Movement Ecology of Chestnut Teal in the Coorong, Lower Lakes, and Murray Mouth, South Australia

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Supervised by Dr Steven Delean and Dr Thomas Prowse

Contents

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Freya Harrihill
November 2024

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Abstract

Wetlands worldwide are being degraded, with up to 90% loss in some areas. Australian wetlands essential for waterbird populations are threatened by changed water regimes, leading to habitat loss. Waterbird populations have declined more than 50% over the past forty years in the Coorong, Lower Lakes and Murray Mouth (CLLMM) wetlands of South Australia. Chestnut Teal is a common, herbivorous waterfowl recognised as an indicator of change within coastal wetlands of the CLLMM region, however there is little information available about its movements or habitat use that could inform drivers of population change. Twelve Chestnut Teal were tracked using Ornitela GPS telemetry for between 15 and 108 days between May and August 2024. Chestnut Teal movements varied across the diurnal cycle, were highest early morning and late afternoon, and males moved further than females. Water depth preferences also varied across the diurnal cycle, but the pattern of behaviour varied across sections of the Coorong. Water depth preferences varied between the sexes, with males spending more time on the water than females. Total distances moved varied considerably between individuals, ranging from 4 to 12 km per day. Home ranges ranged from 40 ha to 38,000 ha (averaging 8000 ha). The study provides a proof-of-concept that tracking Chestnut Teal can inform movement ecology and habitat use and guides development of improved harness and optimal tracking technology to allow longer tracking periods to better understand the impacts of changing environmental conditions over annual and longer cycles on waterfowl populations.

1 Introduction

Wetlands and other waterways create fluctuating spatial mosaics of habitats that influence the movement pathways and dispersal capabilities of water-dependent, opportunistic species (Rogers & Ralph 2011). Wetlands are areas "where water is the primary factor controlling the environment and the associated plant and animal life" (Niering 1985). Water is the main shaper of all wetland ecosystems, as it dictates the timing of growth and succession, such that areas with predictable water movements have more reliable resources (Weller 1999). Species richness within wetlands is assumed to adhere to patterns familiar from island biogeography, in that species richness increases with increasing wetland size and greater isolation (Weller 1999).

Globally, somewhere between 50% and 90% of natural wetlands have been lost (Davidson 2014; Finlayson et al. 1999). Wetlands in Australia are threatened by changed water regimes, habitat loss, pollution and eutrophication, and invasive species (Bunn et al. 1997; Mott et al. 2022). The continuing loss and degradation of wetlands in Australia is largely driven by indirect causes, mainly a lack of coordination between government agencies and poor planning and management of wetlands (Finlayson & Rea 1999). However, existing wetland habitats continue to support populations of migratory and non-migratory waterbirds, providing food, breeding sites, and shelter against predators (Kingsford & Norman 2002).

1.1 Waterbirds as indicators of change in wetland systems

Movement and habitat selection by waterbirds can be driven by environmental cues or resource availability (Abrahms et al. 2021). Birds' dispersal abilities are limited less by physical barriers than other flightless terrestrial vertebrates (Allen & Singh 2016). Studies have found that waterbirds have evolved to track resource availability (Paxton et al. 2023), likely because wetlands are often small patches of suitable habitat within a broad region (Weller 1999).

Monitoring waterbird movement can be used to monitor change in wetland conditions, and guide management practices (McGinness et al. 2019; Stolen, Breininger & Fredrick 2005). Declines in waterbird populations can be directly linked to altered hydrology within systems, such that these birds can be used as indicators of change within wetlands (Frederick et al. 2009; Ogden et al. 2014; Stolen, Breininger & Fredrick 2005; Tankersley 2004). A study of waterbirds using southern Florida's coastal marine ecosystems developed models for species habitat use that can identify pressures on the system (Ogden et al. 2014). For example, if declines in three species using a common habitat occur simultaneously, managers can focus their attention on the shared habitat to identify the cause (Ogden et al. 2014). As well as population level changes, behavioural level changes can indicate system pressures, such as increased foraging behaviours indicating a resource-poor system (Mosley et al. 2018).

1.2 Monitoring waterbird movements within wetlands

Determining the distribution of waterbird species within wetland regions can be difficult, as wetlands use varies for mobile waterbird populations (Kingsford & Norman 2002). Observational bird surveys are limited to daylight hours and cannot discern if individuals are surveyed multiple times across locations. Thermal imaging has been used to observe waterbirds at night but cannot distinguish between species of similar size that are usually identified by plumage colour variations (Austin, Ribot & Bennett 2016). Bird banding (Kingsford & Norman 2002) and feather isotope analysis (Hobson & Wassenaar 2008) provide alternative methods for monitoring bird movements. However, both methods are limited to showing general movement trends by only describing the capture and recapture sites, and not the movement path between the two (Brandis et al. 2021).

GPS telemetry can be used to track individual birds at all times of day and night, and document movements across remote and inaccessible areas of the earth, such as the Himalayas (Prins & Namgail 2017) and inland Australia (McGinness et al. 2019; Mott et al. 2022). GPS telemetry refers to the use of GPS (Global Positioning System) units, satellite-based radio positioning systems, for monitoring of location, speed, and other parameters (Lee 2019). GPS units are attached to birds by using collars, leg tags, 'backpack' style harnesses, internal implants, or gluing (Roshier & Asmus 2009). The use of telemetry to monitor bird movements has been increasing since first use in the 1980's due to advances in the technology of GPS recording devices which has resulted in smaller, cheaper, and more reliable units (Joo et al. 2022; Prins & Namgail 2017).

Studies of waterbirds using GPS telemetry can identify key habitats for nesting, roosting and foraging within wetlands and wetland systems (Hartvigsen-Power et al. 2019; Mott et al. 2022). Tracking waterbird species using GPS units over a number of years by the CSIRO has highlighted the need for basin-scale conservation and water delivery planning, due to population connectivity across the Murray-Darling Basin (McGinness et al. 2019). Data collected from telemetry studies can also be used in combination with environmental variables to describe bird behaviours based on environmental cues (Roshier, Doerr & Doerr 2008).

There are concerns about the behavioural impact of GPS unit attachment, such as higher energy expenditure, reduced reproduction, and increased foraging trip duration (Barron, Brawn & Weatherhead 2010; Bodey et al. 2018). It has become accepted across literature that GPS units between 3% and 5% of a bird's body weight will reduce these behavioural impacts (Bodey et al. 2018). Harness failure can occur in some cases, which limits the tracking duration but is often unreported as failed studies will not be published (Cope et al. 2024). Some studies will test longevity of harness designs on captive birds prior to commencing wild studies (Roshier & Asmus 2009). GPS telemetry studies must balance the potential negative effects with the value of the knowledge gained, and consider potential behavioural effects on the results (Bodey et al. 2018).

1.3 The Coorong, Lower Lakes and Murray Mouth system

The Coorong, Lower Lakes, and Murray Mouth region (CLLMM) is a UNESCO site of international significance for waterbirds in the South-East of South Australia (Brookes, J et al. 2023). The Coorong is a 120km long costal saline wetland at the terminal point of the Murray-Darling Basin. Waterbird populations in the CLLMM region have declined more than 50% over the past forty years due to habitat loss (Paton, D et al. 2009). Overextraction of water upstream in the Murray-Darling Basin has been the most significant cause of habitat loss (Mosley et al. 2018). Natural flows at the end of the Murray River have reduced by up to 77% due to diverted flows from damming upstream (Kingsford 2000). Daily flows at the Murray mouth naturally are zero 1% of the time, however, changes in flow regime mean that flow is now zero 40% of the time (Kingsford et al. 2011). Declines in waterbird populations initiated annual monitoring efforts since the start of the millennium to document changes in distribution and abundance of water birds across the region (Paton, D et al. 2023).

Monitoring efforts found that waterbird declines in the Coorong have been most significant in migratory shorebirds, and herbivorous and piscivorous waterbirds (Paton, D et al. 2009). Declines in herbivorous waterbird species are likely linked to declines in the density of *Ruppia tuberosa*, a seagrass that has been impacted by reduced flows (Chilson et al. 2018; Mosley et al. 2018). Recent surveys in the Coorong found *R. tuberosa* abundances were the lowest recorded since annual monitoring began in 2007 (Paton, D et al. 2024). Additionally, the CLLMM region has not met the threshold ecological targets set for waterbirds by the Murray-Darling Basin Authority for the past twenty years (Paton, D et al. 2024).

Understanding waterbird movements, including variation among individuals and sexes, has been identified as a key knowledge gap for water managers in the Murray-Darling Basin (McGinness et al. 2019). Previous studies have highlighted the need to track waterbirds within the CLLMM, to identify important habitats, and also to document use of alternate wetlands in south-east South Australia that could be conserved as a solution to protect waterbirds, under declining Coorong conditions (Hartvigsen-Power et al. 2019). Three waterbird species (Australian Pelican, Red-necked Avocet, and Sharp-tailed Sandpiper) have previously been tracked using GPS telemetry within the CLLMM (Mott et al. 2022). However, patterns and extent of movement and habitat selection for foraging, roosting and nesting by herbivorous waterfowl within the CLLMM region remain unknown.

1.4 Project aims

Studying indicator species is important for monitoring change within wetland systems (McGinness et al. 2019). Chestnut Teal (*Anas castanae*) are a useful indicator species of waterbird community structure within the Coorong due to their superior tolerance of high saline conditions relative to other dabbling duck species (e.g. Grey Teal and Pacific Black Duck) (Paton, D et al. 2009). Therefore, this study focused on tracking Chestnut Teal using GPS telemetry to measure foraging, roosting, and breeding movements and the water depths that these activities occur at. The specific aims of this study were to:

1. Explore the feasibility of catching and GPS tracking Chestnut Teal within the CLLMM region;

2. Investigate the home range and utilisation distributions of Chestnut Teal during autumn and winter; and
3. Examine how Chestnut Teal behaviour changes over the diurnal cycle, in relation to distance moved and water depth, and possible behavioural differences between the sexes.

2 Methods

2.1 Study species: Chestnut Teal

Chestnut Teal are a small dabbling duck species that mostly live in coastal regions of Australia, and they have never been tracked with GPS anywhere in the country. They are a common species within the Coorong, but numbers have been declining, with the recent observed population of 5000 individuals below the long-term median (Paton, D et al. 2022). Chestnut Teal are mostly herbivorous species, favouring *Ruppia* species as food in the Coorong, but are also known to eat invertebrates, such as Chironomid larvae (O'Connor 2013). Chestnut Teal are known to forage in water depths between 0 cm and 20 cm, but ideal conditions are between 0.5 cm to 1.5 cm (O'Connor, Rogers & Pisanu 2013).

2.2 Identifying suitable trapping locations

Historical data available from the online 'Birdata' portal (Birdlife Australia 2024) and the annual waterbird census (Paton, D et al. 2023) were used to identify sites with high likelihood of Chestnut Teal occurrence in the Coorong. Birdata compiles bird occurrence data collected by citizen science across Australia, and the database provides coordinates of observations as well as the date and time of the survey and information regarding the type of survey undertaken. Annual bird count surveys are used to census waterbirds in the Coorong every summer. Waterbirds are surveyed across 1-km sections by teams of trained observers on foot and by boat, covering shorelines and open water over 7-16 days. Each section is coded for tracking changes over time and allows for identifying high use areas for specific species.

The sites identified as having a high likelihood of Chestnut Teal presence included Noonameena, Parnka Point, and Morella Basin (Figure 1). Noonameena is in the North Lagoon of the Coorong and so it is closer to the Murray Mouth where water flows out of the River Murray into the Southern Ocean. Parnka Point is a narrow channel that separates the north and south Coorong lagoons. Morella basin is a natural wetland that fills from rainwater and groundwater but is then pumped into the south Coorong lagoon through Salt Creek. These sites were visited to investigate feasibility of trapping Chestnut Teal in March and June prior to the trapping field trips. At these sites, I assessed water levels, accessibility and suitability for trap placement, and Chestnut Teal numbers were recorded. Sites selected for trapping were revisited at the beginning of the field trips to re-check for changes in Chestnut Teal numbers and feasibility of trapping based on water levels.

Figure 1: Map of Chestnut Teal trapping sites within the CLLMM region of South Australia. The red pins represent the planned trapping sites, and the yellow outline represents the extent of the RAMSAR wetland of international significance.

2.3 Field trips for trapping Chestnut Teal

2.3.1 Field trip 1

The first trapping field trip occurred from the 28th of April to the 10th of May 2024. Although trapping was planned at both Parnka Point and Noonameena, Chestnut Teal numbers at Noonameena were so low over this period that all pre-trapping effort was done at Parnka Point to increase the probability of successful trapping.

2.3.2 Field trip 2

The second trapping field trip occurred between the 1st of July and 6th of July 2024. On this trip trapping attempts were made at Morella Basin. This site was chosen to try to collect data from birds that were not residing in the main Coorong lagoons. However, this trip was unsuccessful in catching Chestnut Teal, likely due to the shorter time frame available for pre-baiting compared to the first field trip.

2.4 Cage trap design

The design of the cage trap used for capturing Chestnut Teal was adapted from the method used by the Victorian Game Management Authority for catching waterfowl (GMA 2023).

A roll of 1.5 m x 10 m wire mesh with a gauge of 5 cm^2 was set up on the shore with the opening facing the water. Eight 1.8 m steel rebar poles were weaved through two holes in the wire, starting on the inside and pushing into the ground, at even increments around the trap, such that the trap formed a circle (Figure 2). The entrance of the trap was funnelled inwards, and the width was adjusted depending on whether ducks were being caught or not (Figure 2. D).

Black fruit tree netting (5 m x 5 m) was placed over the trap to create a soft top to prevent injury to the ducks if they flew upwards during capture. This soft top was secured by threading the rebar through holes in the net and attaching the net to the wire using zip ties. The net was pulled tight, to prevent the ducks getting caught in it. Any excess net that hung over the side of the trap was rolled up and secured at the top of the wire using a zip tie. Caps were attached to the ends of the rebar to prevent human or animal injury and help ensure the netting didn’t come loose (Figure 2. C).

