Inland Waters & Catchment Ecology

Movement of adult female congolli (*Pseudaphritis urvillii*) in the Upper South East Drainage Network and Coorong, South Australia, over two spawning seasons

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Report to the Department for Environment and Water

Government of South Australia
Department of Primary Industries and Regions

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SARDI
SOUTH AUSTRALIAN RESEARCH AND DEVELOPMENT INSTITUTE

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EXECUTIVE SUMMARY

The South East Flows Restoration Project (SEFRP) was implemented to divert additional water from the Upper South East (USE) region into the Coorong South Lagoon. The primary aim of this diversion was to assist salinity management in the South Lagoon and allow managed inundation of wetlands (e.g. Taratap and Tilley Swamp) along the course of the SEFRP Drain. A secondary aim was to improve biological connectivity between the USE and the Coorong. Numerous flow-regulating structures were constructed as part of the SEFRP, including regulators at the outfall of the Morella Basin and Salt Creek, both of which incorporated rock ramp fishways to facilitate fish passage. Recent fish trapping at these fishways recorded the presence of diadromous fishes (those that must move between marine and freshwaters to complete their lifecycle), including the catadromous congolli (*Pseudaphritis urvillii*). Regionally-specific knowledge regarding the movement ecology of key fish species will better inform management of the USE Drainage Network in an ecologically sensitive manner.

The current study aimed to investigate the movement of adult female congolli in the SEFRP Drain and Coorong over two migration and spawning seasons (i.e., winter), using acoustic telemetry. In May 2023 (*n* = 32) and May 2024 (*n* = 35), adult female congolli (total length = 196–365 mm) were captured in the SEFRP Drain between Petherick Road and the northern end of Morella Basin and implanted with acoustic tags. The movements of these fish were subsequently monitored over periods of approximately six-months using an array of 17 acoustic receivers.

The two years of the study presented contrasting climatic, hydrological and physico-chemical conditions. The winter of 2023 was characterised by moderate to high regional rainfall, high drain discharge and water levels, and low salinities and high water levels in the Coorong South Lagoon (owing to high freshwater discharge from the Murray Barrages). In contrast, the winter of 2024 was characterised by low regional rainfall, low drain discharge and water levels (in part owing to drawdown of Morella Basin), and high salinities and low water levels in the Coorong South Lagoon. Differences in water levels and discharge in the SEFRP Drain network between years influenced the nature of operation of Morella and Salt Creek regulators (i.e. simultaneous operation of regulator gates and fishway, gates only or fishway only).

Across the monitoring periods in 2023 and 2024, a total of 60 of 67 (90%) tagged congolli were detected for periods of 15–161 days. Patterns of movement were consistent, with 85% of detected

individuals exhibiting sedentary behaviour through May before rapid, predominantly nocturnal, downstream migrations were initiated from 8 June–27 July. In 2023, 80% (*n* = 23) of detected individuals passed both flow regulating structures and 40% (*n* = 12) successfully traversed ~100 km of estuarine lagoon with a reverse salinity gradient (commonly 55–35 g.L^{-1} Snipe Island–Rob's Point) and absolute salinities of up to ~60 g.L^{-1} before reaching the Indian Ocean. In 2024, most individuals that initiated migrations were obstructed by the Morella Regulator with just 26% (*n* = 8) passing and reaching the South Lagoon, and subsequently, only 3% (*n* = 1) reaching the Indian Ocean. These fish were also faced with a reverse salinity gradient (commonly 80–30 g.L^{-1} Snipe Island–Rob's Point) but absolute values of up to ~100 g.L^{-1}.

In the SEFRP Drain and Coorong, downstream migration of adult female congolli has three key phases: 1) initiation; 2) passage through flow regulating structures; and 3) movement through the Coorong. We assessed the influence of key environmental and management variables on the probability of success of each of these phases. The strongest predictors of initiation of downstream migration were day of year and distance upstream, with some evidence of high drain discharge and moon phase (new moon) as proximate cues. Passage through the Morella Regulator was most likely during periods of higher discharge, when headwater levels were relatively high and when both the regulator gates and fishway were operated simultaneously. There were no significant predictors of passage through the Salt Creek Regulator, as 97% of fish that approached ultimately passed the structure. Probability of passage between the South and North lagoons was not predicted by any environmental variable, yet low sample size (*n* = 3) during high salinity and low water levels in 2024 likely impacted analyses. The number of days it took congolli to traverse this distance was, however, shortest when the salinity gradient between the North and South lagoons was ~20 g.L^{-1}, suggesting some role of salinity in facilitating timely migration through the lagoons.

This study has provided important information on the outmigration of female congolli during years of contrasting hydrology and connectivity in the SEFRP drain network, and salinity and water level in the Coorong. Ultimately, passage of the Morella Regulator and through the Coorong lagoons was key to successful migration to marine spawning habitats. As such, if the downstream passage of adult female congolli is an objective of management of the SEFRP Drain, we suggest the following for the period June–August:

1) Maintaining water levels in the Morella Basin >3.84 m AHD and Salt Creek >0.95 m AHD to facilitate fishway function. This allows for water to be discharged through the fishways and maintains a minimum water depth of 0.1 m at fishway exit.
2) Providing additional discharge through regulator gates to enable simultaneous operation of fishways and gates. A specific threshold is not apparent from the study, but the lower end of discharges experienced during 2023 (200 $ML.day^{-1}$) provides a guide.

Water level and salinity regimes in the Coorong South Lagoon are unlikely to be managed for congolli migration from the SEFRP Drain, but knowledge of relationships between environmental conditions and migration success provide a context for expected outcomes of migration in given years. As a guide, successful migration appears more likely during years of high discharge from the Murray Barrages, when salinities in the South Lagoon are <60 $g.L^{-1}$.

Keywords: diadromy, migration, fish passage, Coorong.

1. INTRODUCTION

1.1. Background

Diadromous fishes must migrate between freshwater and marine environments to complete their lifecycles (McDowall 1988). These obligate migrations make diadromous fishes susceptible to anthropogenic impacts, particularly the construction of flow-regulating structures (e.g., dams, weirs, barrages) that fragment freshwater habitats, alter flow regimes and limit connectivity witihin waterways (Angermeier 1995). In aquatic systems impacted by flow regulation and barrier construction, an understanding of diadromous fish movement is necessary to support species management aimed at sustaining functioning populations.

The South East region of South Australia was naturally a wetland dominated landscape. Since European settlement, however, the landscape has been highly modified by land clearance and the establishment of a cross-catchment drainage network to reduce water logging and dryland salinity, and promote agricultural production (Taffs 2001, SE NRMB 2019). The network, divided into the lower South East (LSE) and upper South East (USE) schemes, drains surface water from the surrounding land and discharges to the ocean and South Lagoon of the Coorong, respectively. Whilst predominantly operated for agricultural outcomes, in recent years, management of the drainage network has increasingly considered aquatic ecosystem values.

From 2017–2019, the South East Flows Restoration Project (SEFRP) was implemented in the USE, which involved the replacement of the Taratap and Tilley Swamp drains with the SEFRP Drain, and increased the volume of brackish water (typically 6–10 $g.L^{-1}$) able to be diverted from the Blackford Drain and into the Coorong via Salt Creek (Taylor et al. 2014). The primary objectives of the SEFRP were to assist salinity management in the commonly hypersaline Coorong South Lagoon and allow managed inundation of wetlands (e.g. Taratap and Tilley Swamp) along the course of the SEFRP Drain. A secondary objective was to improve biological connectivity between the USE and the Coorong. Numerous additional flow regulators were constructed, including at the outfalls of the Morella Basin and Salt Creek, both of which incorporated rock ramp fishways to facilitate fish passage.

