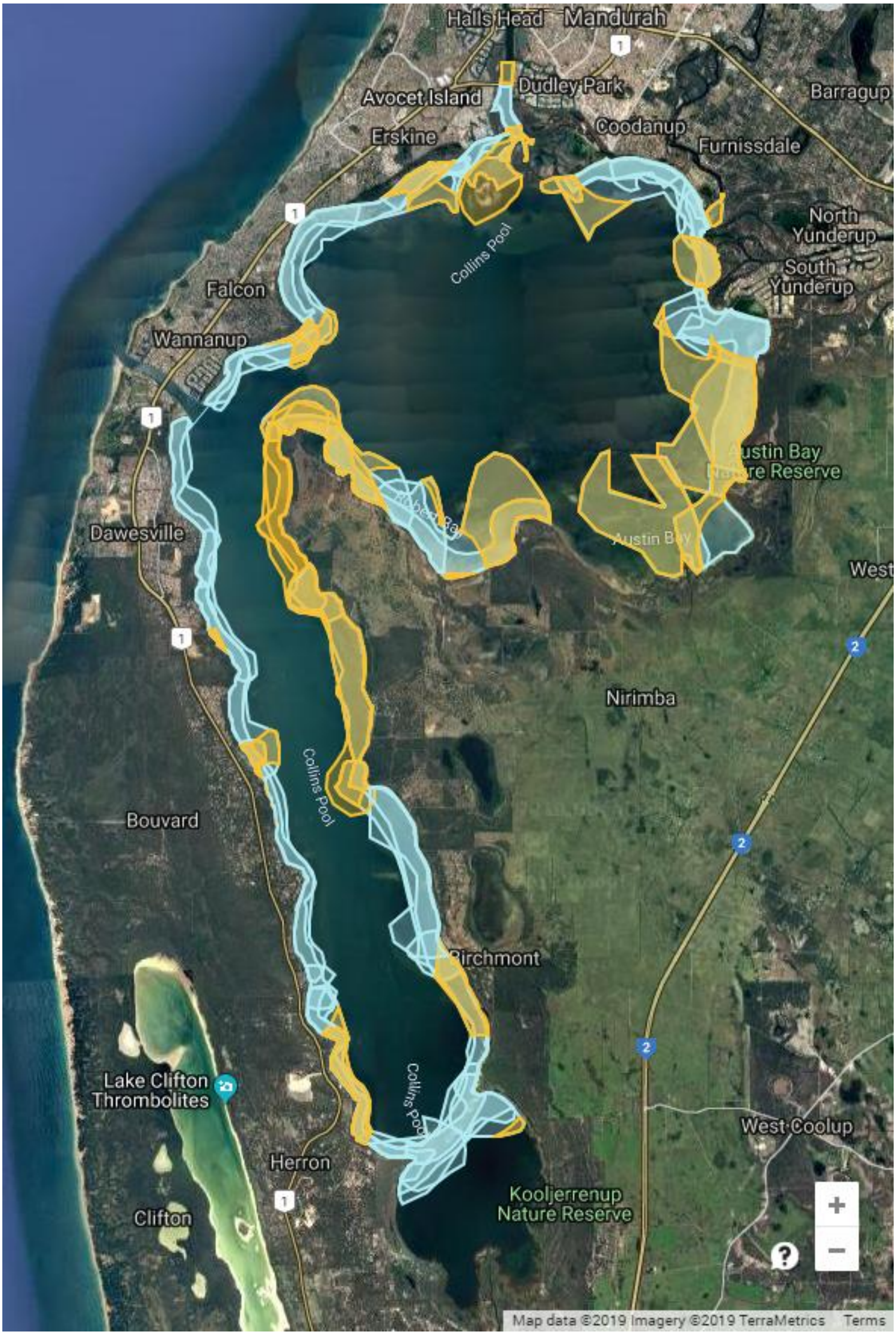
# **Appendix 3.** Peel-Harvey Estuary survey design components