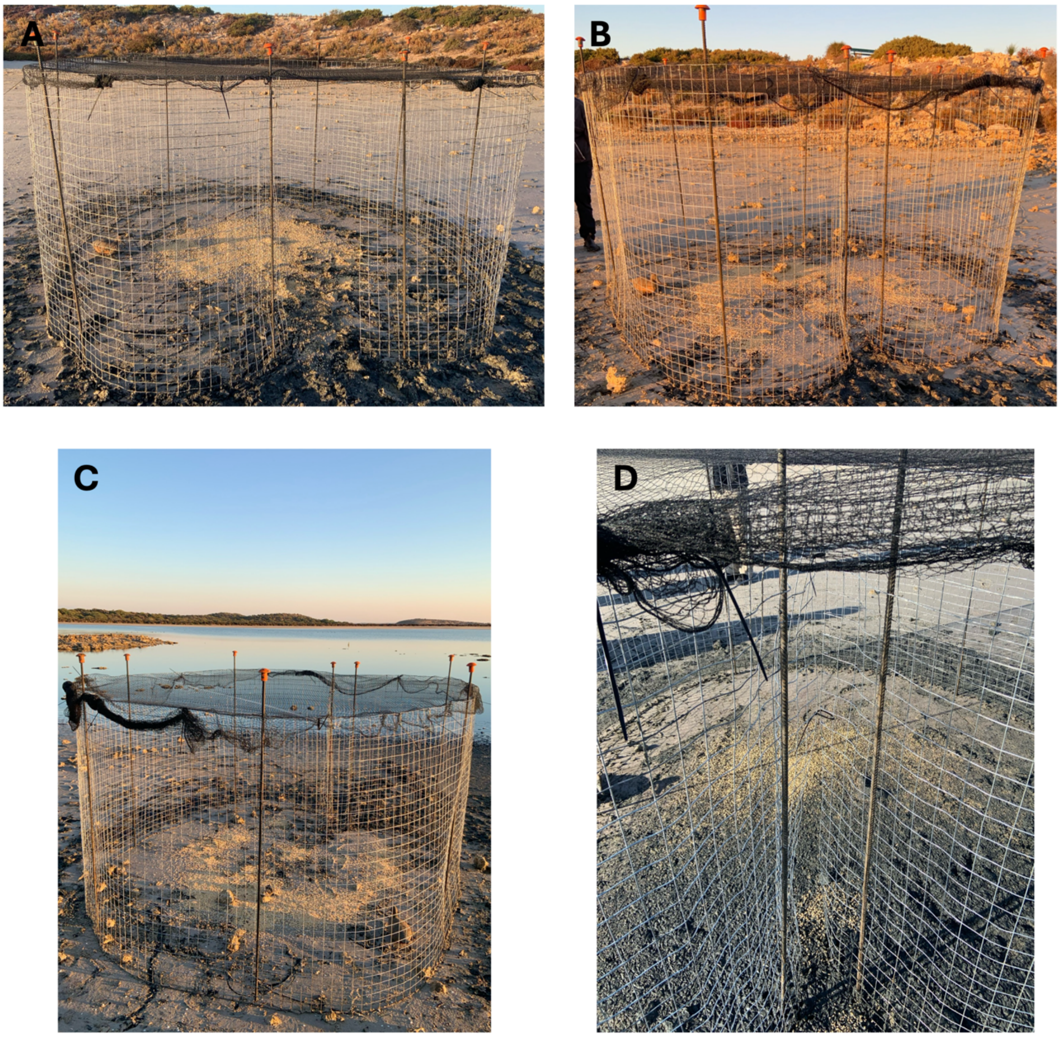

*Figure 2: **A**. Image of trap set up on shoreline at Parnka Point with the entrance open 0.5m wide with bait and decoy duck placed inside. **B**. Image of trap set up on shoreline at Parnka point with entrance funnelled inwards with bait and decoy duck placed inside. **C.** Back view image of the trap set up on the shoreline at Parnka Point with the entrance funnelled inwards, facing the water. **D**. Close up image of the entrance funnelled inwards and the spread of grain in the trap.*

2.5 Trapping Chestnut Teal

2.5.1 Pre-baiting to attract Chestnut Teal

To attract ducks to a selected trap site, 5 kg of mixed wheat and barley grain was spread over approximately 10 m^2 of shoreline at dawn and dusk for three consecutive days. For the following three days, a cage trap was set at the same location and the grain was scattered inside. The entrance of the trap was left open so ducks could freely move in and out and habituate to feeding inside the trap. The trap entrance was set with a 1 m wide opening on the first day, which was then narrowed to 0.5m wide for the following two days.

2.5.2 Trapping process

Trapping was then attempted for the final three days, during which the trap entrance was funnelled inwards, with the widest point at the entrance being a fist width apart (approximately

10 cm) (Figure 2. D). This funnel-shaped entrance ensured that ducks could enter the trap easily but would have difficulty finding the exit once they were inside. The decoy duck was placed at the back of the trap, to lure ducks to the site (as is commonly used in duck hunting) (Figure 2. B). Wheat and barley grain (approximately 5 kg) was scattered throughout the trap, ensuring that it wasn't placed near the wire so ducks couldn't access it from outside the trap. A large amount of grain was placed in the centre of the trap, then a handful was placed approximately one duck length away from the entrance of the trap, and a small sprinkle was placed in the entrance and just in front of the opening (Figure 2. D). This arrangement of grain optimised the likelihood of ducks entering the trap to reach the large amount of grain.

A processing station was set up approximately 100 m away from the trap and was obscured from the ducks' view by vegetation. The trap was checked visually every five minutes for the presence of Chestnut Teal or non-target species. Once three Chestnut Teal had entered the trap, or birds of any species had been in the trap for more than five minutes, all ducks were removed, and any Chestnut teal were stored in a poultry crate (three birds per crate) and transferred to the processing station. The trap entrance was left wide open while processing occurred.

2.6 Deployment of GPS units on individual birds

2.6.1 Bird harness construction

Harnesses to hold GPS units (Figure 4) were constructed using the method developed for Grey Teal by Roshier & Asmus (2009), with adjustments to accommodate for the larger body size of Chestnut Teal (Figure 3). Two 45 cm lengths of 63.5 mm Teflon ribbon (Bally Ribbon, Bally, PA) were glued together perpendicularly to form a cross with cyanoacrylate glue. Once dry, one length was then folded over, to create a "T" configuration. The y-section (Figure 3) was then glued 4 cm along, offset by 3 mm. A 3.7 cm piece of 1.7 cm wide shrink tubing (polyolefin) was threaded along and warmed using a heat gun to shrink it flat at the top of the y-section. A white marker was used to create lines 1 cm apart, 10 cm down each of the lengths, and dots were placed in-between the lines at 0.5 cm intervals. The harness was attached to the GPS unit using 1.8 x 18 mm aluminium crimps that were resized to 9 mm (Hook'em Fishing, Eltham, Vic). A crimping tool (Jinkai, Japan) was used to secure the crimps.

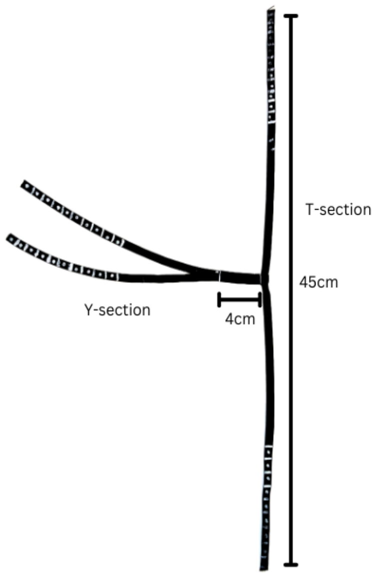

Figure 3: Image of completed harness before attachment to GPS unit, with the T and Y sections labelled.

Figure 4: Image of the base of the GPS unit with the front and rear labels corresponding to the orientation of the unit on the duck

2.6.2 Preparations before harness attachment

Prior to the day of trapping, the GPS units were turned on and placed in full sun to generate a GPS fix (as they can take 24 hours for the location to update when they are moved a large distance turned off) and become fully charged. On the trapping day, GPS units were attached to the harnesses by threading the lengths of the t-section (held flat against each other) through the rear hole of the GPS unit (see Figure 4). The two lengths were then similarly threaded through one aluminium crimp leaving approximately 3cm out of the end of the crimp. It was checked before attaching to the duck to ensured that the loops would lay flat against the bird's body (Figure 5).


Figure 5: Image of the underside of a female Chestnut Teal showing the harness lying flat against the body

2.6.3 Harness attachment

At the processing station, trapped Chestnut Teal were removed from the poultry crates for one-at-a-time processing. The duck was placed in a black pillowcase and weighed using a digital hanging scale (0-10 kg/5 g precision). Having removed the animal from the pillowcase, the duck was placed in the lap of the handler and held firmly around the wings and body with two hands (Figure 6. C). A small sock with the toe cut out was placed over the duck's head to cover the bird's eyes and keep it calm for processing (Figure 6. C).

As an index of duck size, the right wing was measured using a 300 mm metal wing ruler with end stop. (Figure 6. B). To attach the harness, the back loop of the harness was placed over the duck's body so that the GPS unit sat between the wings, with the top of the GPS aligned with the top of the wings (Figure 6. A). The back loops were placed over the duck's wings on both sides and the lengths were slightly tightened to maintain the position of the GPS device. The front loops of the harness were threaded through the corresponding holes in the GPS unit on either side, and one aluminium crimp was threaded through the ribbon on each side. The front harness loops were tightened until they were slightly taut against the duck's body, and then clamped using stainless steel surgical clamps on each side to hold them in place.

The back harness lengths were then pulled tight so that one index finger could be slid under the GPS unit on the duck's belly. Having checked to ensure they were of equal lengths using the markings, clamps were placed behind the crimps to hold the tension. The front loops were then tightened and crimped in the same way.

A crimping tool was used to compress the crimps on the back loops which locked them in place. The tension in the harness was checked, and the front loops were tightened if necessary and then crimped intro place. The harness tightness and position were rechecked a final time, and the exposed ribbon ends were trimmed, leaving approximately 3mm of ribbon protruding beyond the crimps. To prevent fraying, a small amount of superglue was dabbed on to the cut ribbon ends, while ensuring the wet glue did not touch the duck's feathers (Figure 6. A). For one trapped Chestnut teal, the harness tension was deemed too loose after crimping, so the harness was removed, and the duck was released.

To release a duck, the sock was removed from the duck's head and the duck was placed back in the pillowcase and returned to the shoreline. The duck was taken 10-20 m to one side of the trap and released by placing it on the ground and carefully opening the pillowcase, ensuring the duck was facing the direction of the water. If birds of prey were present, the release was delayed until they left the area as per ethics protocols.

The released duck was observed for at least 5 minutes to ensure normal behaviour, as per ethics protocols. The ducks commonly preened feathers for some time after the release. There was protocol in place to immediately attempt to re-trap and remove the harness of any individual observed during this period that displayed abnormal behaviours (eg. unable to fly or swim) or appeared injured. However, no adverse events were observed during this study. The entire harness attachment procedure including the post-release observation period, took approximately thirty minutes.

*Figure 6: **A**. Image showing the position of a GPS unit attached to a male Chestnut Teal with a Teflon harness. **B**. Image showing the measuring of the wing of a male Chestnut Teal. **C**. Image showing the position of the hands holding a female Chestnut Teal whilst the harness is being attached, and the sock covering the duck's eyes.*

2.6.4 Data collection

The GPS units used were Orni-Track-10 (Ornitela UAB, Vilnius, Lithuania), with a weight of 12g (less than 3% of the average Chestnut Teal's body weight), which are solar-powered devices that transmit location data via the 3G and 4G Global System for Mobile Communications (GSM) network. The units were programmed to record a GPS location every 10 minutes, which was deemed the highest fix frequency permitting adequate battery charge. The units were initially programmed to transmit data on a 12-hour GSM interval, but this was later changed in July to a 24-hour interval to conserve battery charge during the shorter winter days when solar recharge was limited.

The GPS location data were uploaded to the Glosendas manufacturer's data acquisition system (http://www.glo sendas.net). The software interface displays information on the battery charge (as a percentage of maximum), the times of the last and next scheduled GPS data transfer, and provides access to all GPS location fixes. Using this platform, the locations, movements and GPS battery life of tagged Chestnut teal were monitored remotely. For one female duck, relatively unchanged GPS locations for multiple days suggested a mortality event approximately 30 days after trapping, and an attempt was made to recover the tracker.

Chestnut Teal were labelled with a unique identification label based on the site of capture (e.g., PP for Parnka Point), the numerical order of capture, and their sex ('M' or 'F'). The final data for each GPS unit was downloaded as a CSV file. The variables provided for every GPS fix included the time, number of satellites contact for positions, battery charge, latitude and longitude, altitude, speed (km/h), direction (degrees), and temperature (°C).

2.7 Data analysis

The first 12 days of tracking data post-capture were discarded prior to data visualisation and analysis to control for behavioural changes caused by the baiting and trapping that could affect the results. This 12-day time frame was chosen based on a clearly visible shift in track locations away from Parnka Point that occurred twelve days after the first trackers were deployed, which was seven days after all trapping at the site ceased.

2.7.1 Chestnut Teal movement and home range size within the CLLMM region

Minimum Convex Polygon (MCP) plots represent the smallest area that encompasses some fixed percentage of an individuals' movements. The 95% MCP represents the area covered by an individual during its 'normal' activities, with any movement sitting outside the 95% region being classed as 'exceptional activities'. The Minimum Convex Polygon (MCP) area was calculated for each individual from 50% to 100% confidence intervals at 5% increments using *adehabitatHR* package (Calenge & Fortmann-Roe 2023) in R (R Core Team 2024). The MCP areas for the 95% confidence interval was plotted with the track locations for each individual onto a map of the Coorong using *ggplot2* (Whickham 2016) and *ggmap* (Kahle & Whickham 2013) packages in R.

During the relatively short tracking periods some individuals did not move far from the trapping location at Parnka Point, whereas others did disperse further. Given the contrasting information provided, I categorised ducks as 'Movers' or 'Non-Movers'. The individuals were split into the two groups by assessing the movements away from Parnka Point using *ggplot2* (Whickham 2016) and also by listing the 95% MCP areas in descending order, to identify the largest dispersal segments.

Kernel Utilisation Distribution (KUD) was used to assess the home range areas of an individual. This approach differs from MCP as it estimates the probability distribution of an occurrence using a smoothing function around each GPS point. The KUD was calculated for each individual at 50% and 95% confidence intervals using the *adehabitatHR* package (Calenge & Fortmann-Roe 2023). The KUD areas for 'Movers' and 'Non-Movers' were plotted separately, with the KUDs for each individual overlayed to identify the 'hot spots' of activity for these two groups.

2.7.2 Movement patterns

The straight-line trajectories for each individual over the tracking periods were calculated within 15-minute intervals, using the function *as.ltraj* from the package *adehabitatLT* (Calenge, Dray & Royer 2023). Due to a GPS transmission issue, the data for the individual labelled PP06F was recorded at hourly instead of 15-minute intervals, so hour intervals were used for the trajectory calculations instead. To categorise each trajectory as occurring either during the day or night, the time of twilight before sunrise and after sunset of each day were calculated using the package *suntools* (Bivand & Luque 2023). Daytime was further separated into morning (sunrise to 10:00), midday (10:00 to 14:00) and afternoon (14:00 to sunset). To understand movement away from the trapping site, the distance from the trapping site at Parnka Point to the coordinate of each trajectory segment was calculated using the *st_distance* function of the *sf* package (Pebesma 2018; Pebesma & Bivand 2023).

A Generalised Linear Mixed Model (GLMM) was used to model average distance per unit of time as a function of sex and time of day, assuming a Tweedie distribution for the response variable, and including a random intercept for each individual. The model was fitted using the *glmmTMB* package (Brookes, M et al. 2017). The estimated marginal means from this model were calculated to display the main effects of time of day using the *emmeans* package (Lenth 2024). A GLMM was also undertaken after excluding data for one individual (PP02F) with the longest tracking duration, to assess whether the statistical results remained consistent.