Since 2002, periodic monitoring of fishes has occurred across the Taratap and Tilley Swamp drains, and associated wetlands (Hammer 2002, Tuck et al. 2017). Assemblages were dominated by the estuarine smallmouth hardyhead (*Atherinosoma microstoma*), with low abundances of obligate freshwater (e.g., southern pygmy perch, *Nannoperca australis*) and diadromous species (e.g., congolli, *Pseudaphritis urvillii*). In 2021–2023, monitoring of the newly constructed fishways at Morella and Salt Creek recorded seven fish species, including the diadromous congolli, common galaxias (*Galaxias maculatus*) and short-finned eel (*Anguilla australis*) (Ye et al. 2022, Ye et al. 2024). Nevertheless, the importance of the SE Drainage Network to the regional population dynamics of diadromous fishes is unknown. Furthermore, the movements of these diadromous fishes throughout this system, with regards to timing, direction and destination, and the influence of environmental conditions on these parameters, remains unclear. This information is critical to inform ecologically sensitive management of the USE Drainage Network.

Congolli is a medium-bodied catadromous fish found across southeastern mainland Australia and Tasmania. The species exhibits sexual dimorphism and habitat segregation, with larger females (up to 350 mm Total Length, TL) and smaller males (typically <150 mm TL) mostly residing in freshwater and estuarine habitats, respectively. In freshwater habitats, adult females are predominantly sedentary but following maturation, undertake rapid downstream migration to marine spawning habitats during winter, which appears to be followed by mortality (i.e. 'semelparity'; Crook et al. 2010, Bice et al. 2018b). Juveniles make corresponding upstream migrations during spring and summer (Bice et al. 2018a). Congolli are the most abundant diadromous species in the USE Drainage Network (Hammer 2002, Tuck et al. 2017) and adult females represent an appropriate fish model to investigate movement and passage in association with flow, water level and regulator management.

1.2. Objectives

The primary objective of this project was to use acoustic telemetry to monitor the movements of tagged adult female congolli in the SEFRP Drain Network and Coorong, and assess the influence of hydrology and system management on migration. Specifically, we aimed to:

1) Monitor movement from May–October, which covers the purported migration season (June–August), over two years (2023 and 2024);
2) Summarise movement (i.e., direction, timing, passage past flow-regulating structures, destination) and assess the influence of key environmental variables and management actions on key phases of migration; and
3) Provide recommendations for future system management to support movements of adult female congolli.

2. METHOD

2.1. Study site and receiver array

The USE Drainage Network extends from the Blackford Drain (near Kingston SE) in the south to Salt Creek in the north and east to approximately Keith and Padthaway. The SEFRP Drain flows in a northerly direction between the Blackford Drain and Salt Creek, where it discharges to the Coorong (Figure 1). The SEFRP Drain is also fed by a series of subsidiary drains that enter from the south and east. Numerous structures regulate flow along the course of the drain alignment. Notably, a regulator is positioned at the junction with the Blackford Drain to deliver water into the SEFRP Drain. Further regulators are positioned along the length of the drain to regulate water flow into lateral wetlands. At the terminus of the network, a regulator on the Morella Basin outfall controls discharge to Salt Creek and water levels within the basin, while the Salt Creek Regulator ultimately controls discharge to the Coorong South Lagoon (Figure 1 inset). Salt Creek meets the Coorong approximately 95 km southeast of the Murray Mouth.

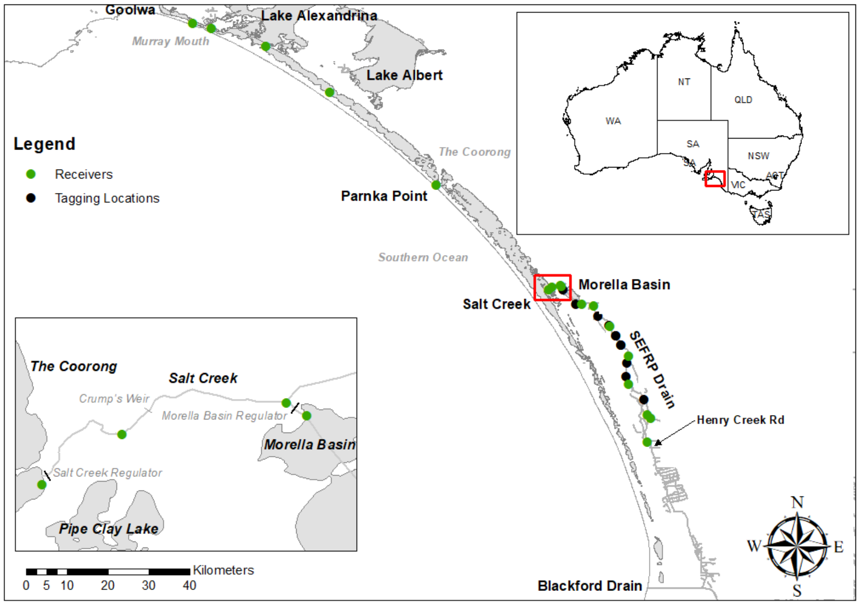

Figure 1. Map of the upper South East and Coorong regions, South Australia, depicting the location of acoustic receivers (green circles) and fish tagging sites (black circles) in the SEFRP Drain and Coorong. Receivers immediately upstream and downstream of the Morella and Salt Creek regulators (inset) were those used to determine passage dates

An array of 17 VEMCO VR2W (180 kHz) acoustic receivers was deployed in the SEFRP Drain and Coorong from 27 April–3 October 2023 and 27 April–10 October 2024 (Figure 1). Within the drain network, receivers were deployed along the drain approximately equidistant (every 7–9 km) between Henry Creek Road and the Salt Creek outlet, and several hundred metres upstream of junctions in connecting drains. Receivers were also located immediately upstream and downstream (<50 m) of flow-regulating structures at the Morella and Salt Creek outlets to assess passage through these structures. Due to the length of the Coorong, receiver spacing was typically greater (15–30 km). To maximise tagged fish detection probability in the Coorong, receivers were placed at natural constrictions at Parnka Point, Long Point and Pelican Point, as well as immediately east and west (<500 m) of the Murray Mouth. All receivers were deployed using stainless steel cable and anchored with star pickets (drain receivers) or attached to manmade structures (e.g., navigation marks) or specially designed moorings (Coorong receivers). The data from all receivers was downloaded annually in October.

2.2. Fish capture and surgery

In 2023 (2–5 May), 32 adult female congolli (mean TL ± SE = 289 ± 4 mm, range = 254–332 mm TL; mean weight ± SE = 235 ± 9 g, range = 156–336 g) were captured from 10 locations in the SEFRP Drain between Petherick Road and the northern end of Morella Basin and implanted with acoustic tags (Appendix A). In 2024 (30 April–2 May), 35 adult female congolli (mean TL ± SE = 242 ± 6 mm, range = 196–365 mm TL; mean weight ± SE = 139 ± 12 g, range = 59–365 g) were captured and tagged from 11 locations across the same reach of the SEFRP Drain. All fish were sampled with a combination of single- and double-wing fyke nets set overnight.