| | | Roving on-site survey | | RPAS survey |
|---|---|---|---|---|
| **Persons in scope** | **Residency status** | All | | All |
| | **Age** | All | | All |
| **Activities in scope** | **Platform** | Shore-based wading activity | | Shore-based wading activity |
| | **Fishing methods** | All shore-based methods: scoop-net, drop net, gill net, rod and line | | All shore-based methods: scoop-net, drop net, gill net, rod and line |
| **Temporal scope** | **Dates** | 01/03/2018 to 30/04/2019 | | 28/01/2018; 09/02/2018; 08/12/2018; 22/12/2018; 01/02/2019; 23/02/2019 |
| | **Time of day** | 05:00 to 22:59 | | 05:00 to 22:59 |
| **Spatial scope** | | Area between the high water mark and 0.8 m depth within the main basins of Peel-Harvey Estuary | | Area between the high water mark and 0.8 m depth within the main basins of Peel-Harvey Estuary |
| **Area to survey** | | ≈35 $km^2$ | | ≈66 $km^2$ |
| **Sampling frame** | | Spatio-temporal | | Spatio-temporal |
| **Strata** | **Fishing season** | Medium: March to May<br>Low: June to August<br>Closed: September to October<br>High: November to February | | High: November to February |
| | **Day type** | Weekday<br>Weekend/Public Holiday | | Weekday<br>Weekend/Public Holiday |
| **Primary sampling unit** | **Fishing day** | 68: random sample | | 6: non-random sample |
| **Secondary sampling units** | **Time of day** | 05:00 – 10:59<br>11:00 – 16:59<br>17:00 – 22:59 | | 05:00 – 10:59<br>11:00 – 16:59<br>17:00 – 22:59 |
| | **Region** | North-east: Caddadup to Herron Point<br>East-west: South Yunderup to Wannanup<br>North-west: Island Point to Coodanup | | North-east: Caddadup to Herron Point<br>East-west: South Yunderup to Wannanup<br>North-west: Island Point to Coodanup |
| **Selection probability** | **Fishing season** | Medium<br>Low<br>Closed<br>High | 0.13<br>0.13<br>0.07<br>0.67 | Not applicable (targeted dates) |
| | **Day type** | Weekday<br>Weekend/PH | 0.50<br>0.50 | Not applicable (targeted dates) |
| | **Time of day** | 05:00 – 10:59<br>11:00 – 16:59<br>17:00 – 22:59 | 0.35<br>0.25<br>0.40 | Not applicable (targeted dates) |
| | **Region** | North-east<br>East-west<br>North-west | 0.33<br>0.33<br>0.33 | |
| **Starting location** | | Random selection: 8 sites | | Non-random selection (matched roving survey) |
| **Travel direction** | | Random selection: Clockwise/anticlockwise | | Non-random selection (matched roving survey) |

| | | Roving on-site survey | RPAS survey |
|---|---|---|---|
| **Data collection** | **Daylight equipment [a]** | Bushnell Elite Rangefinder (TruPulse 200X)<br>iPad internal compass (Helikon KS-BUS-AL-02 compass) | DJI Matrice 210 – X4S sensor (DJI Phantom 4 Pro – inbuilt sensor) |
| | **Night-time equipment [a]** | Mobotix S16A with T237 lens (Bushnell 7x50 binoculars)<br>also see Daylight equipment | DJI Matrice 210 – XT sensor |
| | **Data entry** | Real-time entry in Filemaker database on iPad Pro | Post-survey analysis into Filemaker database |

[a] details in parentheses are for the backup equipment if the primary equipment is not working

## **Appendix 4.** RPAS areas surveyed for Peel-Harvey Estuary




RPAS survey areas that were in-scope (blue shading) and out-of-scope (orange shading) for the roving on-site survey at Peel-Harvey Estuary for all flights carried out.