2.7.3 Obtaining water depths at Chestnut Teal locations

Tide height data at four water logger sites (Long point, Parnka Point, Woods Well, and Snipe Island) within the north and south Coorong lagoons was obtained (Figure 7) (WaterDataSA 2024). Vectors were created within a polygon created around the Coorong extent between the midpoints of each water logger site using ArcGIS Pro to delineate sectors of the Coorong lagoon. Chestnut Teal fixes within each sector were matched to the recorded water level in the sector at the time of the fix. In combination with elevation data from a Digital Elevation Model (DEM; (Hobbs, O'Connor & Gibbs 2019), this allowed calculation of the water depth at each Chestnut Teal location. For each Chestnut Teal coordinate, the elevation at that site was subtracted from the tide height value from the respective water logger at the nearest five-minute time interval to produce a water depth value (as both were referenced to the Australian Height Datum). Water depth at the Chestnut teal locations was modelled as a function of sex, time of day, and water logger site was examined using a GLMM, a random effect for individual differences, and a T-distribution for the response. Another GLMM was undertaken with PP02F excluded from the data set to, to assess whether the statistical results remained.

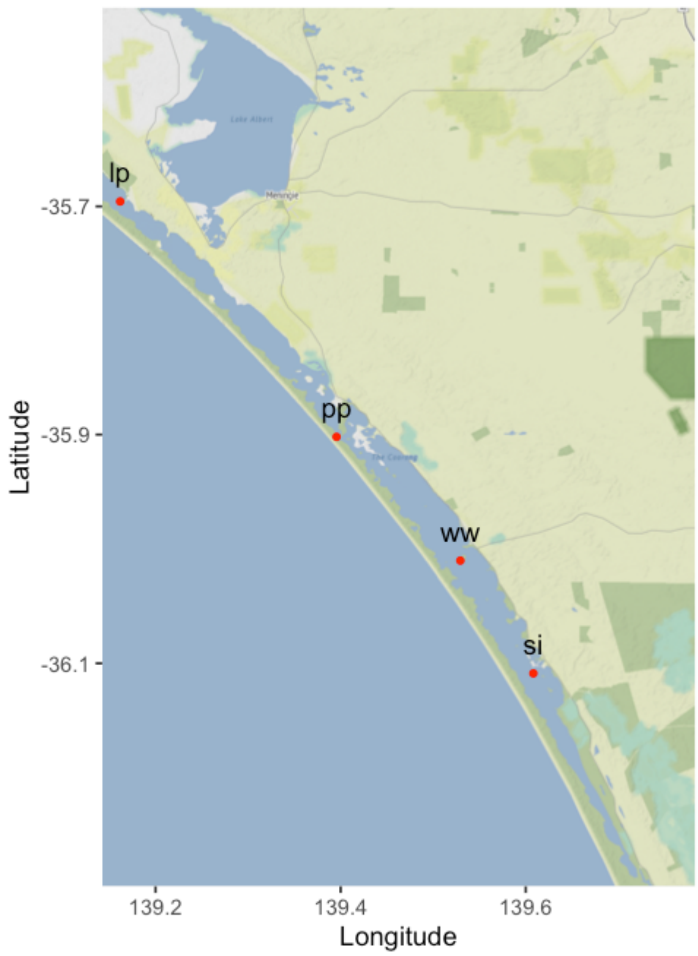

Figure 7: Map of the Coorong with the locations of the water logger sites indicated with red points. The two-letter site name abbreviations refer to; lp- Long Point, pp- Parnka Point, ww- Woods Well, and si- Snipe Island.

3.1 Trapping results

Twelve Chestnut Teal, 8 males and 4 females, were successfully caught in May 2024 at Parnka Point and released with GPS units attached. Grey Teal were also caught in the trap at Parnka Point, in higher numbers than Chestnut Teal, and were immediately released when the trap was cleared after Chestnut Teal captures. The average weight was 568 g for males and 515 g for females and the trackers weighed 2.2% of average body weight (Appendix A). Chestnut Teal were not successfully caught on a second sampling occasion in July 2024 at Morella Basin, which was more limited due to time constraints that restricted the period of pre-baiting and the duration of catching efforts.

The deployed GPS trackers recorded coordinates for 15-108 days with a median of 25 days (Figure 8, Appendix A). The causes of the short deployment periods before most trackers stopped recording were unknown. One individual was assumed to be deceased as the tracker was transmitting from the same location for over a 24h period before it stopped transmitting. The longest tracked individual, PP02F, was observed resting on the shore during the second trapping trip at Morella Basin in July. The movement patterns of this individual do not suggest a reason as to why it kept transmitting considerably longer than the others.

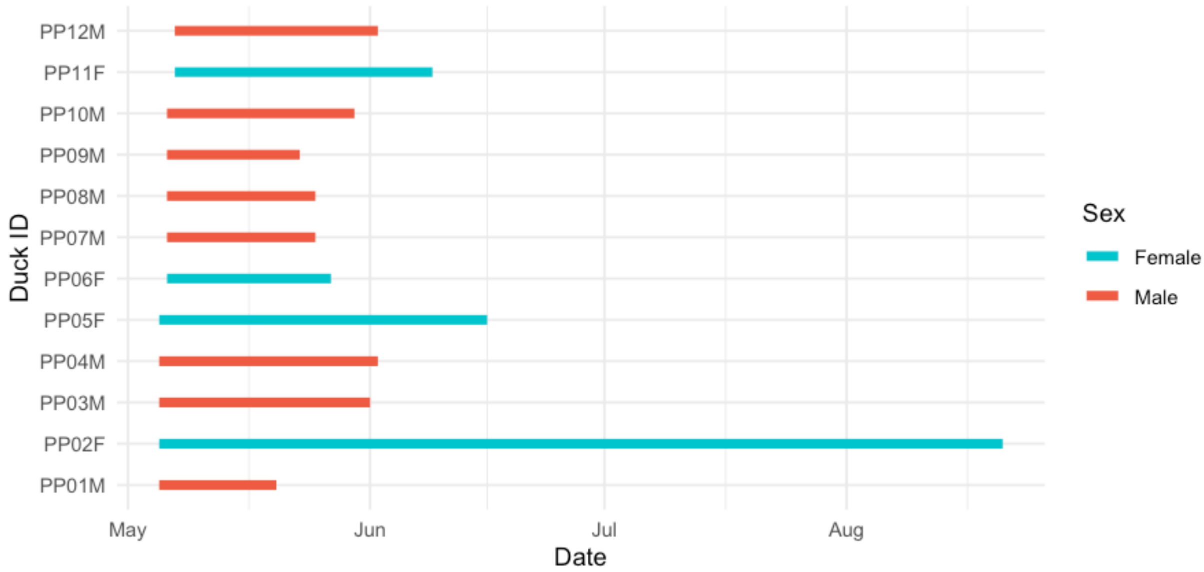

Figure 8: The tracking period for each Chestnut Teal individual with dates from May to August. The start date varies as the GPS units were deployed on Chestnut Teal over three days. The colour indicates the sex of the Chestnut Teal.

3.2.1 Minimum Convex Polygon (MCP)

Within the 'Movers' group, the 95% MCP area for three individuals was over 1000 ha but was under 1000 ha for PP10M, since PP10M's movements away from Parnka Point did not fit within the 95% MCP (Table 1). The 95% MCP areas for the 'Non-Movers' were all under 1000 ha, but vary from 22 ha (PP08M) to 731 ha (PP05M) (Table 1).

Within the 'Movers' group, PP02F and PP11M had substantially more movements away from Parnka Point than PP06F and PP10M (Appendix B). However, it must be considered that PP02F was tracked for a longer period. PP06F moved further north than any other individual and did not travel south of Parnka Point. The plots in Appendix C show a tendency for the 'Non-Movers' to aggregate around the point of Parnka Point and along the other shorelines of the peninsula.

The MCP area for each duck changes depending on the confidence level used, and the amount of change varies between individuals (Table 1, Appendix D). For individuals whose movements were more spread out (e.g., PP02F, PP06F and PP11M) the slope of home range level (confidence level) against home range size is less steep than those that locations are more clustered (e.g., PP10M, PP01M) (Appendix D).

Table 1: Minimum Convex Polygon (MCP) and Kernel Utilisation Distribution (KUD) areas (ha to the nearest whole number) at 50% and 95% confidence intervals for each individual with the percent change between 50% and 95% confidence intervals and mean and median of each value below

Duck	MCP area (ha)			KUD area (ha)		
ID	50%	95%	% change	50%	95%	% change
PP01M	44	55	24	36	177	386
PP02F	6014	20726	245	3508	21334	508
PP03M	166	302	81	97	557	476
PP04M	45	363	711	84	490	481
PP05F	510	731	43	108	704	551
PP06F	68	3740	5397	6224	35876	476
PP07M	119	401	238	140	675	382
PP08M	10	22	113	8	41	394
PP09M	47	212	354	144	710	393
PP10M	118	161	36	338	1391	312
PP11F	7952	14838	87	6598	38235	479
PP12M	65	600	818	84	578	586
Mean	1263	3513	679	1447	8397	452
Median	93	382	176	124	689	476

3.2.2 Kernel Utilisation Distribution (KUD)

The 95% KUD areas for the 'Movers' were over 10000 ha, and were under 10000 ha for the 'Non-Movers' (Table 1). PP10M was moved from the 'Movers' group into the 'Non-Movers' group for the KUD analysis since the movement outside Parnka Point was not within 95% of total movement. The 95% KUD areas for the 'Non-Movers' ranged from 41 ha (PP08M) to 1391 ha (PP10M) (Table 1). The 50% and 95% KUD for the 'Movers' and for the 'Non-Movers' overlapped at Parnka Point (Figure 9 and Figure 10).

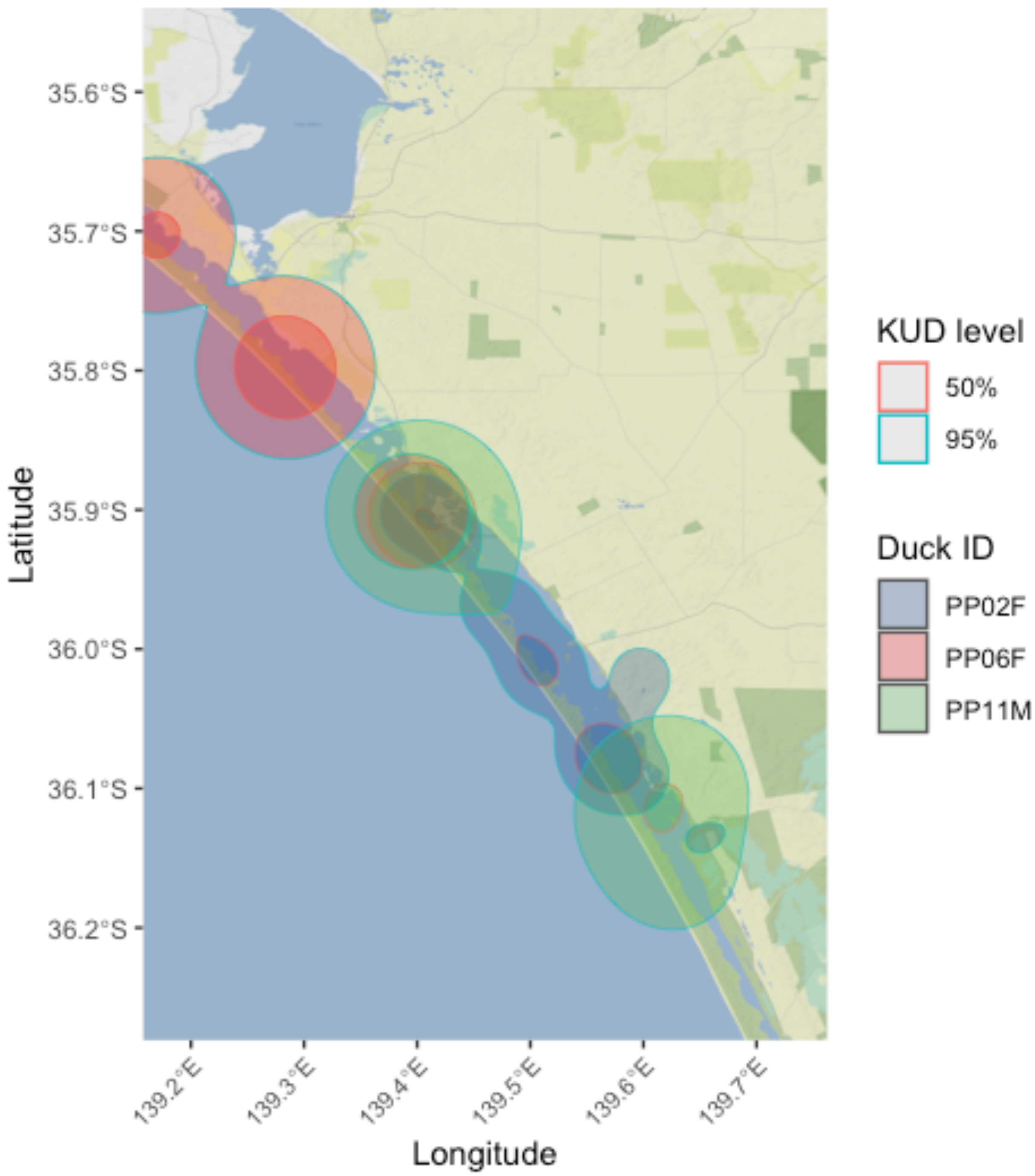

Figure 9: Map of the Coorong with the KUD areas at 50% and 95% confidence levels coloured for the individuals grouped as 'Movers'. The 50% and 95% KUD areas represent the area of utilisation for that individual's movements for 50% and 95%, respectively, of the tracking period.