Following capture, fish were anaesthetised using a 0.05 ml. L^{-1} solution of AQUI-S in a 20 L dosing tank. When fully anaesthetised – characterised by loss of equilibrium and unresponsiveness to stimulus – fish were weighed (g), measured (mm TL) and placed ventral side up into a V-shaped support. During surgery, a 0.02 ml. L^{-1} solution of AQUI-S was irrigated over the gills to maintain anesthesia. A small incision was made off-centre on the ventral surface, midway between the pelvic fins and anus, through which acoustic tags were inserted into the peritoneal cavity. All fish were fitted with a VEMCO model V5-2x (dimensions 12.7 x 5.7 mm; weight 0.77 g in air) acoustic tag. These tags have a random delay of 70–150 seconds, and estimated battery life of 179 days. Tag weight aimed to maintain a transmitter to fish weight ratio of <2% (Jepsen et al. 2002). Incisions were closed using a single cruciate suture. Following full recovery (i.e. fish able to maintain their balance and freely swim) in an aerated tank, fish were released at their original capture location.

2.3. Data analysis

Summary statistics

Data on tagging locations and acoustic detections were combined to create an overall movement data set. Each tagging location and acoustic receiver was assigned a relative stream distance (± km) from a reference receiver at Henry Creek Road, at the southeastern end of the receiver array. These distances were used to visualise movements of each individual fish along the drain network and estimate displacement, defined as the linear stream distance (± km) from the point of final detection and the tagging location. The final detection was also used to summarise each fish's ultimate destination, defined as: 1) SEFRP Drain; 2) South Lagoon; 3) North Lagoon; 4) Murray Estuary; or 5) Indian Ocean. Transition to the ocean was assumed when individuals were last detected on one of the two receivers positioned east and west of the Murray River Mouth following a driven downstream migration (see definition below).

Key drivers of migration and passage

Quantitative analyses were undertaken to determine key drivers – environmental (e.g. water temperature) and management-related (e.g. structure/fishway operation) – of the migration of adult female congolli. Based on knowledge of congolli life history and migration behaviour from past studies (Crook et al. 2010, Bice et al. 2018b), and preliminary review of data from the current project, there were determined to be three key stepwise phases in successful migration: 1) initiation of migration; 2) passage past flow regulating structures at Morella and Salt Creek; and 3) successful migration through the Coorong lagoons towards the Murray Mouth. As such, analyses followed a three-step process with each being assessed against a specific suite of relevant environmental and management variables. Each fish's movement profile was assessed to identify those individuals that undertook driven downstream migrations, defined as: 1) fish that were detected within the upstream vicinity of the Morella Regulator at either of the two closest receivers (i.e. 0.1–7 km upstream); and 2) where this detection was preceded by rapid downstream movement from the tagging site or area of residence.

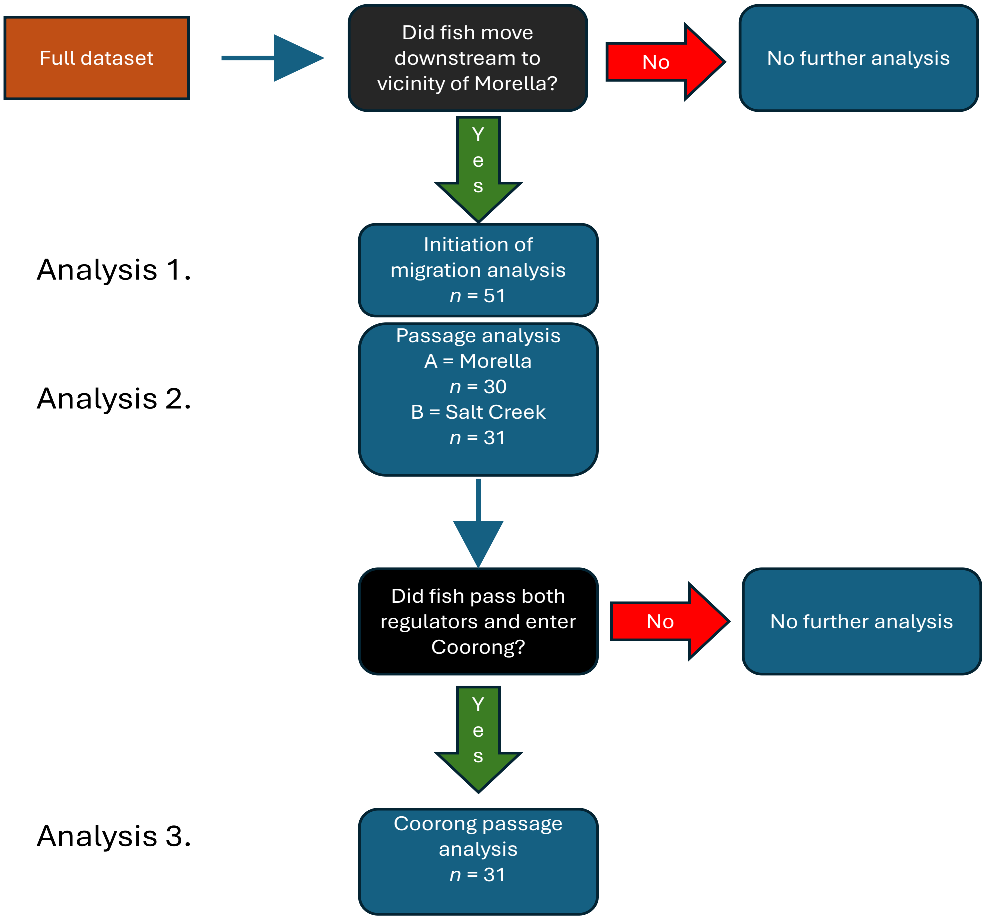

Figure 2. Conceptual diagram of step-wise approach to analysis. Black boxes represent key questions in progression of workflow and blue boxes represent steps in analysis. Sample sizes (*n*) represent the number of fish used in analysis. Note two fish that passed the Morella Regulator were excluded from analysis due to missed detections.

For initiation of migration, the daily location of each tagged fish was classified as a binary response variable of 'resident' (0) or 'migrating' (1) based upon its detection in the receiver array. Day of initiation of downstream migration was taken as last detection on a given receiver that was followed by detection within upstream vicinity of Morella Regulator within a 7d period. These analyses were limited to the first driven downstream migration undertaken by individuals. Each fish location/day was allocated predictor variable values for day-of-the-year (DOY), and its corresponding moon-phase, water temperature (average and change), water level (average and change) and study year (2023 or 2024; Table 1). There are no gauges to record discharge along the SEFRP drain upstream of the Morella Regulator, and as discharge at Morella may not always represent discharge in the drain network (e.g. during drawdown of Morella Basin), a rainfall metric was used as a proxy for discharge. Environmental data (i.e. water temperature, water level, discharge and salinity presented hereafter) were sourced from various gauges from Data - Water Data SA (Table 1) and in the case of rainfall data, from the Australian Bureau of Meteorology (Climate Data Online - Map search). Moon-phase data were obtained for the study dates using the lunar.phase function in the R package 'lunar' (ver. 0.2-01, E. Lazaridis, see http://CRAN.R-project.org/package=lunar).