# Appendix 5. RPAS configuration

| | DJI Matrice 210 System | | DJI Phantom 4 Pro System |
|---|---|---|---|
| **Aircraft** | | | |
| **Model** | DJI Matrice 210 | | DJI Phantom 4 Pro |
| **Dimensions** | 887×880×378 mm (unfolded) | | 250x250x200 mm |
| **Weight** | ≈3.84 kg (with TB50 batteries) | | 1.39 kg |
| **Maximum speed** | S Mode: 18 m s$^{-1}$ (≈35 knots)<br>P Mode: 17 m s$^{-1}$ (≈33 knots)<br>A Mode: 17m s$^{-1}$ (≈33 knots) | | S Mode: 20 m s$^{-1}$ (≈39 knots)<br>P Mode: 16 m s$^{-1}$ (≈31 knots)<br>A Mode: 14 m s$^{-1}$ (≈27 knots) |
| **Maximum wind resistance** | 12 m s$^{-1}$ (≈23 knots) | | 10 m s$^{-1}$ (≈19 knots) |
| **Maximum flight time** | 27 minutes (TB50 batteries, no payload) | | 30 minutes |
| **Operating temperature** | -20° to 45°C | | 0° to 40°C |
| **IP rating** | IP43 | | |
| **Reference** | https://www.dji.com/au/matrice-200-series/info#specs | | https://www.dji.com/au/phantom-4-pro/info#specs |
| **Camera** | | | |
| **Model** | Zenmuse X4S | Zenmuse XT | Inbuilt |
| **Dimensions** | 125x100x80 mm | 103×74×102 mm | |
| **Weight** | 253 g | 270 g | |
| **Sensor** | CMOS, 1" (20 MP) | Uncooled VOx Microbolometer | CMOS, 1" (20 MP) |
| **Lens** | F/2.8-11, 8.8 mm | F/1.4, 9 mm | F/2.8-11, 8.8 mm |
| **Sensitivity** | | <50 mK at f/1.0 | |
| **Video resolution** | H.264<br>4K: 3840×2160<br>23.976/24/25/29.97/<br>47.95/50/59.94p<br>@100Mbps | 640x512 | H.264<br>4K:3840×2160<br>24/25/30/48/50/60p @100Mbps |
| **Frame Rate** | 20 fps | 9 fps | 30 fps |
| **Reference** | https://www.dji.com/au/zenmuse-x4s/info#specs | https://www.dji.com/au/zenmuse-xt/specs | https://www.dji.com/au/phantom-4-pro/info#specs |
| **Battery** | | | |
| **Model** | TB50 | | PH4-5870 |
| **Weight** | 515 g | | 468 g |
| **Capacity** | 4280 mAh | | 5870 mAh |
| **Voltage** | 22.8 V | | 15.2 V |
| **Type** | LiPo 6S | | LiPo 4S |
| **Energy** | 97.58 Wh | | 89.2 Wh |
| **Operating temperature** | -10°C to 40°C | | 0° to 40°C |
| **Charging temperature** | 5° to 40°C | | 5° to 40°C |
| **Max charging power** | 180 W | | 160 W |
| **Reference** | https://store.dji.com/product/inspire-2-intelligent-flight-battery | | https://store.dji.com/product/phantom-4-pro-intelligent-battery-high-capacity |

| | DJI Matrice 210 System | DJI Phantom 4 Pro System |
|---|---|---|
| **Battery Charger** | | |
| **Model** | Inspire 2 charging hub (IN2CH) | Phantom 4 charging hub |
| **Input voltage** | 26.1 V | 17.5 V |
| **Input current** | 6.9 A | |
| **Charging time** | 90 min (2 batteries)<br>180 min (4 batteries) | 210 min (3 batteries) |
| **Reference** | https://store.dji.com/product/inspire-2-charging-hub | https://store.dji.com/product/phantom-4-battery-charging-hub |
| **Remote controller** | | |
| **Model** | GL800A | |
| **Operating frequency** | 2.400 - 2.483 GHz; 5.725 - 5.825 GHz | 2.400 - 2.483 GHz; 5.725 - 5.825 GHz |
| **Maximum transmission distance** (Unobstructed, free of interference) | 2.400-2.483 GHz<br>FCC: 7 km; CE: 3.5 km; SRRC: 4 km<br>5.725-5.825 GHz<br>FCC: 7 km; CE: 2 km; SRRC: 5 km | 2.400-2.483 GHz<br>FCC: 7 km; CE: 3.5 km; SRRC: 4 km<br>5.725-5.825 GHz<br>FCC: 7 km; CE: 2 km; SRRC: 5 km |
| **Transmitter power**<br>FCC: USA standard<br>CE: European standard<br>SRRC: Chinese standard | 2.400 - 2.483 GHz<br>FCC: 26 dBm; CE: 17 dBm; SRRC: 20 dBm<br>5.725 - 5.825 GHz<br>FCC: 28 dBm; CE: 14 dBm; SRRC: 20 dBm | 2.400 - 2.483 GHz<br>FCC: 26 dBm; CE: 17 dBm; SRRC: 20 dBm<br>5.725 - 5.825 GHz<br>FCC: 28 dBm; CE: 14 dBm; SRRC: 20 dBm |
| **Battery** | 4923 mAh LiPo | 6000 mAh LiPo 2S |
| **Operating current/voltage** | iOS: 1 A @ 5.2 V (Max)<br>Android: 1.5 A @ 5.2 V (Max) | 1.2 A @ 7.4 V |
| **Operating temperature** | -20° to 40°C | 0° to 40°C |
| **Reference** | https://www.dji.com/au/matrice-200-series/info#specs | https://www.dji.com/au/phantom-4-pro/info#specs |
| **App** | | |
| **Model** | DJI Go 4 | DJI Go 4 |
| **Live view working frequency** | 2.4 GHz ISM; 5.8 GHz ISM | 2.4 GHz ISM; 5.8 GHz ISM |
| **Live view quality** | 720P @ 30fps | 720P @ 30fps |
| **Latency** | 220 ms (depending on conditions and mobile device) | 220 ms (depending on conditions and mobile device) |
| **Reference** | https://www.dji.com/au/matrice-200-series/info#specs | https://www.dji.com/au/phantom-4-pro/info#specs |