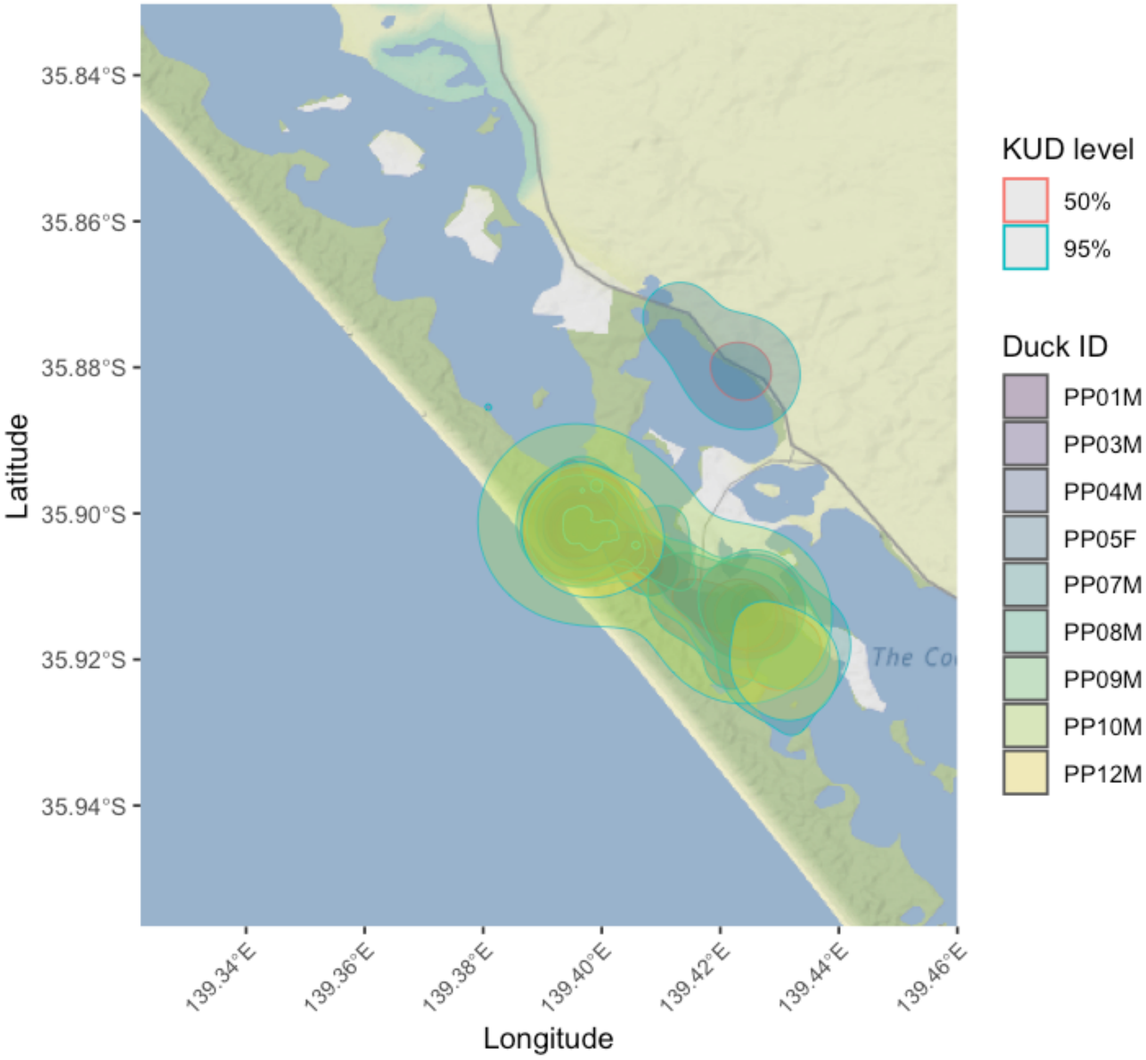

Figure 10: Map of the Coorong with the KUD areas at 50% and 95% confidence levels coloured for the individuals grouped as 'Non-Movers'. The 50% and 95% KUD areas represent the area of utilisation for that individual's movements for 50% and 95%, respectively, of the tracking period.

3.3 Movement patterns

The total distance moved by each Chestnut Teal increased with the length of the tracking period, but it was not a direct rank correlation (Table 2). For example, PP11M moved the second longest total distance but was not the second longest tracked (Table 2). The average distance moved per day and overall median distance moved per day for all Chestnut Teal was 8 km. The same value for mean and median indicates that large individual daily distances were not common. There was variation in the maximum distance moved on a particular day, with the highest being 60kms and the lowest being 5km (Table 2, Appendix E).

Table 2: Summary of total distance travelled for the whole tracking period, the average distance travelled each day, the median distance travelled each day, the maximum distance travelled on one day (km) for each duck ID. The values are rounded to the nearest whole number.

ID	Total distance (km)	Average distance per day (km)	Median distance per day (km)	Maximum distance per day (km)
PP01M	16	4	5	7
PP02F	1025	11	9	60
PP03M	130	8	8	16
PP04M	145	10	9	19
PP05F	131	4	2	16
PP06F	58	7	2	20
PP07M	83	10	12	20
PP08M	28	3	3	5
PP09M	83	12	13	17
PP10M	126	9	10	16
PP11M	263	11	6	60
PP12M	125	7	9	16
Mean		8		
Median			8	

3.3.1 Effect of time of day on movement patterns

Chestnut Teal moved significantly more in the afternoon and at night than at other time of the day (Appendix F). It was also found that males moved more than females, but this effect varies with time of day (Figure 11). The time of day with the largest difference between movement of males and females was the morning (Figure 11). The analysis undertaken excluding PP02F from the data set found very similar results (Appendix G).

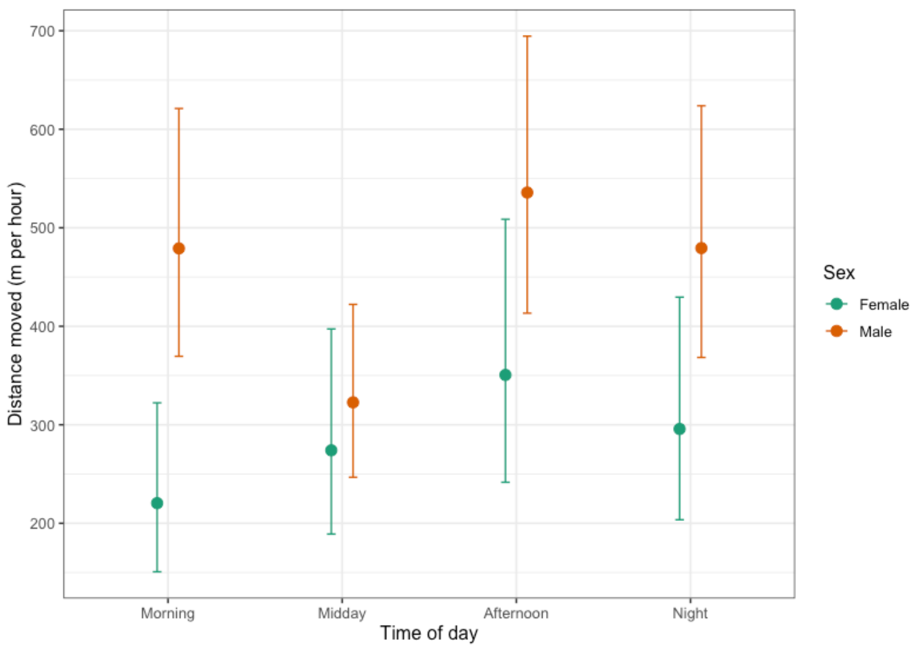

Figure 11: Average distance (m) moved per hour across each time of day for all Chestnut Teal with bars representing 95% confidence intervals. The colours represent the sex.

The difference between average daytime movement per hour and nighttime movement varied between individuals (Appendix H). Movement was not consistently higher during either night or day. Between individuals, the difference between average movement per hour at different times of days varied, as some move more than others (Appendix I). No specific time of day consistently shows more movement than another across all individuals (Appendix G).

3.3.2 Movements away from Parnka Point

Time spent away from the capture site (Parnka Point) varied between individuals. Most departed and returned many times throughout the tracking period, but some did not return after their departure (eg. PP06F, PP02F) (Figure 12, Figure 13). For PP01M, PP03M, PP04M, and PP12M, the times away from Parnka Point seem to be mostly during the night (Figure 12). PP02F spent most of the tracking period between 20-30 kms away from Parnka Point (Figure 13).

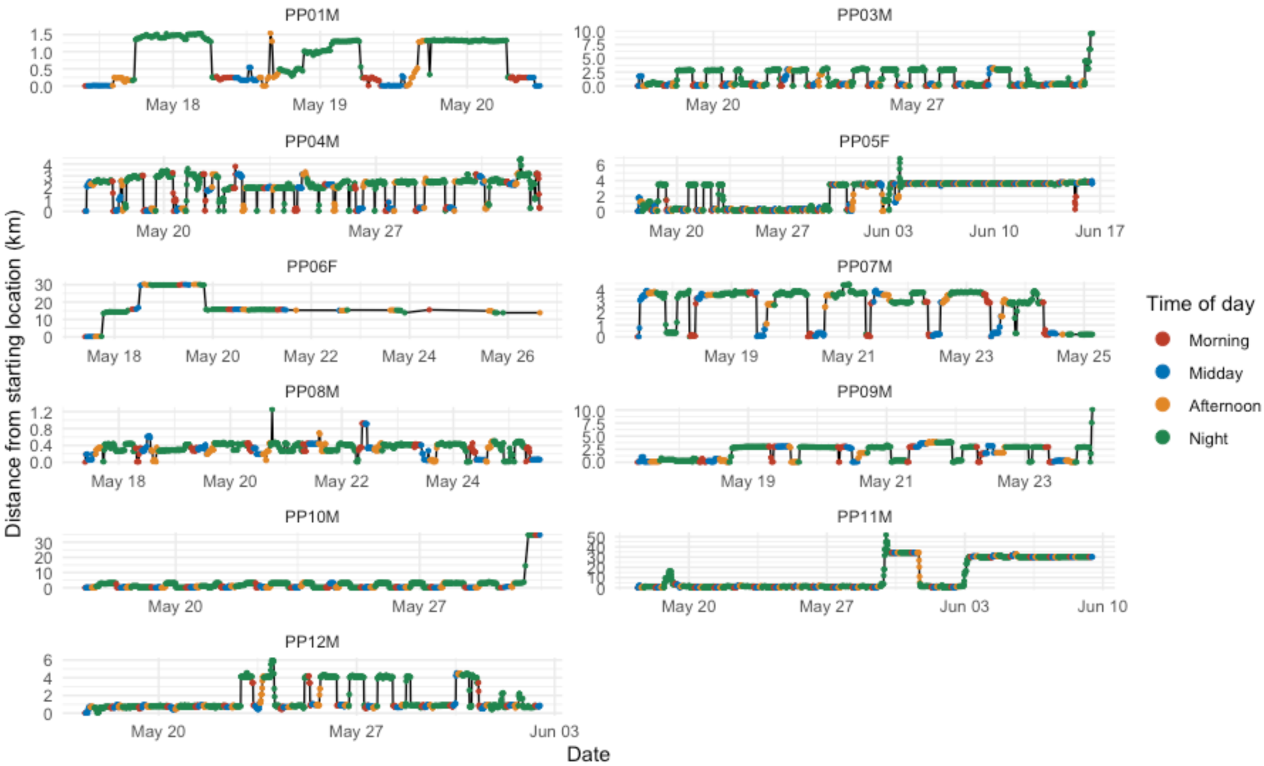

Figure 12: Distance (km) of each Chestnut Teal away from the starting location (capture site) over the tracking periods. The points are coloured based on time of day.

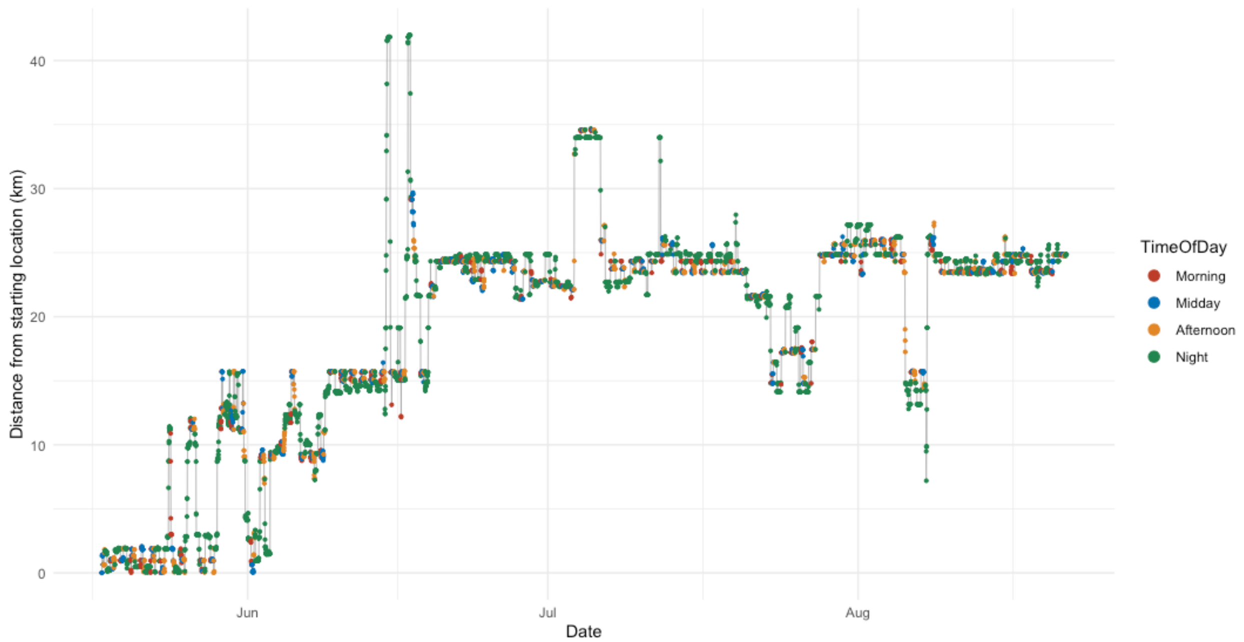

Figure 13: Distance (km) of PP02F away from the starting location (capture site) over the tracking period. The points are coloured based on time of day.

3.4 Ecological requirements- water depth

Male Chestnut Teal are found in deeper water than females and are more likely to be on water than on land relative to females (Figure 14, Appendix J). However, there is no data recorded for males at Long Point, so the comparison is only between the other three sections. The depth at the different sites varies with Snipe Island and Woods Well having significantly shallower depths than Long Point (Figure 14). Individuals at Long Point were more likely to be found in the water than any other site. Individuals at Snipe Island and Woods Well were likely to be found out of the water. At night, the depths at Snipe Island and Woods Well were significantly deeper than other times of day. The analysis of water depth undertaken excluding PP02F from the data set found very similar results (Appendix K).

Chestnut Teal were found in depths ranging from 2.9 m in the water to 29 m out of the water and mean and median values of 0.04 m out of the water and 0.02 m in the water, respectively (Appendix L). The water depth occupied did not change significantly as individuals moved across the Coorong (Appendix L). The range of water depths occupied by individuals changes minimally over the tracking period, except for a short period between July and August when PP02F was not in the water (Appendix L).