For all fish that initiated a downstream migration, each day spent within the upstream vicinity of a regulator was assessed as the binary response of whether passage occurred (1) or did not (0). For the Morella Regulator, this time period began when a fish was detected within the vicinity (<7 km) of the regulator following a downstream movement. The period was paused if the individual subsequently moved back upstream. We adopted this rule to ensure our analyses focused on conditions experienced by fish proximate to the regulator.

Given the close proximity of the Morella and Salt Creek regulators (~3 km), the time calculation for the Salt Creek Regulator began following passage through the Morella Regulator. The day of passage through the regulators was generally defined by sequential detection on receivers immediately upstream and downstream (Figure 1). If detected on the downstream receiver of a regulator, the first detection on this receiver was taken as the day of passage. Nonetheless, detection on receivers immediately downstream of the regulators was imperfect, likely due to a combination of the narrow nature of Salt Creek, the speed with which individuals passed the area, and the fact that 'noisy' zones downstream of regulating structures can result in lower detection efficiency (Ingraham et al. 2014). If not detected on the downstream receiver, but passage was known to occur (indicated by detection on a further downstream receiver), then last detection on the upstream receiver was taken as the day of passage. For the few individuals not detected on either upstream or downstream receiver, the day equidistant between when the fish was detected on further upstream and downstream receivers was taken as the day of passage. For two individuals that passed the Morella Regulator, these conditions were not met, and a day of passage could not be estimated. These individuals were excluded from this phase of statistical analysis. Each day a fish was present in the vicinity or passed a regulator was allocated a daily discharge (as measured at the Salt Creek flow gauging weir), upstream and downstream water level (m AHD), headloss (m), a categorical status of fishway and regulator operation, and study year (Table 1).

Table 1. Name and description of predictor variables used in each analysis. Specific water quality stations where environmental data were derived are presented (Water Data SA, Department for Environment and Water).

Name	**Description**
Initiation migration analysis	
DOY	Julien day of year
Distance	Km from Henry Creek Road (smaller numbers mean a fish was further upstream when it initiated a driven downstream movement)
Water temperature (Temp_7d)	Average water temperature in drain network over previous 7d (station A2391274).
Water temperature change (Temp_change)	Average water temp in drain network over previous 7d, minus the average water temp over the preceding 7d (station A2391274).
Rainfall (21d rolling total)	Total rainfall (mm) over the preceding 20d at Kingston SE (gauge 026012).
Moonphase	At 1200 hours in radians, new moon = 0, full moon = π, first quarter = π ÷ 2, third quarter = 3 π ÷ 2
Year (study year)	2023 or 2024.
Passage analysis	
Discharge	Daily discharge (ML.d^{-1}) as measured at the Salt Creek flow gauging weir (A2390568)
Water level upstream	Daily water level (m AHD) measured upstream of each regulator (Morella = A2391274, Salt Creek = A2391285)
Water level downstream	Daily water level (m AHD) measured downstream of each regulator (Morella = A2390568, Salt Creek = A4261165)
Headloss	Difference in water level (m) between upstream and downstream of each regulator
Fishway operation	Was fishway operating? Fishway exit sill heights require +0.1 m free board for fishway operation at Morella (>3.84 m AHD) and Salt Creek (>0.86 m AHD). Categorical, 0 = not operating, 1 = operating.
Regulator operation	Was water discharging through regulator gates? categorical, 0 = no, 1 = yes.
Regulator permeability	Measure of the combined impact of fishway and regulator operation. Categorical, 0= neither fishway or regulator was open, 1= either the fishway or regulator was open, 2 = both fishway and regulator were open.
Either open	Alternative measure of the combined impact of fishway and regulator operation. Categorical, 0= neither fishway or regulator was open, 1= either the fishway or regulator was open.
Year (study year)	2023 or 2024.

Table 1 continued

Name	Description
Coorong passage analysis	
Salinity (Sal_daily)	Daily average salinity (g.L^{-1}) in the Coorong South Lagoon at the Woods Well station (A4261209)
Salinity (Sal_7d)	Average salinity (g.L^{-1}) over the previous 7d in the Coorong South Lagoon at the Woods Well station (A4261209)
Salinity gradient (Sal_grad)	Daily average gradient in salinity (g.L^{-1}) between South (A4261209) and North lagoons (Robs Point, A4260572) of the Coorong.
Salinity gradient (Sal_grad7d)	Average gradient in salinity (g.L^{-1}) between South (A4261209) and North lagoons (Robs Point, A4260572) of the Coorong over preceding 7d.
Water level (WL)	Water level (m AHD) at Parnka Point (A4260633)
Water level (WL_7d)	Water level (m AHD) at Parnka Point (A4260633) over the preceding 7d
Days migrating	Number of days since individual was deemed to have commenced migration
Moon-phase	At 1200 hours in radians, new moon = 0, full moon = π, first quarter = π ÷ 2, third quarter = 3 π ÷ 2
Year (study year)	2023 or 2024.

For Coorong passage analysis, an *a priori* assumption was that passage between the South and North Lagoons was the likely key step in successful migration through this region due to: 1) the shallow water depths experienced in the vicinity of Parnka Point and the Needles (bed elevation commonly >0 m AHD; Gibbs et al. 2018); and 2) the extreme hypersalinity that commonly characterises the Southern Lagoon (Mosley et al. 2023). The North Lagoon and Murray Estuary were considered to not comprise major physical or physico-chemical impediments to migration. This analysis was only undertaken for fish that passed the Salt Creek Regulator. Passage between the South and North lagoons was then defined as detection on the Parnka Point receiver (in the constriction point) and a subsequent receiver north of Parnka Point. Following passage of the Salt Creek Regulator, every subsequent day a fish was considered ‘active’ (i.e. it registered further detections), was assigned a binary response variable of no passage (0) or passage occurred (1) and was defined as the day of detection at Parnka Point. All days in the dataset were assigned values for salinity (daily, 7d average and gradient), water level (daily, 7 d average and gradient), days since individual fish commenced migration and study year (Table 1).

Statistical models

We modelled a fish's daily migration status as a function of different combinations of spatial, temporal, environmental and management-related predictors using a generalised additive mixed model (GAMM) formulation of the Cox proportional hazards model (i.e., time-to-event model). These models were fitted with a Poisson distribution and an offset term to convert each fish's daily-resolved binary response observations (0/1; not migrating/migrating) into a rate (Whitehead 1980, Yau 2001, Cartensen 2006, Fieberg and DelGiudice 2011). A random intercept for each fish accounted for the repeated measures nature of our data. This model structure has successfully been employed to analyse fish migration dynamics in other telemetry-based studies (Crook et al. 2010, Bice et al. 2018b, Koster et al. 2023).

In analysis 1, we allowed for potentially non-linear effects of predictor variables on a fish's rate of migration by fitting cubic regression spline smoothers to DOY, distance, the two water temperature variables, and rainfall. We fitted a cyclic penalised cubic regression spline to moon phase so that there were no discontinuities between last quarter and new moon phase endpoints of the spline (Wood 2017). Year was fitted as a parametic fixed effect. We first explored within and among-year spatio-temporal variation in environmental effects by fitting tensor product smooth terms (allows for the construction of smooths of covariates measured in different units) (Wood et al. 2013) to combinations of DOY and distance, with factor smooths by Year. We then explored whether environmental predictor variables could explain migration dynamics by including these as independent smoothers, smoothers that differed by Year, and tensor product smoothers with DOY or Distance that allowed for spatio-temporal variation in their effects. Models included only one environmental predictor variable (aside from DOY, Distance and Year) at a time.