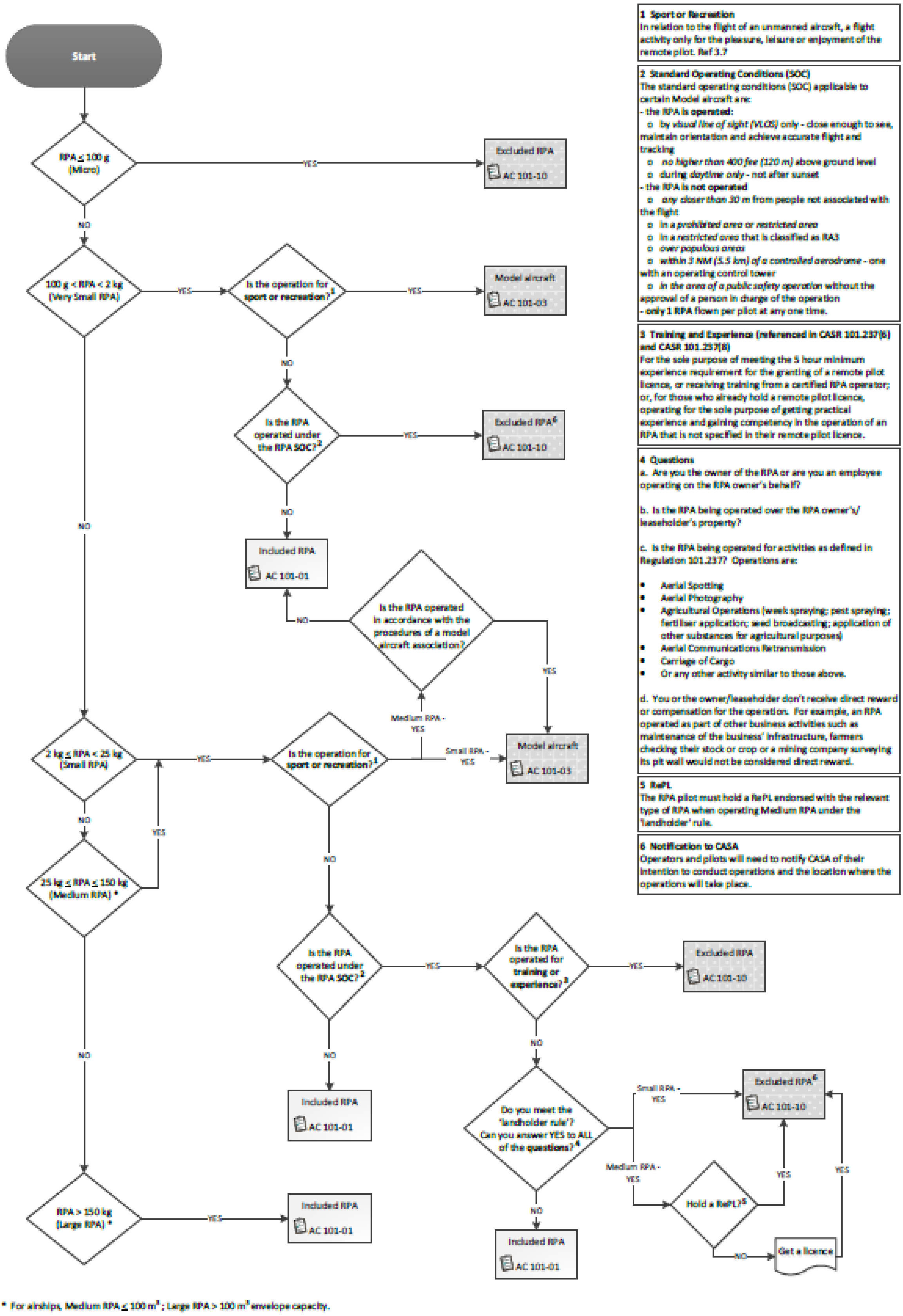
## **Appendix 6.** Vessel-based RPAS retrieval (video)

https://www.youtube.com/watch?v=zzblg5BPFVA

## **Appendix 7.** Comparison of footage between a fixed-wing aircraft and the RPAS (video)

https://www.youtube.com./watch?v=GfLOkjAvPAE

# Appendix 8. Excluded RPAS decision flowchart




Flowchart for determining excluded RPAS operations under CASA guidelines (source: CASA, 2018: p. 18)