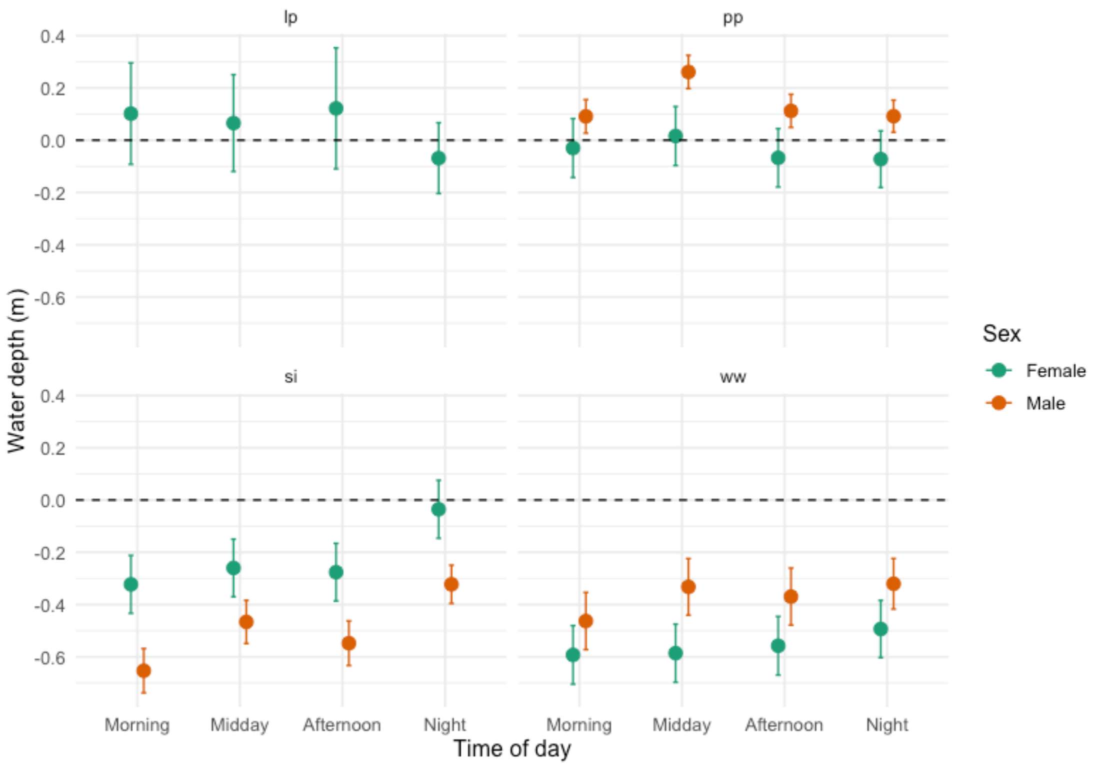

Figure 14: Average water depth (m) that Chestnut Teal are found in at different times of day. Positive values represent Chestnut Teal in water and negative values represent Chestnut Teal out of water. The four plots represent each water logger site. The points are coloured by sex and the bars represent 95% confidence intervals of males and female. Long Point is missing values for males as there are no records of male Chestnut Teal at the site.

4 Discussion

Using GPS telemetry, this study shows that the behaviour of Chestnut Teal varies over the diurnal cycle, in terms of the distances moved and water depths occupied. Parnka Point was identified as a hotspot of activity for most tracked individuals, and movement away from this trapping site was isolated to a few individuals. GPS tracking allowed the night-time movements of Chestnut Teal to be documented (which is unachievable with day-time visual surveys) and continuous tracking of individuals for up to three months provided insight into how these ducks respond to seasonal water level changes in the Coorong. Finally, this study provides some understanding of Chestnut Teal habitat use in the Coorong and can inform appropriate trapping methodologies for future research on this species.

4.1 Behavioural Changes over a diurnal cycle

Chestnut Teal distances moved peaked in the morning and afternoon (Figure 11), which suggests that their behaviours change across the diurnal cycle. Increased movement is associated with an increased probability of foraging relative to roosting behaviours in other waterfowl (Overton & Casazza 2023). Therefore, increased Chestnut Teal movement in the morning and afternoon is likely due to increased foraging during these periods. Surveys of Chestnut Teal during the day identified early morning and late afternoon as peak feeding activity times (Hamilton, Taylor & Hepworth 2002) and surveys conducted during day and night (where Grey Teal and Chestnut Teal observations were combined for night surveys) also observed the same feeding patterns (Austin, Ribot & Bennett 2016). Diurnal movement patterns in waterbirds may function as predator avoidance, adapting to distinct threats posed by diurnal versus nocturnal predators that require different evasion strategies (Austin, Ribot & Bennett 2016). Additionally, diurnal feeding patterns have been suggested to coincide with cycles of emergence of insects that waterbirds feed on at sunrise and sunset (Hamilton, Taylor & Hepworth 2002). During annual waterbird condition monitoring, the percent of birds foraging when counted is used as a measure of the quality of habitat in the Coorong (Paton, D et al. 2023). Therefore, the timing of Chestnut Teal foraging activity can be used to inform these monitoring efforts to ensure the index is measured correctly.

Waterfowl are known to have a preferred foraging depth (Collazo, O'Harra & Kelly 2002). Therefore, water depths occupied will change during foraging and non-foraging activities. The water depths occupied by Chestnut Teal varied throughout the diurnal cycle and differed across the four sites (Figure 14), indicating that distinct water depth preferences are likely associated with patterns of behaviour. Studies of water depth preferences in other *Anas* species in North America found average foraging depths of < 5 cm, with the smaller species foraging in shallower water (Johnson & Rohwer 2000). Chestnut Teal are known to be able to forage between 0 cm to 20 cm water depth, but ideal foraging conditions are 0.5 cm to 1.5 cm (O'Connor, Rogers & Pisanu 2013). In the Coorong, Chestnut Teal feeding in shallow water are likely targeting areas where the seagrass *R. tuberosa* is more abundant and accessible (Paton, F & Paton 2023). Chestnut Teal locations in water deeper than 20cm or on land are likely to represent roosting behaviours.

Chestnut Teal foraging and roosting depths can be used to infer duck behaviours across the diurnal cycle and across the four sites (Figure 14). Assuming a foraging depth range of 0-20 cm, it appears the Woods Well site was largely used for roosting because mean depths occupied here were all out of the water. Similarly, roosting out of the water appeared common at the Snipe Island site, except there was evidence that females moved to the shoreline to forage at night here. Parnka Point and Long Point were likely used by Chestnut Teal for roosting and feeding. However, Parnka Point was the only area where both male and female Chestnut Teal occupied depths suitable for feeding and roosting, which suggests that conditions here might be suitable for both behaviours.

Throughout the tracking period, water depth increased throughout the Coorong (Appendix M) which is characteristic for the time of year, due to increased rainfall and low average daily temperatures. There was no distinct pattern of the female Chestnut Teal which was tracked the longest occupying increasing water depths over the tracking period, suggesting that it was adjusting their locations to maintain a relatively constant foraging depth (Appendix L). The movement of waterfowl in North America is known to track food availability (McDuie et al. 2019), and similarly Chestnut Teal are likely to move to access suitable foraging habitats (O'Connor, Rogers & Pisanu 2013).

Understanding the depths at which Chestnut Teal forage and roost is crucial for predicting habitat use in response to changing conditions in the Coorong. The Coorong faced severe drought in the 2000s (Leterme et al. 2015), and more recently a flood in 2022-2023 (DEW 2023). Changes in water depth across the Coorong will affect food availability, mainly availability of *R. tuberosa* for waterfowl (O'Connor, Rogers & Pisanu 2013; Paton, D et al. 2024). This study shows that Chestnut Teal consistently occupied certain depths, even as water levels increased during winter (Appendix M), and might exhibit similar behaviours during large-scale flood events.

4.2 Difference between male and female Chestnut Teal movements

Male Chestnut Teal moved more than female Chestnut Teal on average over the diurnal cycle (Figure 11), which suggests a difference in behaviours between the sexes. This could be due to different activity budgets between the sexes, which has been observed in waterfowl

(Mukherjee, Pal & Mukhopadhyay 2020). Increased movement in male waterfowl in North America was suggested to reflect male individuals seeking out breeding opportunities (Lamb et al. 2021). Observational surveys of Mandarin ducks breeding in China found male waterfowl spent more time standing and fighting, and female waterfowl spent more time foraging, and that these behavioural differences were consistent throughout the day (Trang et al. 2023). An observational study of *Anas* species in North America out of breeding season also found female waterfowl to forage more than male waterfowl (Johnson & Rohwer 2000). Without also conducting observational studies on the behaviours of Chestnut Teal, the GPS data alone cannot conclude why male individuals moved more than females, and whether females foraged more, as is seen in other studies. Between-sex movement differences were not likely to be caused by breeding behaviours as the tracking period for all male Chestnut Teal was outside the range of the breeding season (Simpson, Day & Trusler 2010). Inconsistent differences between male and female movements across the diurnal cycle suggest that the influencing factor also varies across the cycle. Understanding the behavioural differences between sexes is crucial for assessing how habitat use differs.

Difference in male and female Chestnut Teal behaviour is further suggested by male Chestnut Teal spending more time in water on average than female Chestnut Teal (Figure 14). Difference in water depths could be related to males' larger body size allowing them to forage in deeper water (Simpson, Day & Trusler 2010), but is unlikely since the variation was not uniform over time of day and between sites (Figure 14). However, males' larger body size may require more foraging to meet higher energy demands, which would require more time to be spent in the water, and more time moving. Identifying the reason for variation in water depth preference between sexes can lead to understanding how male and females use the system differently, in terms of key foraging and roosting habitats. Additionally, differences in water depth preferences between male and female Chestnut Teal could have implications for breeding suitability, if changing water levels create conditions more suitable for one sex over another.

4.3 Extent of movement in the Coorong

The trapping site at Parnka Point was a hotspot for Chestnut Teal activity and most individuals did not move far from this site during the tracking period (Figure 10, Figure 12). Consequently, the home ranges for most Chestnut Teal were concentrated around Parnka Point. This could be due to better conditions, such as more suitable foraging and roosting areas at Parnka Point over other areas of the Coorong (as suggested above). Repeated movements away from Parnka Point at night (Figure 12) suggests more suitable roosting conditions elsewhere at night, while Parnka Point may be primarily used as a roosting site during the day. Home range sizes for other waterbird species that have been tracked in the Coorong were all found to be over 10,000 Ha (Mott et al. 2022), which is similar to the 95% KUD of the Chestnut Teal 'Movers' but significantly higher than the 'Non-Movers'. However, longer tracking times have been found to increase the accuracy of home range estimation (Mitchell, White & Arnold 2019). Therefore, the longer tracking durations of waterbirds previously tracked in the Coorong make direct comparisons of these with the Chestnut Teal home ranges challenging. Identifying home ranges for Chestnut Teal is important to direct conservation effects to areas of most frequent use, and comparing conditions at high- and low-use areas could help to understand what defines suitable habitat for this species.

The reason for some Chestnut Teal to travel greater distances than others was not identified in the analysis. The individual that was tracked the longest could be assumed to travel further based on its extended tracking period, but this doesn't indicate why the other three individuals would also travel away from Parnka Point. This individual travelled the furthest distance of any Chestnut Teal from Parnka Point, reaching 40 kms south, near Salt Creek in the southern Coorong lagoon. All individuals stayed within the Coorong region during the tracking period, with most staying within the main lagoons, and a few using small inland water reserves (Appendix B, Appendix C). The variation in movement timing suggests that the tracked Chestnut Teal did not travel together (Figure 12, Figure 13) despite their tendency to flock and form monogamous pairs that remain together outside the breeding season (Williams 2023; Birdlife Australia n.d.). Further studies to track of larger groups of Chestnut Teal might better inform how these flocks are formed. Recognising the factors that attract Chestnut Teal to move between areas is essential for predicting population abundances within the system.

4.4 Trapping success

This study successfully trapped Chestnut Teal in the Coorong, a region where trapping of this species had previously been attempted but was not achieved (Mott et al. 2022). The process used for trapping Chestnut Teal was successful when undertaken over a two-week period at

Parnka Point but was not successful within a one-week period at Morella Basin. Although site differences cannot be ruled out, this result suggests that the numerous days of baiting prior to using the trap, as well as subsequent baiting within the open trap, could be important for conditioning the Chestnut Teal to feed at the trapping site and inside the trap itself. The number of teal caught each day decreased over the trapping period at Parnka Point (Appendix A), while the same number of ducks remained in the area, indicating that trap weariness was developed. Trap weariness has been observed in studies for a range of animals, where the trapping process effects a change of state, and individuals will adapt their behaviour after being caught (Pradel & Sanz-Aguilar 2012). These trapping results can be used to inform future studies that require trapping of Chestnut Teal or related *Anas* species in similar habitats.

4.5 Limitations

Whilst the tracking data collected provided valuable insights into Chestnut Teal habitat use, the results obtained relate only to the tracking period of May to August which limits conclusions of year-round habitat use. This study was also limited by the short tracking duration (less than one month) of many individuals. The GPS units that were deployed on twelve Chestnut Teal were successful in collecting location data (Figure 8, Appendix A), however the reason why the GPS units stopped transmitting data is unknown. Possibly, some Chestnut Teal moved beyond GSM (phone network) coverage and therefore data transmission was lost. However, it is unlikely that Chestnut Teal could travel out of GSM range within 12 hours (the time between transmissions) since coverage is widespread within SA. Alternatively, the saline waters of the Coorong might have degraded the GPS units. When contacted, the manufacturer Ornitela stated that the GPS units have not been tested in high salinity environments (Ramunas Zydelis Ornitela, Pers. Comm., 16 Oct 2024). Interestingly, the individual tracked longest spent more time on land than in water (Appendix H), while those tracked for shorter periods spent more time in water, suggesting that reduced saltwater exposure could have been a factor in extended tracker transmission.

The tracking duration of one GPS unit was shortened due to the presumed death of the tagged Chestnut Teal. The death may not be a direct effect from the GPS unit or harness itself and might have been caused by a natural predator (e.g., a fox). The GPS unit was retrieved but it was not clear how the harness was dislodged from the body of the Chestnut Teal (Figure 16).

A researcher who has used Teflon harnesses on birds previously suggested that the Teflon appears to have been cut due to the minimal fraying (Liberty Olds Green Adelaide, Pers. Comm. 17 Oct 2024). The damage on the seal of the GPS unit also suggests that the conditions in the Coorong, such as hyper salinity, may have caused some damage (Figure 15).

Figure 16: PP11F GPS unit as it was found in the Coorong. The broken Teflon was separated from the rest of the harness, and the crimps are still intact as they were when it was deployed.

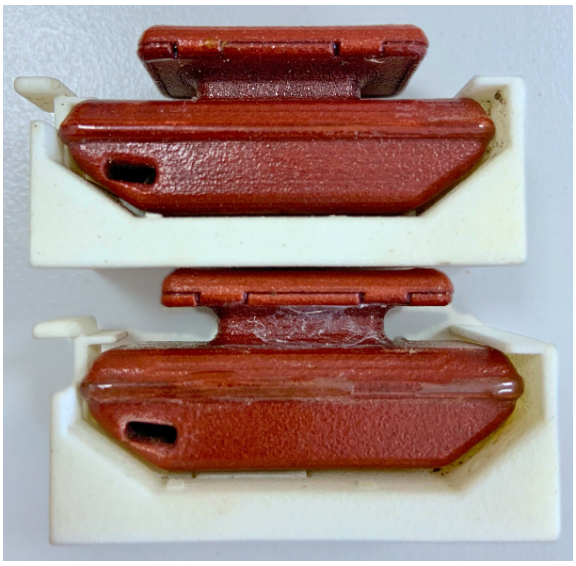

Figure 15: An unused GPS unit (top) compared to PP11F GPS unit (bottom). The PP11F unit has a lighter colour and damage to the seal.

Another limitation to the results is the small number of individuals that were tracked, and the skewed male to female ratio. Chestnut Teal were unable to be caught at Parnka Point in higher numbers due to the trap weariness that developed, and the field staff limitations restricted the number of individuals caught. The male to female ratio was unable to be controlled during trapping and between-sex behavioural differences may explain why more males entered the trap. Hence, comparisons of male and female movements are based on unequal sample sizes, and unique aspects of female habitat use may have been overlooked because only four females were tracked.