Models in analysis 2 focused on how environmental conditions affected the probability of fish passage through first the Morella and then Salt Creek regulators. We adopted a similar approach to analysis 1, fitting cubic regression splines to continuous predictors and exploring among year variation in their effects via factor smooths with Year. We also explored whether the effect of continuous predictor variables differed across levels of regulator and fishway operation using factor smooths, as well as including these operation predictor variables as parametric fixed effects themselves. The fishway and regulator operation variables defined different ways of describing barrier permeability and so were only fit in competing models. The regulator passage models focused on a smaller set of days compared to the migration initiation models and also occurred later in the year. Rainfall data and discharge data were highly skewed over this period and so both were log-transformed to ensure linearity between predictors and the link function.

Each of our analysis 3 models included just one of the environmental predictor variables (fitted with cubic regression spline, except moon phase that was a cyclic penalised cubic regression spline) with or without a factor smooth by Year. We log-transformed days migrating and 7-day average salinity to meet model assumptions.

Within each set of analyses, competing models were compared using scaled Akaike's Information Criterion corrected for small sample sizes (ΔAICc) (Burnham and Anderson 2002). All smoothers across the three sets of analyses that involved an environmental predictor variable had a basis dimension (maximum smoothness) of k=4 degrees of freedom to allow for some, but not excessive, potential non-linearities in model fits. Analyses, model selection and graphing were performed in R version 4.4.0 (R Core Team 2024), accessed via RStudio (2024.04.2), using the 'gamm4' (Wood et al. 2017), 'bbmle' (Bolker and Bolker 2017), 'mgcViz' (Fasiolo et al. 2020) and 'gratia' (Simpson and Singmann 2018) packages.

3. RESULTS

3.1. Hydrology and water physico-chemistry

In SE South Australia, rainfall over the period 1 February–30 June 2023 was substantially greater than the same period in 2024, with the Kingston SE weather station (026012) recording 364 and 121 mm, respectively (www.bom.au/sa/). While there is no flow gauge within the drain network upstream of Morella to assess discharge within the drain network, rainfall may act as a proxy. The rolling 21d total rainfall metric suggests substantial stream flow in the drain from May–September 2023, with a peak in late-June (Figure 3a). In the following year, substantial stream flow likely did not commence till mid-June and continued till September 2024, but likely with substantially lower peak discharge than 2023.

Water levels upstream of the Morella Regulator, in part, reflected this variability in rainfall and likely inflows, but also annual differences in the operation of the Morella Regulator to manage water level in the Morella Basin. In 2023, water level upstream of Morella was relatively high and stable, ranging from 3.96–4.31 m AHD, and as such, discharge from the Morella and Salt Creek regulators likely mirrored discharge in the drain upstream. Daily discharge at the Salt Creek flow gauging weir (a proxy for both Morella and Salt Creek regulator discharge) ranged from 29–885 ML.d^{-1}, with greatest discharge recorded from mid-June–early August when discharge was predominantly >200 ML.d^{-1} (Figure 3a). Contrastingly in 2024, water levels upstream of the Morella Regulator were lower and more variable, ranging 3.42–4.09 m AHD, with water level not exceeding 4 m AHD until September. In part, this was due to ‘managed drawdown’ of Morella Basin (to expose mudflat habitat and provide food resources for waterbird populations) during summer–autumn, and low rainfall resulting in minimal drain inflows. Consequently, in 2024, discharge over the Morella and Salt Creek regulators ranged just 1–64 ML.d^{-1} over the tracking period.

Water levels upstream of the Morella Regulator influence the operation of the associated fishway. To allow water flow through the fishway and a minimum water depth of 0.1 m at the fishways exit, upstream water levels must be >3.84 m AHD. As such, in 2023 regulator gates and the fishway were operated simultaneously throughout the migration season, whilst in 2024, all discharge occurred via the regulator until 28 July when a water level of 3.84 m AHD was met, and subsequently all discharge passed through the fishway.

Water level within Salt Creek varies independently of that upstream of Morella and more closely reflects discharge from the Morella Regulator and fishway (Figure 3b). Upstream of the Salt Creek flow gauging weir in 2023, water level ranged 1.36–2.06 m AHD, with peak levels in July, while in 2024, water levels were generally lower and more stable ranging from 1.05–1.34 m AHD. These water levels were sufficient for continual operation of the Salt Creek fishway. In 2023, this was supplemented by continuous discharge over regulator gates, while in 2024 there were periods of simultaneous fishway and gate operation, and periods where all discharge passed via the fishway.

In the Coorong South Lagoon at Snipe Island in 2023, water level was relatively high throughout the tracking period, ranging from 0.35–1.01 m AHD, and was >0.5 m AHD throughout June–August. In contrast, in 2024, water level was generally lower, ranging from -0.18–1.19 m AHD over the tracking period, and not reaching 0.5 m AHD until late July. Differences in intra-annual water level variability between 2023 and 2024 were the result of disparity in freshwater discharge from the Murray Barrages across the two years.

In early 2023, large volumes of freshwater were discharged from the Murray Barrages, with flows peaking at >120,000 $ML.d^{-1}$ in January (Figure 4a). Throughout the 2023 tracking period, while variable, barrage discharge was commonly >20,000 $ML.d^{-1}$. The tracking period of 2024 was preceded and characterised by barrage discharge that was predominantly <5,000 $ML.d^{-1}$. This annual variability in barrage discharge also had a large influence on salinity in the Coorong.

In both years, salinity was highly variable across the length of the acoustic array (Figure 4b and c). Over the peak period for downstream migration in June–July, mean daily salinities in the SEFRP Drain were predominantly 7–11 $g.L^{-1}$ at Morella and Salt Creek, with mean values of ~9 $g.L^{-1}$, in both years. Within the Coorong, salinities transitioned longitudinally from hypermarine to brackish in a northwesterly direction from the South Lagoon to the North Lagoon and Murray Estuary but there were notable differences between 2023 and 2024. Specifically, reduced freshwater discharge from the Murray Barrages in 2024 was associated with much higher salinities in the South Lagoon in June–July 2024 (Woods Well 10th to 90th percentile range = 60–97 $g.L^{-1}$) than during 2023 (43–53 $g.L^{-1}$). In both years, while variable, salinities were generally brackish (10–35 $g.L^{-1}$) in the North Lagoon and Murray Estuary.