An additional constraint on the generalisability of these results is that trapping Chestnut Teal was only successful at one site (Parnka Point). Time restraints on the project meant that Chestnut Teal were unable to be caught at an additional site (although this was attempted). Trapping individuals from different sites would have allowed comparison of habitat use within multiple areas and identified more hotspots of Chestnut Teal activity within the Coorong.

Due to time constraints, it was not possible to conduct additional data analysis to discriminate duck locations on land or water from those locations where ducks were in flight. This would require consideration of the animal's speed at each location fix, to identify periods when ducks were moving between habitats rather than occupying the habitat at that location. Additionally, inference regarding Chestnut Teal behaviours was only based on distances moved and the calculated water depth at GPS locations. Visual surveys at duck hotspots (Hamilton, Taylor & Hepworth 2002), or additional technology such as accelerometers (Yu et al. 2022), could be used in tandem with GPS location data for more accurate behavioural classification.

Although these limitations constrain the generalisability of the results, such as understanding year-round habitat use, and across the whole Coorong system, they do not diminish the value of the data collected. The findings provide insights on a small scale and provide a foundation for further research to build on.

4.6 Future recommendations

To address the limitations of this study, future research should consider the following recommendations. GPS units should be tested prior to deployment, under Coorong-like conditions. This could include submerging trackers in salt water and testing battery life under different weather conditions (e.g. high cloud cover, rain). Harness durability should be tested to ensure longevity. This has been done in other tracking projects by testing the harness design on a captive bird population, prior to deployment on wild birds (Roshier & Asmus 2009). By optimising these methods, longer tracking durations could be achieved for Chestnut Teal in the CLLMM and thereby improve our understanding of how their behaviour and habitat preferences change over an annual cycle.

Additional resources should be allocated to ensure trapping higher numbers of Chestnut Teal is possible. More field staff present on the first few trapping days would allow more Chestnut Teal to be caught simultaneously, without increasing the time taken to deploy the GPS units on each individual. Increased trapping of Chestnut Teal should allow a balanced sex ratio of tagged ducks to be achieved. Furthermore, successful trapping at additional CLLMM locations and a higher sample size of tracked Chestnut Teal would increase the generalisability and management relevance of the results.

5 Conclusion

This study aimed to use GPS tracking to investigate home ranges of Chestnut Teal and examine changes in behaviour over the diurnal cycle, in relation to distances moved and water depths occupied. The findings indicate that Chestnut Teal roost mostly during midday and at night, across three sites in the Coorong. Chestnut Teal are likely to forage in the morning and afternoons, and mostly at Parnka Point. This outcome has identified Parnka Point as an ideal habitat for Chestnut Teal as conditions are suitable for both roosting and foraging. The successful trapping methods used is beneficial to inform best practice for future waterbird projects in wetland systems. However, the limited tracking period and small sample size of individuals suggests that further tracking of Chestnut Teal is needed to increase the applicability of the findings. Further tracking of Chestnut Teal, especially across additional sites, is recommended such that the findings can be used to inform management to support Chestnut Teal populations within the broader CLLMM region.

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Supplementary materials

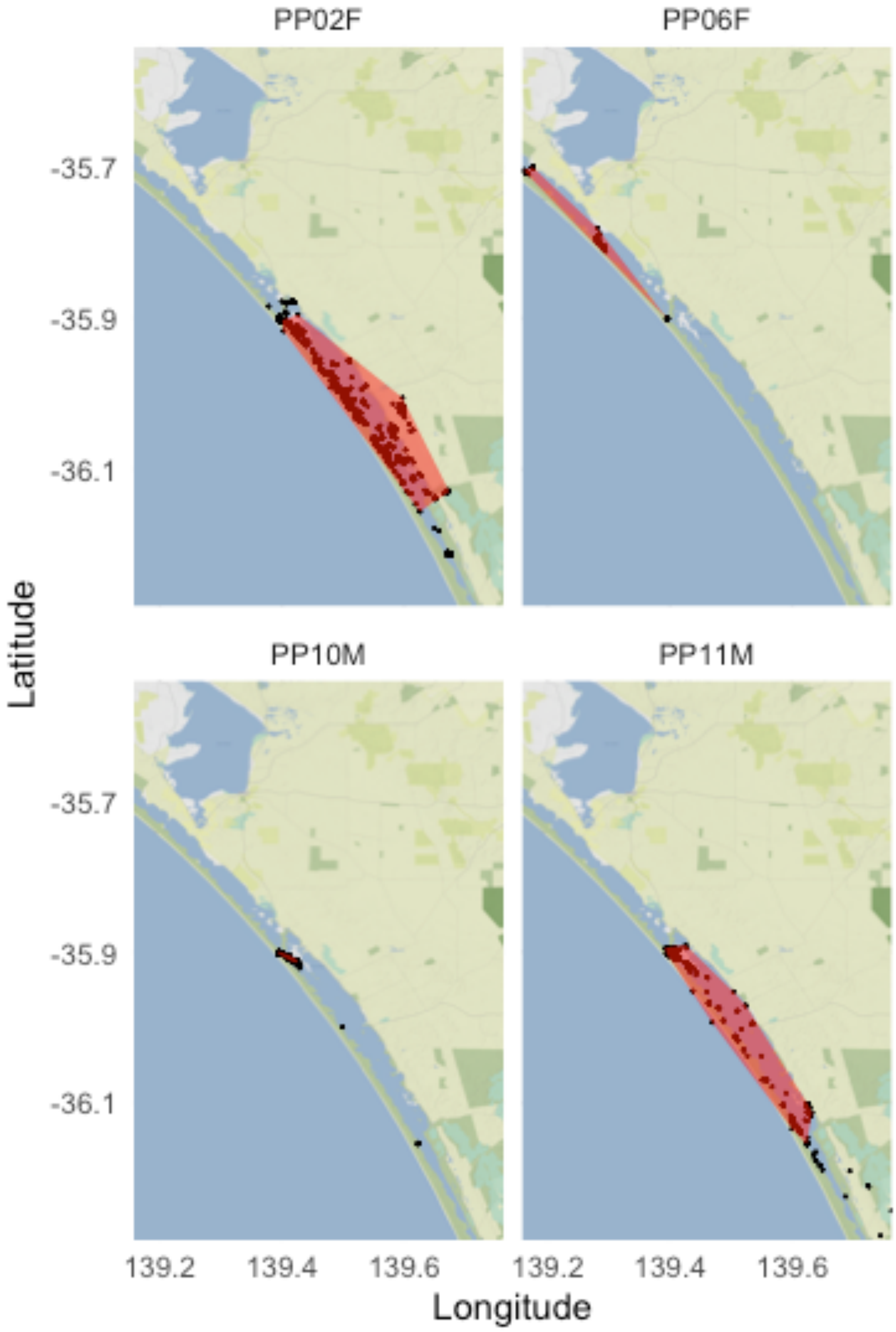
Appendix A   Summary of GPS unit deployment

Capture date weight, the % of body weight of the trackers, length of time tracked, and the number of GPS fixes for each Chestnut Teal ID.

Individual ID	Date caught	Weight (g)	Tracker % body weight	Total days tracked	Total no. of GPS fixes
PP01M	5/5/2024	540	2.2	15	1725
PP02F	5/5/2024	485	2.5	108	13067
PP03M	5/5/2024	615	2.0	27	3535
PP04M	5/5/2024	630	1.9	28	3434
PP05F	5/5/2024	470	2.6	42	5357
PP06F	6/5/2024	560	2.1	21	1239
PP07M	6/5/2024	480	2.5	19	2231
PP08M	6/5/2024	610	2.0	19	2364
PP09M	6/5/2024	600	2.0	17	2128
PP10M	6/5/2024	510	2.4	24	2760
PP11F	7/5/2024	545	2.2	33	4265
PP12M	7/5/2024	560	2.1	26	3367

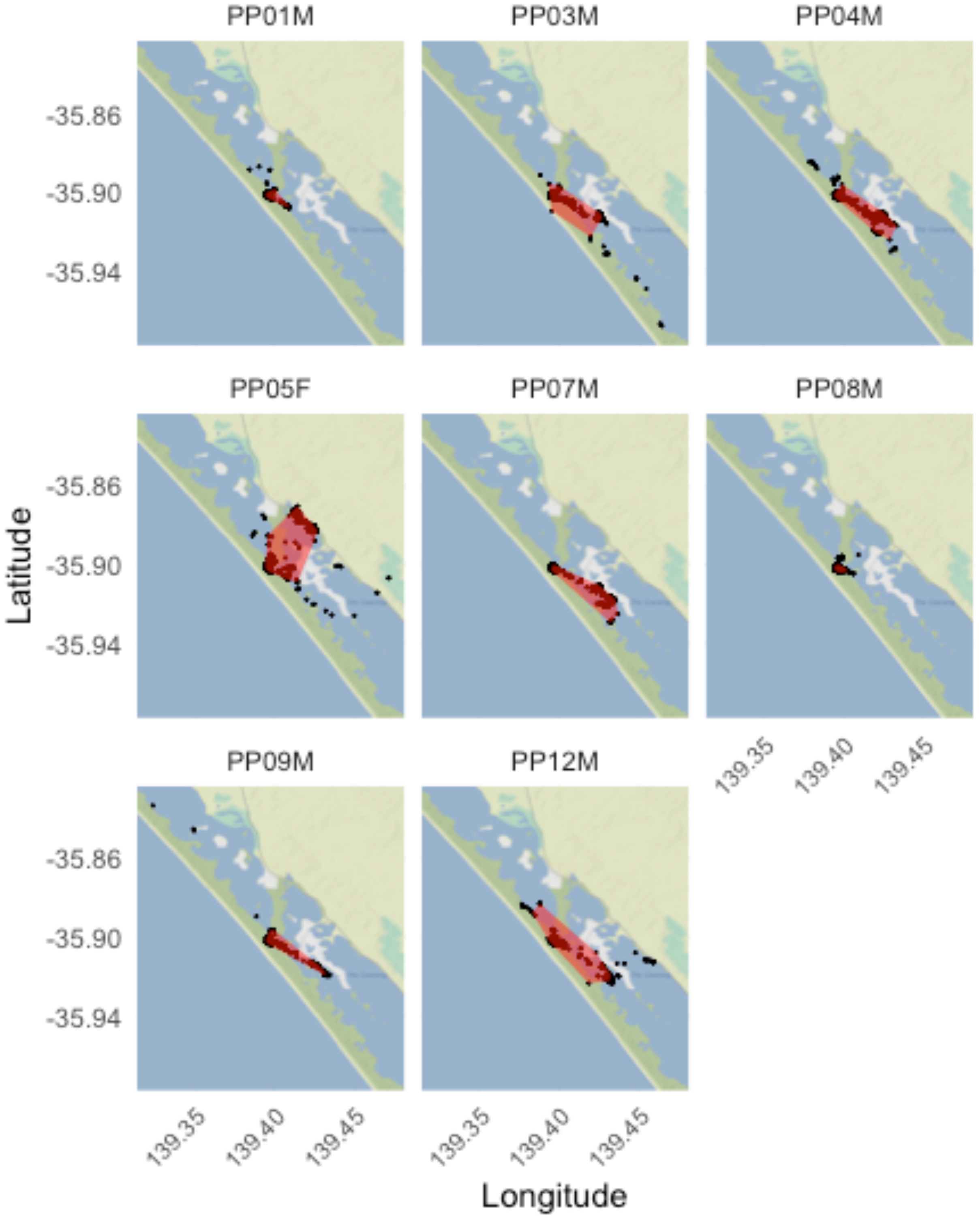
Appendix B 95% MCP polygons for 'Movers'

Map of the Coorong with the points of the locations for the individuals grouped as 'Movers' with the 95% MCP areas coloured in red.



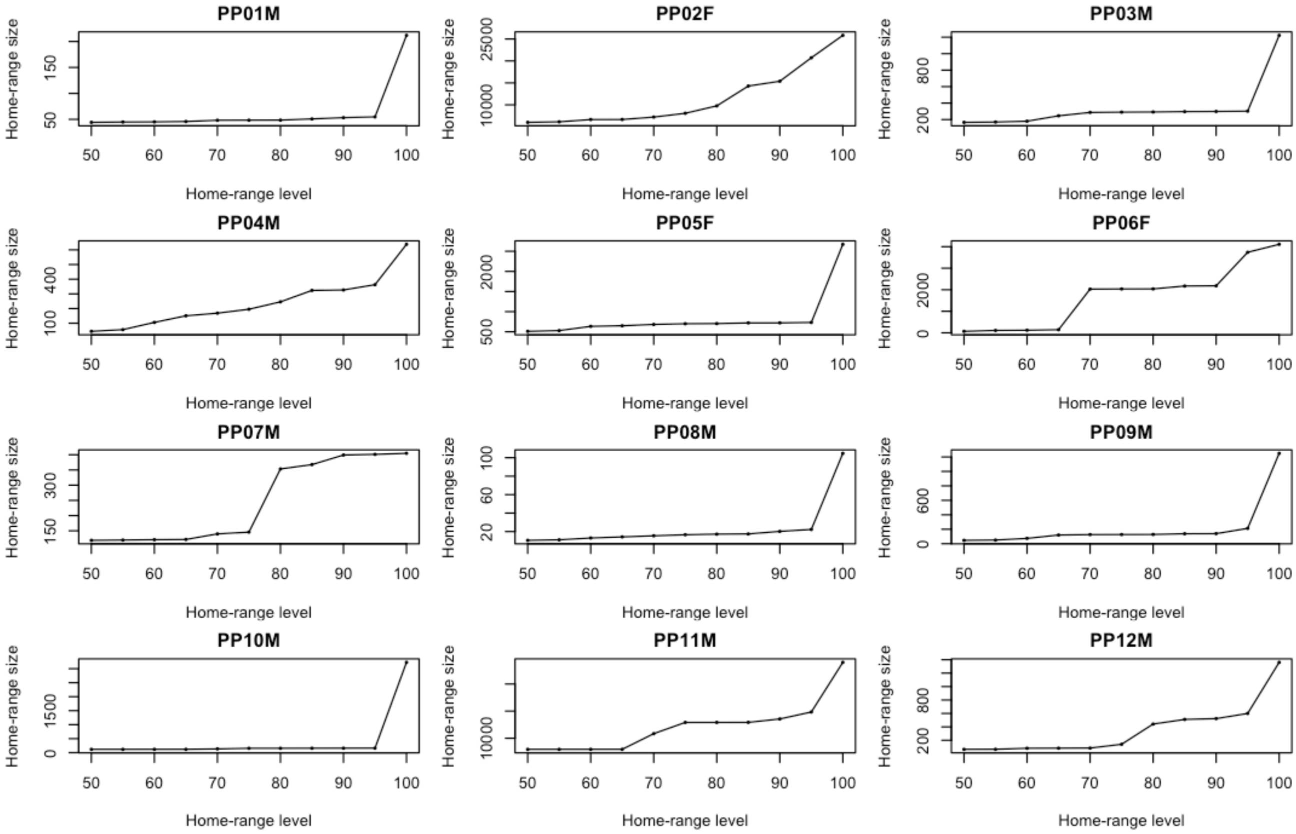
Appendix C 95% MCP polygons for 'Non-Movers'

Map of the Coorong with the points of the locations for the individuals grouped as 'Non-Movers' with the 95% MCP areas coloured in red.



Appendix D MCP home range size across 50-100% confidence levels

Plots of MCP home range size (ha) for each duck ID at increasing confidence levels from 50% to 100% in 5% increments. The point of exponential increase in home range size represents the confidence level that excludes all ‘exceptional movements’ for that individual.



Appendix E Distance moved each day for each individual

Distance (m) moved each day across the tracking periods for each individual. Colours are assigned for days with movement (blue) and days without movement (red).

Appendix F Modelling Chestnut Teal distances moved

Appendix F.1

GLMM results of the effect of time of day and sex on distance per hour with ID as a random effect. Significance codes are 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Family: tweedie (log)				
Formula	totDist/nHrs ~ TimeOfDay * Sex + (1 | ID)			
Data	trajectoriesID0_todSum			
AIC	BIC	logLik	deviance	df.resid
13352.9	13406.5	*-6665.4*	13330.9	960
Random effects				
Conditional model				
Groups	Name	Variance	Std.Dev.	
ID	(Intercept)	0.07862	0.2804	
Number of obs	971			
Groups	ID, 12			
Dispersion parameter for tweedie family	9.24			
Conditional model:				
	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	5.3957	0.1938	27.846	< 2e-16 ***
TimeOfDayMidday	0.2178	0.1259	1.730	0.083634
TimeOfDayAfternoon	0.4640	0.1228	3.777	0.000159 ***
TimeOfDayNight	0.2938	0.1249	2.352	0.018655 *
SexMale	0.7762	0.2342	3.314	0.000919 ***
TimeOfDayMidday:SexMale	-0.6127	0.1834	-3.340	0.000838 ***
TimeOfDayAfternoon:SexMale	-0.3521	0.1777	-1.982	0.047503 *
TimeOfDayNight:SexMale	-0.2932	0.1803	-1.627	0.103832

Appendix F.2

ANOVA results of the GLMM in Appendix F.1. Significance codes are 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Analysis of Deviance Table (Type II Wald chisquare tests)			
Response:	totDist/nHrs		
	Chisq	Df	Pr(>Chisq)
TimeOfDay	19.5509	3	0.0002103 ***
Sex	4.9238	2	0.0264889 *
TimeOfDay:Sex	11.3022	3	0.0101993 *

Appendix F.3

Estimated Marginal Means of the GLMM in Appendix F.1. Confidence level used: 0.95 Intervals are back-transformed from the log scale.

Sex = Female:					
TimeOfDay	response	SE	df	asymp.LCL	asymp.UCL
Morning	220	42.7	Inf	151	322
Midday	274	51.9	Inf	189	397
Afternoon	351	66.6	Inf	242	509
Night	296	56.3	Inf	204	430
Sex = Male:					
TimeOfDay	response	SE	df	asymp.LCL	asymp.UCL
Morning	479	63.5	Inf	370	621
Midday	323	44.2	Inf	247	422
Afternoon	536	70.9	Inf	413	695
Night	479	64.4	Inf	368	624

Appendix G Modelling Chestnut Teal distances moved excluding PP02F from the data set

Appendix G.1

GLMM results of the effect of time of day and sex on distance per hour with ID as a random effect. Significance codes are 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Family: tweedie (log)				
Formula	totDist/nHrs ~ TimeOfDay * Sex + (1 | ID)			
Data	trajectoriesID0_todSum			
AIC	BIC	logLik	deviance	df.resid
8115.6	8163.6	-4046.8	8093.6	572
Random effects				
Conditional model				
Groups	Name	Variance	Std.Dev.	
ID	(Intercept)	0.05893	0.2428	
Number of obs	583			
Groups	ID, 11			
Dispersion parameter for tweedie family	9.24			
Conditional model:				
	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	4.9594	0.2511	19.753	< 2e-16 ***
TimeOfDayMidday	0.6781	0.2359	2.874	0.00405 **
TimeOfDayAfternoon	0.4889	0.2372	2.061	0.03931 *
TimeOfDayNight	0.4956	0.2391	2.073	0.03816 *
SexMale	1.2133	0.2785	4.356	1.33e-05 ***
TimeOfDayMidday:SexMale	-1.0720	0.2675	-4.007	6.14e-05 ***
TimeOfDayAfternoon:SexMale	-0.3755	0.2672	-1.405	0.15992
TimeOfDayNight:SexMale	-0.4929	0.2693	-1.830	0.06725

Appendix G.2

ANOVA results of the GLMM in Appendix G.1. Significance codes are 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Analysis of Deviance Table (Type II Wald chisquare tests)			
Response:	totDist/nHrs		
	Chisq	Df	Pr(>Chisq)
TimeOfDay	10.191	3	0.0170067 *
Sex	10.183	1	0.0014175 **
TimeOfDay:Sex	16.823	3	0.0007686 ***

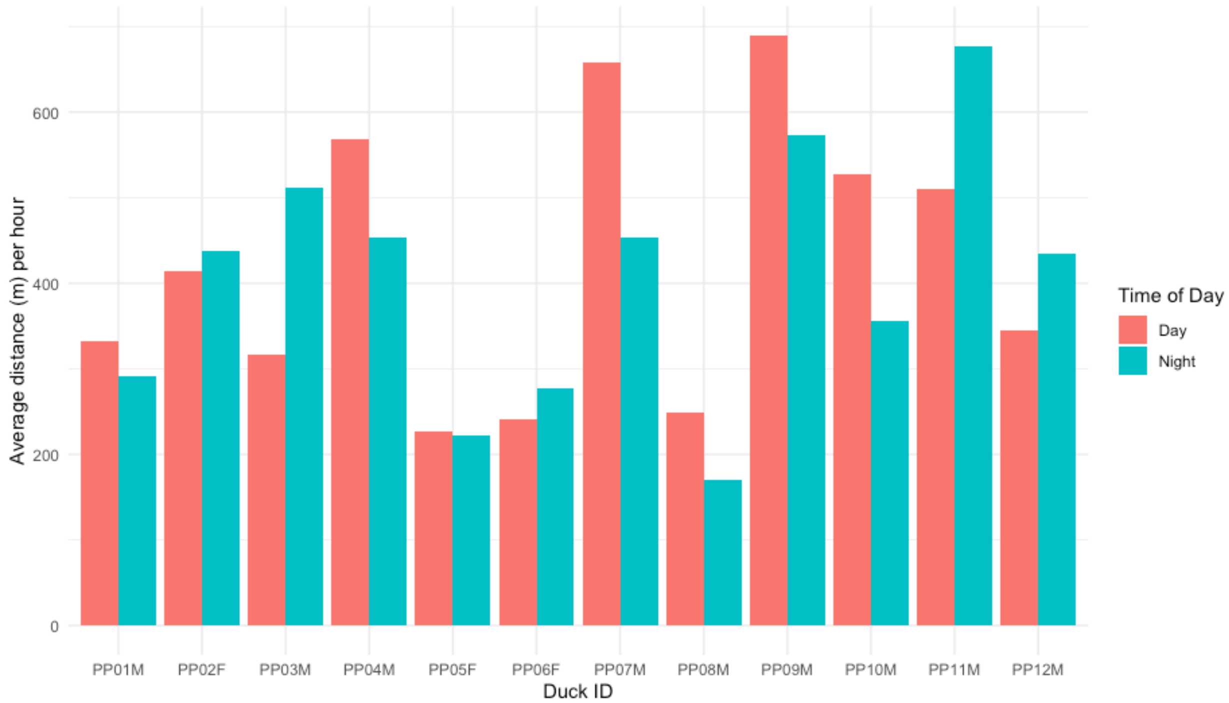
Appendix G.3

Estimated Marginal Means of the GLMM in Appendix G.1. Confidence level used: 0.95 Intervals are back-transformed from the log scale.

Sex = Female:					
TimeOfDay	response	SE	df	asymp.LCL	asymp.UCL
Morning	143	35.8	Inf	87.1	233
Midday	281	65.6	Inf	177.6	444
Afternoon	232	55.8	Inf	145.2	372
Night	234	56.0	Inf	146.3	374
Sex = Male:					
TimeOfDay	response	SE	df	asymp.LCL	asymp.UCL
Morning	479	57.9	Inf	378.4	608
Midday	323	40.1	Inf	253.6	412
Afternoon	537	64.9	Inf	423.8	681
Night	481	58.9	Inf	378.1	611

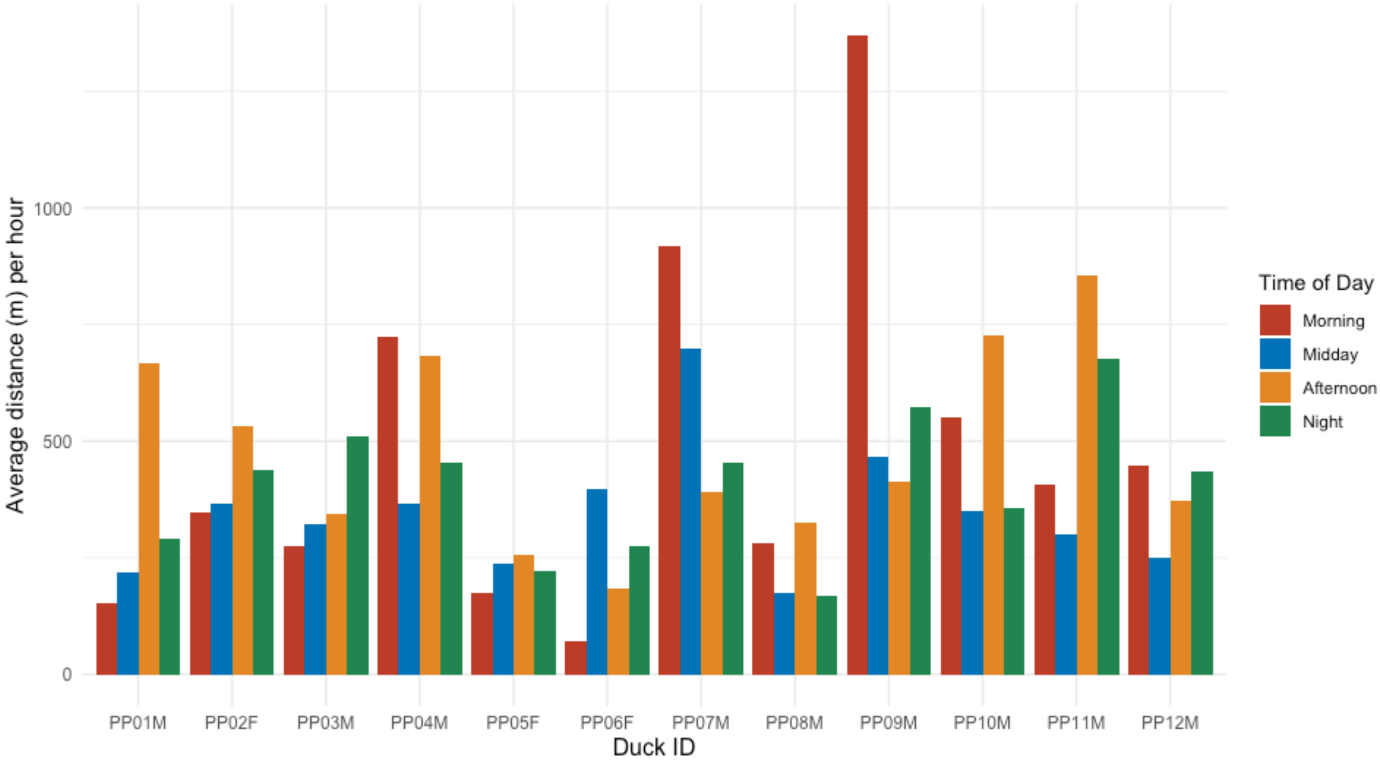
Appendix H Average distance moved during day v night

Average distance (m) moved per hour during day and night for each Chestnut Teal.



Appendix I Average distance moved across each time of day

Average distance (m) moved per hour for each time of day for each Chestnut Teal. The colours of the bars represent the time of day



Appendix J Modelling Chestnut Teal water depths

Appendix J.1

GLMM results of the effect of time of day, sex and site on water depth with ID as a random effect. Significance codes are 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Family: T (identity)					
Formula	water_depth ~ TimeOfDay * Sex * site - TimeOfDay:Sex:site + (1 | ID)				
Data	filter(trajectoriesID0_merge06_distStart, water_depth < 40)				
AIC	BIC	logLik	Deviance	Df.resid	
24839.0	25038.0	-12394.5	24789.0	21133	
Random effects					
Conditional model					
Groups			Name	Variance	Std.dev
ID			(intercept)	0.008708	0.09332
Number of obs			21158		
Groups			ID, 12		
Dispersion estimate for t family ($sigma^2$)			0.0591		
Conditional model					

	Estimate	Std. Error	Z value	Pr(>|z|)
(intercept)	0.10169	0.09893	1.028	0.3040
TimeOfDayMidday	-0.03623	0.10906	-0.332	0.7398
TimeOfDayAfternoon	0.02004	0.12995	0.154	0.8774
TimeOfDayNight	-0.17040	0.08794	-1.938	0.0527
SexMale	0.12966	0.07730	1.677	0.0935
sitepp	-0.13175	0.08830	-1.492	0.1357
sitesi	-0.42443	0.08766	-4.842	1.29e-06 ***
siteww	-0.69445	0.08813	-7.880	3.27e-15 ***
TimeOfDayMidday:SexMale	0.12401	0.02673	4.640	3.48e-06 ***
TimeOfDayAfternoon:SexMale	0.05853	0.02679	2.184	0.0289 *
TimeOfDayNight:SexMale	0.04338	0.02029	2.138	0.0325 *
TimeOfDayMidday:sitepp	0.08224	0.11161	0.737	0.4612
TimeOfDayAfternoon:sitepp	-0.05747	0.13209	-0.435	0.6635
TimeOfDayNight:sitepp	0.12782	0.08969	1.425	0.1541
TimeOfDayMidday:sitesi	0.09903	0.11012	0.899	0.3685
TimeOfDayAfternoon:sitesi	0.02664	0.13084	0.204	0.8386
TimeOfDayNight:sitesi	0.45774	0.08956	5.111	3.21e-07 ***
TimeOfDayMidday:siteww	0.04293	0.11075	0.388	0.6983
TimeOfDayAfternoon:siteww	0.01500	0.13160	0.114	0.9092

TimeOfDayNight:siteww	0.26958	0.08950	3.012	0.0026 **
SexMale:sitepp	-0.00852	0.04007	-0.213	0.8316
SexMale:sitesi	-0.46016	0.04458	-10.323	< 2e-16 ***
SexMale:siteww	NA	NA	NA	NA

Appendix J.2

ANOVA results of the GLMM in Appendix J.1. Significance codes are 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Analysis of Deviance Table (Type II Wald chisquare tests)			
Response: water_depth	totDist/nHrs		
	Chisq	Df	Pr(>Chisq)
TimeOfDay	106.0457	3	< 2.2e-16 ***
Sex	5.6959	1	0.017 *
Site	3320.0432	3	< 2.2e-16 ***
TimeOfDay:Sex	23.5654	3	3.078e-05 ***
TimeOfDay:Site	344.4247	9	< 2.2e-16 ***
Sex:site	360.7632	2	< 2.2e-16 ***

Appendix J.3

Estimated Marginal Means of the GLMM in Appendix J.1 with sex only. The confidence level used was 0.95 and results are averaged over the levels of site. NA could be due to lack of data or insufficient variation in the data.