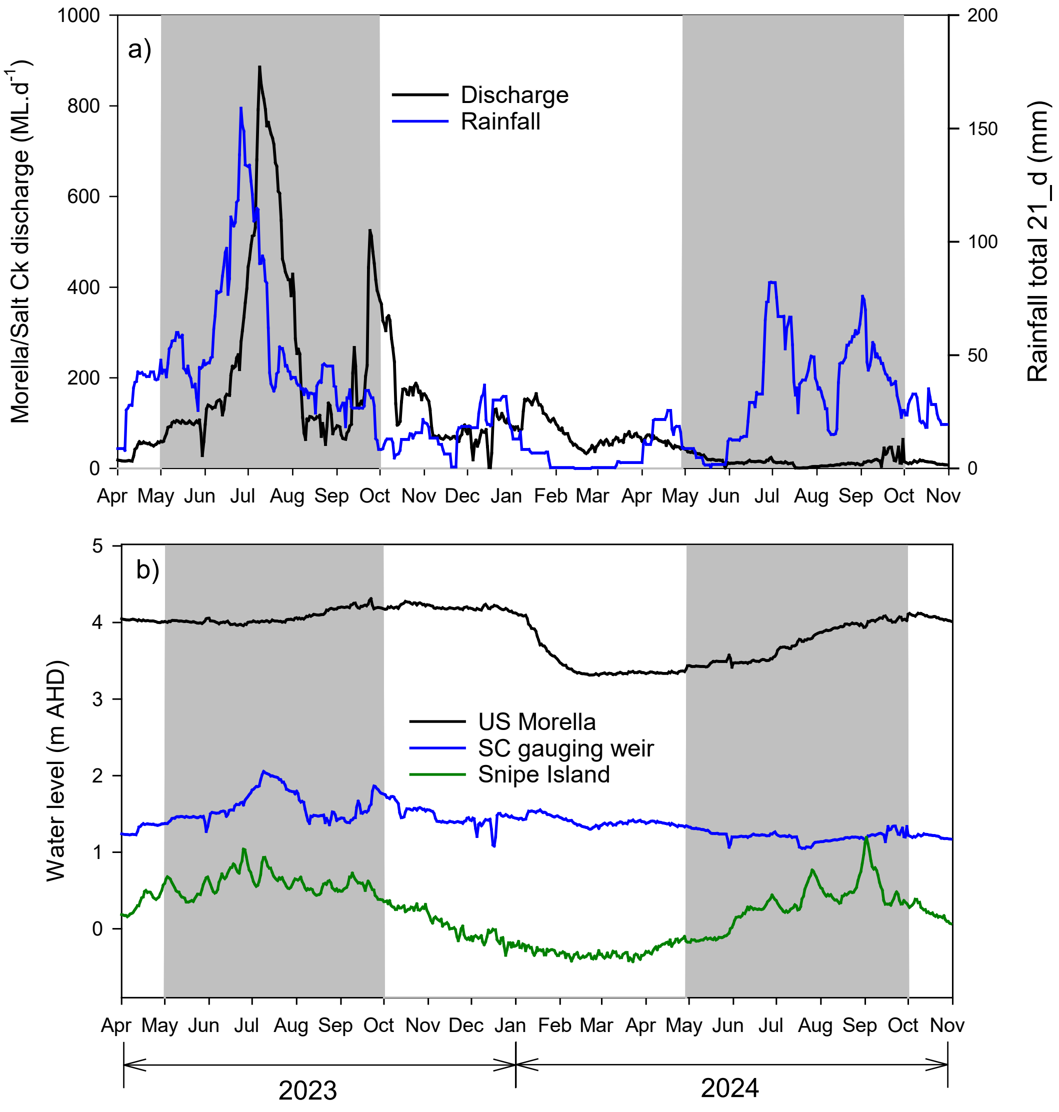

Figure 3. a) Discharge (ML.d^{-1}) through the Salt Creek flow gauging weir (representative of discharge at the Morella/Salt Creek regulators; black line) and 21-d rolling total rainfall (mm) and b) water level upstream of the Morella Regulator (black line), Salt Creek flow gauging weir (blue line) and in the Coorong South Lagoon at Snipe Island (green line) April 2023–November 2024. Tracking periods in 2023 and 2024 are indicated by grey shading. Data from Water Data SA (Department for Environment and Water) and Australian Bureau of Meteorology.

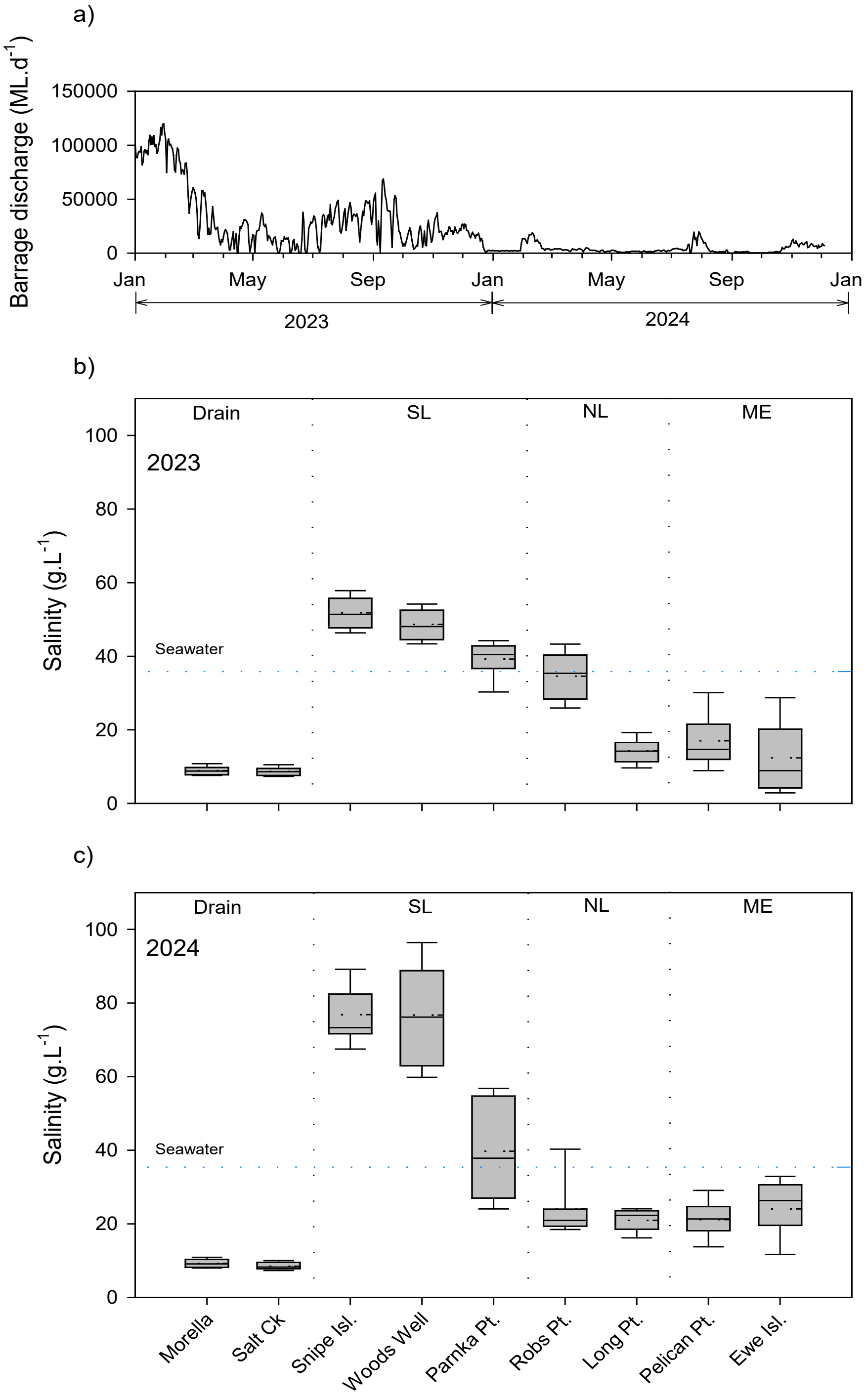

Figure 4. a) Freshwater discharge from the Murray Barrages from January 2023–December 2024, and box and whisker plot presenting mean daily salinity data ($g.L^{-1}$ ± SE) at several water quality stations in the SEFRP Drain and South Lagoon (SL), North Lagoon (NL) and Murray Estuary (ME) reaches of the Coorong in June–July of (b) 2023 and (c) 2024. Boxes represent 25th and 75th percentiles, and error bars 10th and 90th percentiles. Median (solid black horizontal line) and mean (dashed black horizontal line) salinities, and the value of typical seawater salinity (the dashed blue line) are also indicated.