Sex = Female:					
TimeOfDay	emmean	SE	df	asymp.LCL	asymp.UCL
Morning	-0.211	0.0579	Inf	-0.324	-0.0974
Midday	-0.191	0.0575	Inf	-0.304	-0.0785
Afternoon	-0.195	0.0601	Inf	-0.313	-0.0771
Night	-0.168	0.0549	Inf	-0.275	-0.0599
Sex = Male:					
TimeOfDay	emmean	SE	df	asymp.LCL	asymp.UCL
Morning	nonEst	NA	NA	NA	NA
Midday	nonEst	NA	NA	NA	NA
Afternoon	nonEst	NA	NA	NA	NA
Night	nonEst	NA	NA	NA	NA

Appendix J.4

Estimated Marginal Means of the GLMM in Appendix J.1 with sex and site. The confidence level used was 0.95 and results are averaged over the levels of site. NA could be due to lack of data or insufficient variation in the data.

Sex = Female site = lp					
TimeOfDay	emmean	SE	df	asymp.LCL	asymp.UCL
Morning	0.1017	0.0989	Inf	-0.0922	0.2956
Midday	0.0655	0.0945	Inf	-0.1198	0.2508
Afternoon	0.1217	0.1181	Inf	-0.1097	0.3532
Night	-0.0687	0.0691	Inf	-0.2040	0.0666
Sex = Male site = lp					
TimeOfDay	emmean	SE	df	asymp.LCL	asymp.UCL
Morning	nonEst	NA	NA	NA	NA
Midday	nonEst	NA	NA	NA	NA
Afternoon	nonEst	NA	NA	NA	NA
Night	nonEst	NA	NA	NA	NA
Sex = Female site = pp					
TimeOfDay	emmean	SE	df	asymp.LCL	asymp.UCL
Morning	-0.0301	0.0575	Inf	-0.1428	0.0826
Midday	0.0160	0.0576	Inf	-0.0969	0.1288
Afternoon	-0.0675	0.0571	Inf	-0.1793	0.0444
Night	-0.0726	0.0553	Inf	-0.1809	0.0357
Sex = Male site = pp					
TimeOfDay	emmean	SE	df	asymp.LCL	asymp.UCL
Morning	0.0911	0.0328	Inf	0.0268	0.1553
Midday	0.2611	0.0325	Inf	0.1974	0.3248
Afternoon	0.1122	0.0323	Inf	0.0488	0.1755
Night	0.0919	0.0314	inf	0.0304	0.1534
Sex = Female site = si					
TimeOfDay	emmean	SE	df	asymp.LCL	asymp.UCL
Morning	-0.3227	0.0565	Inf	-0.4335	-0.2120
Midday	-0.2599	0.0562	Inf	-0.3702	-0.1497
Afternoon	-0.2760	0.0562	Inf	-0.3862	-0.1658
Night	-0.0354	0.0567	Inf	-0.1464	0.0756
Sex = Male site = si					
TimeOfDay	emmean	SE	df	asymp.LCL	asymp.UCL
Morning	-0.6532	0.0432	Inf	-0.7380	-0.5685
Midday	-0.4664	0.0421	Inf	-0.5490	-0.3839

Afternoon	-0.5480	0.0435	Inf	-0.6333	-0.4627
Night	-0.3225	0.0373	Inf	-0.3957	-0.2493
Sex = Female site = ww					
TimeOfDay	emmean	SE	df	asymp.LCL	asymp.UCL
Morning	-0.5928	0.0572	Inf	-0.7049	-0.4806
Midday	-0.5861	0.0567	Inf	-0.6972	-0.4749
Afternoon	-0.5577	0.0572	Inf	-0.6699	-0.4455
Night	-0.4936	0.0559	Inf	-0.6031	-0.3841
Sex = Male site = ww					
TimeOfDay	emmean	SE	df	asymp.LCL	asymp.UCL
Morning	-0.4631	0.0559	Inf	-0.5726	-0.3536
Midday	-0.3324	0.0552	Inf	-0.4406	-0.2242
Afternoon	-0.3695	0.0557	Inf	-0.4787	-0.2603
Night	-0.3205	0.0494	Inf	-0.4173	-0.2238

Appendix K Modelling Chestnut Teal water depths excluding PP02F from the data set

Appendix K.1

GLMM results of the effect of time of day, sex and site on water depth with ID as a random effect. Significance codes are 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Family: T (identity)					
Formula	water_depth ~ TimeOfDay * Sex + site + (1 | ID)				
Data	filter(trajectoriesID0_merge06_distStart, water_depth < 40)				
AIC	BIC	logLik	Deviance	Df.resid	
12396.5	12501.1	-6184.2	12368.5	12949	
Random effects					
Conditional model					
Groups		Name	Variance	Std.dev	
ID		(intercept)	0.003882	0.0623	
Number of obs		12963			
Groups		ID, 11			
Dispersion estimate for t family ($sigma^2$)		0.0717			
Conditional model					
		Estimate	Std. Error	Z value	Pr(>|z|)
(intercept)		-0.030318	0.060926	-0.498	0.618758
TimeOfDayMidday		0.067956	0.034033	1.997	0.045852 *
TimeOfDayAfternoon		0.005193	0.031026	0.167	0.867085
TimeOfDayNight		-0.086447	0.023757	-3.639	0.000274 ***
SexMale		0.200860	0.057929	3.467	0.000526 ***
sitepp		-0.086206	0.050093	-1.721	0.085263
sitesi		-0.706360	0.054645	-12.926	< 2e-16 ***
siteww		-0.484654	0.065575	-7.391	1.46e-13 ***
TimeOfDayMidday:SexMale		0.110520	0.036646	3.016	0.002563 **
TimeOfDayAfternoon:SexMale		0.021323	0.033936	0.628	0.529789
TimeOfDayNight:SexMale		0.097215	0.026233	3.706	0.000211 ***

Appendix K.2

ANOVA results of the GLMM in Appendix K.1. Significance codes are 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Analysis of Deviance Table (Type II Wald chisquare tests)			
Response: water_depth	totDist/nHrs		
	Chisq	Df	Pr(>Chisq)
TimeOfDay	334.909	3	< 2.2e-16 ***
Sex	27.968	1	1.234e-07 ***
Site	886.196	3	< 2.2e-16 ***
TimeOfDay:Sex	21.804	3	7.167e-05 ***

Appendix K.3

Estimated Marginal Means of the GLMM in Appendix K.1 with sex only. The confidence level used was 0.95 and results are averaged over the levels of site.

Sex = Female:					
TimeOfDay	emmean	SE	df	asymp.LCL	asymp.UCL
Morning	-0.3496	0.0521	Inf	-0.4517	-0.2475
Midday	-0.2817	0.0536	Inf	-0.3867	-0.1767
Afternoon	-0.3444	0.0513	Inf	-0.4449	-0.2440
Night	-0.4361	0.0478	Inf	-0.5297	-0.3424
Sex = Male:					
TimeOfDay	emmean	SE	df	asymp.LCL	asymp.UCL
Morning	-0.1488	0.0289	Inf	-0.2055	-0.0921
Midday	0.0297	0.0284	Inf	-0.0259	0.0853
Afternoon	-0.1222	0.0285	Inf	-0.1782	-0.0663
Night	-0.1380	0.0273	Inf	-0.1914	-0.0846

Appendix K.4

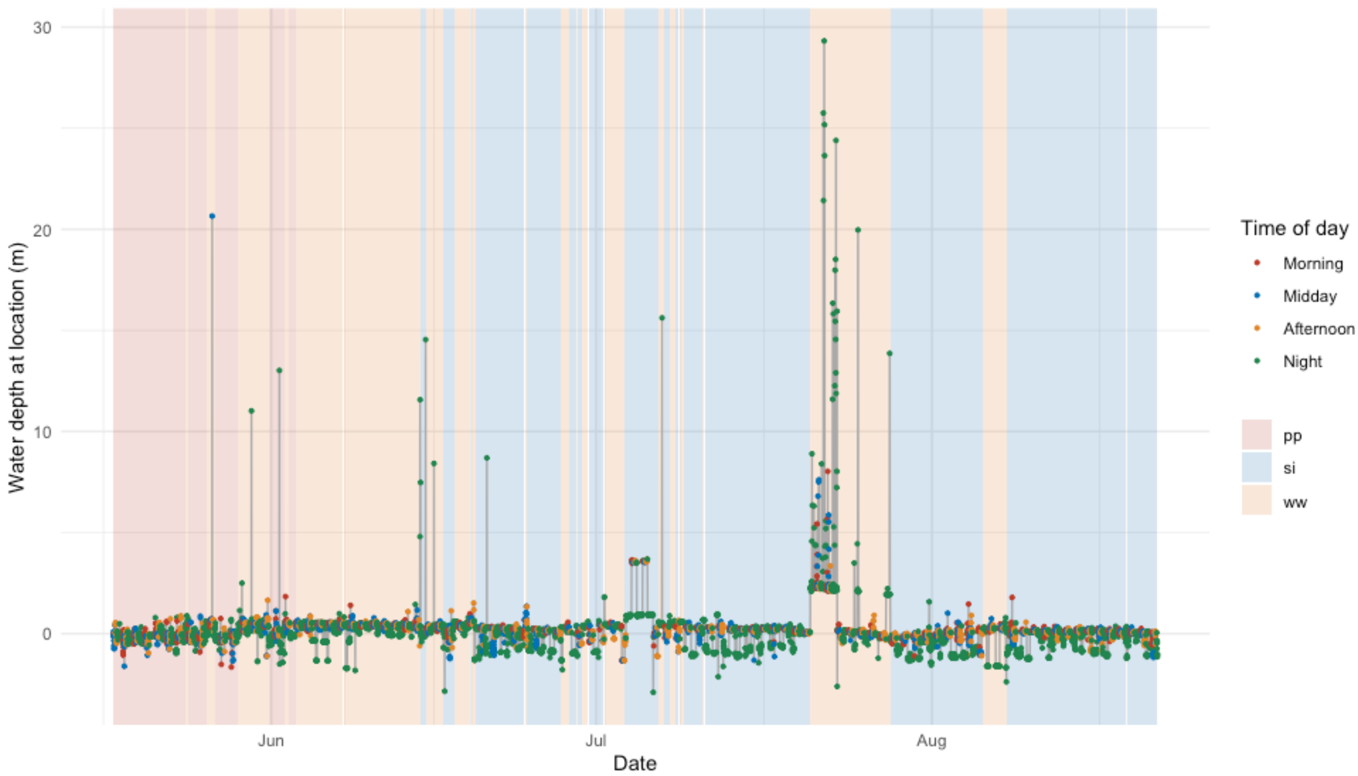
Estimated Marginal Means of the GLMM in Appendix K.1 with sex and site. The confidence level used was 0.95 and results are averaged over the levels of site.

Sex = Female site = lp					
TimeOfDay	emmean	SE	df	asymp.LCL	asymp.UCL
Morning	-0.0303	0.0609	Inf	-0.1497	0.08910
Midday	0.0376	0.0623	Inf	-0.0844	0.15972
Afternoon	-0.0251	0.0621	Inf	-0.1469	0.09668
Night	-0.1168	0.0582	Inf	-0.2307	-0.00278
Sex = Male site = lp					
TimeOfDay	emmean	SE	df	asymp.LCL	asymp.UCL
Morning	0.1705	0.0552	Inf	0.0623	0.27874
Midday	0.3490	0.0550	Inf	0.2413	0.45678
Afternoon	0.1971	0.0550	Inf	0.0893	0.30478
Night	0.1813	0.0544	Inf	0.0748	0.28786
Sex = Female site = pp					
TimeOfDay	emmean	SE	df	asymp.LCL	asymp.UCL
Morning	-0.1165	0.0531	Inf	-0.2205	-0.01254
Midday	-0.0486	0.0545	Inf	-0.1554	0.05824
Afternoon	-0.1113	0.0514	Inf	-0.2122	-0.01050
Night	-0.2030	0.0485	Inf	-0.2122	-0.10794
Sex = Male site = pp					
TimeOfDay	emmean	SE	df	asymp.LCL	asymp.UCL
Morning	0.0843	0.0233	Inf	0.0387	0.12998
Midday	0.2628	0.0227	Inf	0.0387	0.30728
Afternoon	0.1109	0.0227	Inf	0.0664	0.15533
Night	0.0951	0.0212	inf	0.0536	0.13666
Sex = Female site = si					
TimeOfDay	emmean	SE	df	asymp.LCL	asymp.UCL
Morning	-0.7367	0.0573	Inf	-0.8489	-0.62446
Midday	-0.6687	0.0585	Inf	-0.7834	-0.55408
Afternoon	-0.7315	0.0560	Inf	-0.8411	-0.62182
Night	-0.8231	0.0531	Inf	-0.9272	-0.71901
Sex = Male site = si					
TimeOfDay	emmean	SE	df	asymp.LCL	asymp.UCL
Morning	-0.5358	0.0313	Inf	-0.5973	-0.47438
Midday	-0.3573	0.0306	Inf	-0.4172	-0.29746
Afternoon	-0.5093	0.0312	Inf	-0.5705	-0.44814

Night	-0.5251	0.0302	Inf	-0.5842	-0.46586
Sex = Female site = ww					
TimeOfDay	emmean	SE	df	asymp.LCL	asymp.UCL
Morning	-0.5150	0.0679	Inf	-0.6480	-0.38190
Midday	-0.4470	0.0691	Inf	-0.5824	-0.31166
Afternoon	-0.5098	0.0666	Inf	-0.6403	-0.37927
Night	-0.6014	0.0644	Inf	-0.7276	-0.47526
Sex = Male site = ww					
TimeOfDay	emmean	SE	df	asymp.LCL	asymp.UCL
Morning	-0.3141	0.0483	Inf	-0.4088	-0.21939
Midday	-0.1356	0.0481	Inf	-0.2298	-0.04143
Afternoon	-0.2876	0.0481	Inf	-0.3818	-0.19340
Night	-0.3033	0.0471	Inf	-0.3956	-0.21108

Appendix L Water depth range of PP02F

Water depth (m) of PP02F over the tracking period, with the time of day delineated with a coloured point for each location and the site of the locations delineated with the background shading of the plot. The positive water depth values indicate distance out of the water, and negative values indicate depth in water.



Appendix M Tidal height across the tracking period

Temporal change in tidal height (m) at each water logger site along the Coorong over the tracking period. Each site is represented with a different colour. The tidal height represents the water level recorded by the water logger at each site.