3.2. General movement patterns

Over the course of the study, 60 of 67 (90%) tagged congolli were detected on the receiver array (30,273 total detections). Total detection periods (i.e., the number of days between tagging and last detection) ranged from 15–161 d and were generally greater for fish tagged in 2024 (mean ± SD = 93 ± 8 d) than 2023 (mean ± SD = 63 ± 6 d) (Figure 5a and Appendix 1). The number of receivers on which individuals were detected ranged from 1–10, with a larger proportion of individuals detected on >five receivers in 2023 (63%) than 2024 (34%) (Figure 5b). Approximately 80% of all detections occurred between sunset (~18:00) and sunrise (~07:00) (Figure 5c).

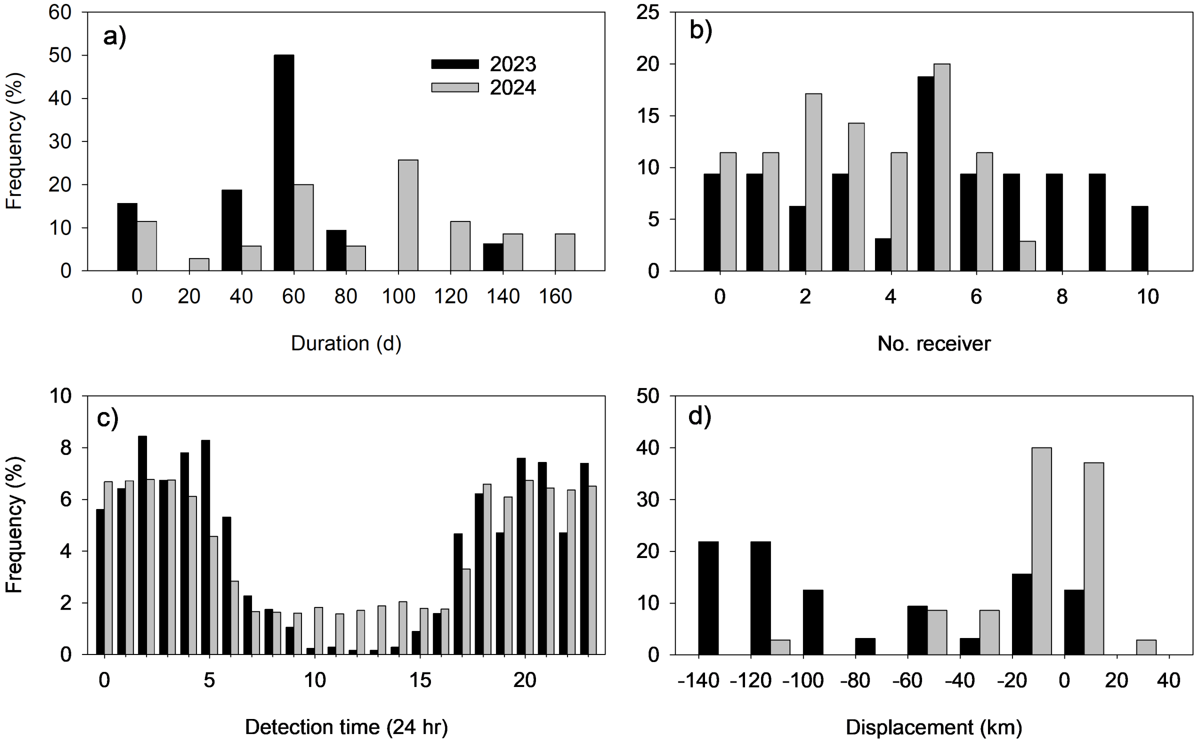

Figure 5. Summary of detection patterns from 2023 and 2024, depicting a) frequency of fish against duration of detection (i.e. tag date to last detection), b) frequency of fish against the number of receivers on which detected, c) frequency of detections by time (24 hr), and d) frequency of fish against distance of displacement from tagging site (i.e. final detection distance upstream (+) or downstream (-) of tagging site).

In 2023, patterns of gross movement were consistent across individuals (movement plots for all individuals are presented in Appendix B), with 28 of 29 detected fish (97%) last detected downstream from their tagging location. Displacement (from tagging) ranged from 11.4 km upstream to 138.7 km downstream, with a mean (±SE) of 82.4 ± 8.2 km downstream (Figure 5d). All detected individuals exhibited limited movement and high site fidelity through May and early June, and six fish (~20% of detected fish) continued to exhibit site fidelity for the remainder of tracking and were last detected within the SEFRP Drain (Figure 6 and 7a). The majority (*n* = 24; ~83%), however, initiated rapid downstream movements (defined in section 3.3) from 8 June–19 July, passed the Morella and Salt Creek regulators and entered the Coorong from 12 June–26 July (Figure 7a). Of these, five (17%) were last detected in the South Lagoon, two in the North Lagoon (7%), four (14%) in the Murray Estuary and 12 (41%) transitioned to the Indian Ocean as indicated by being last detected on receivers adjacent the Murray Mouth (Figure 6). Exit of the Murray Mouth occurred from 20 June–8 August, 8–21 days following passage of the Salt Creek regulator.

In 2024, 21 of 31 detected fish (68%) were last detected downstream from their tagging location with displacement ranging from 29.9 km upstream to 108 km downstream and a mean (±SE) of 11 ± 4 km downstream (Figure 5d). Similar to 2023, fish tagged in 2024 exhibited limited movement and high site fidelity through May and four (~13% of detected fish) continued to exhibit site fidelity for the remainder of tracking and were last detected within the SEFRP Drain (Figure 6 and 7b). The majority (*n* = 27; 87%), however, initiated rapid downstream movements from 5 June–27 July (Figure 7b). Most (*n* = 19, 61%) resided in the vicinity upstream of the Morella Regulator for extended periods (often weeks) from June–August, before detections ceased or fish were recorded returning upstream. The remaining eight detected fish (26%) that initiated downstream movements, passed downstream over the Morella and Salt Creek regulators and entered the Coorong from 25 June–26 August (Figure 7b). Of these, five (16%) were last detected in the South Lagoon and two (~6%) in the Murray Estuary, while one (~3%) transitioned to the ocean (Figure 6). Exit of the Murray Mouth occurred for this individual on 3 September, seven days following regulator passage.

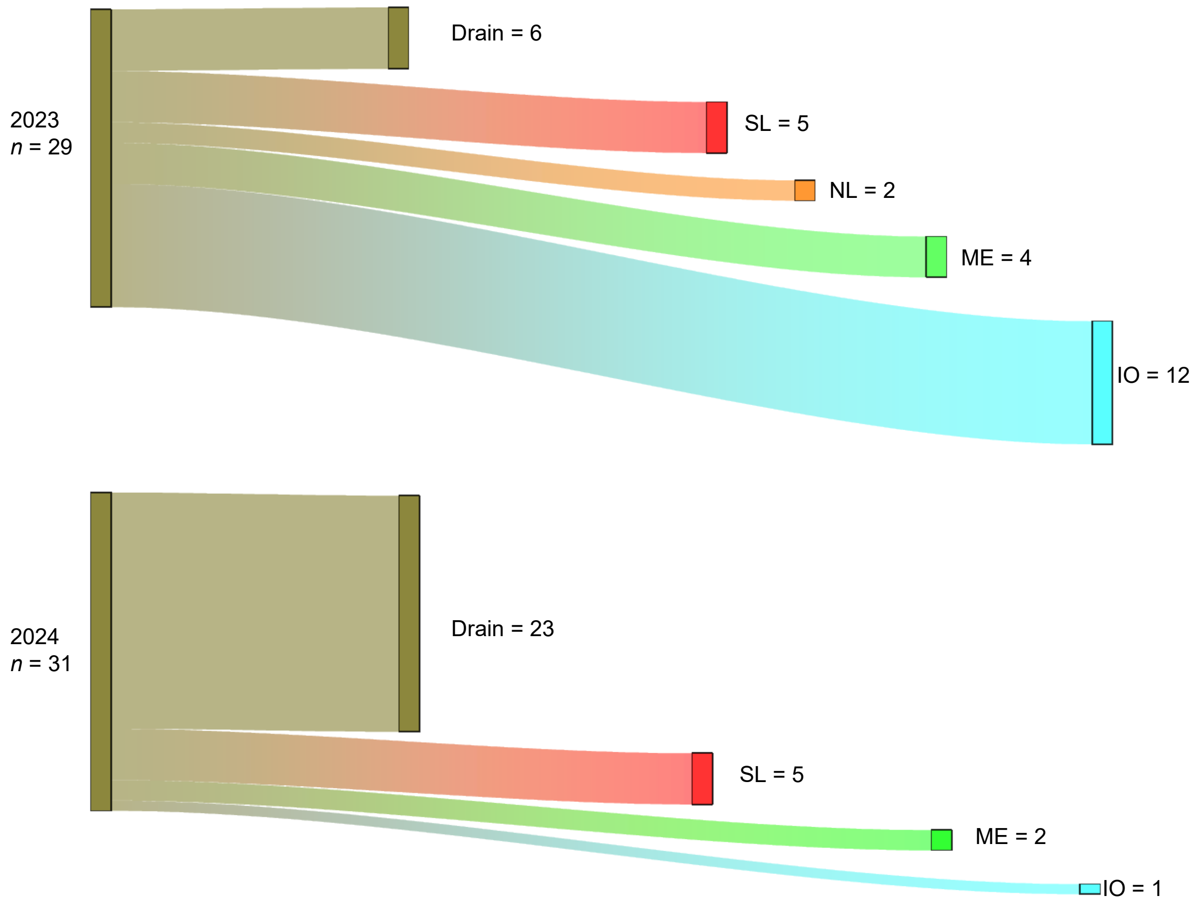

Figure 6. Sankey plots depicting final location (last known detection within SEFRP Drain [Drain], South Lagoon [SL], North Lagoon [NL], Murray Estuary [ME] or Indian Ocean [IO]) of detected female congolli in 2023 and 2024.

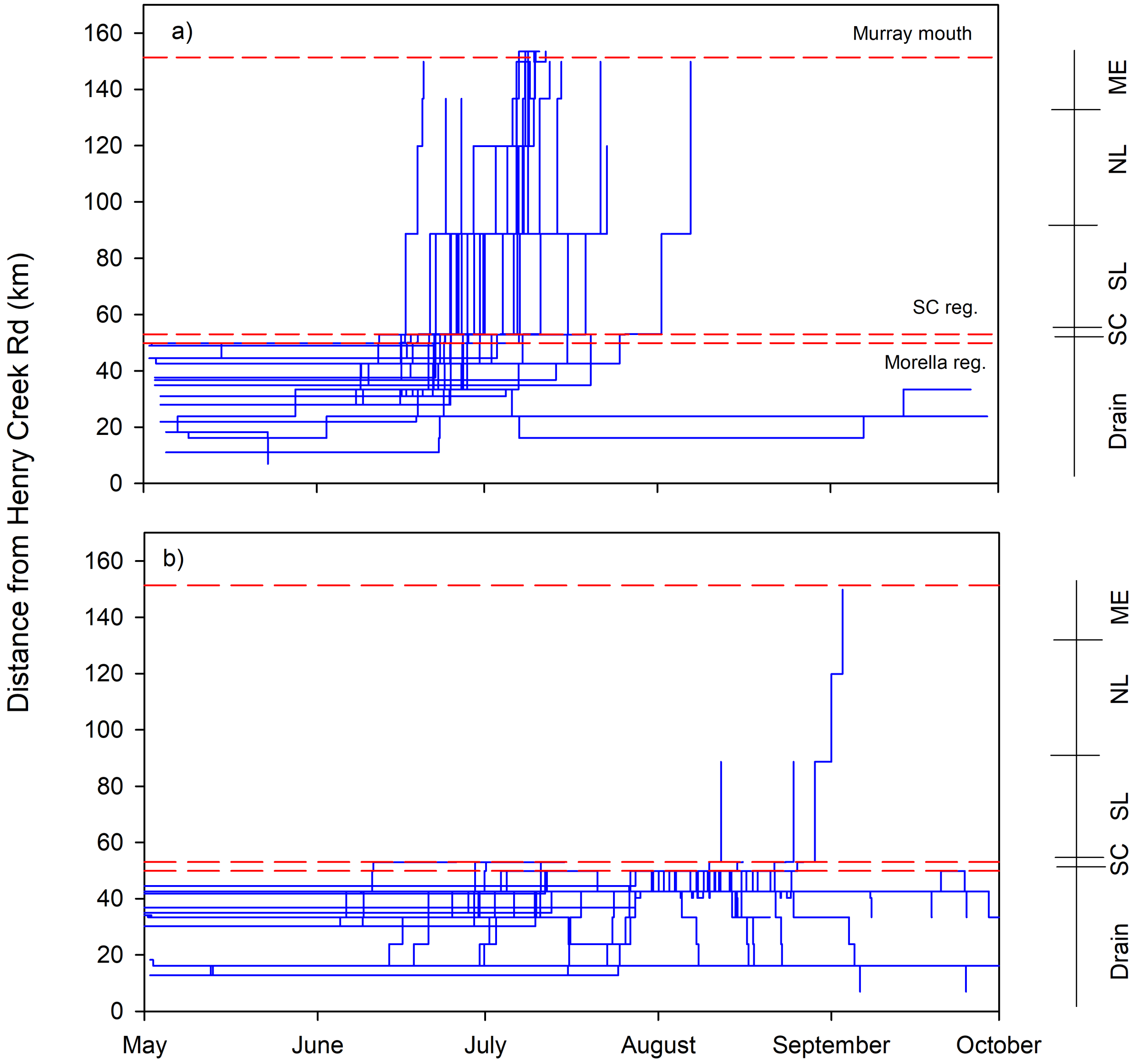

Figure 7. Movement profiles for all acoustically tagged adult female congolli in a) 2023 and b) 2024. The y-axis indicates the distance (km) of fish from Henry Creek Road at the southeastern end of the acoustic array. The position of the Morella and Salt Creek regulators, and the Murray Mouth, are indicated by dashed red lines, while the borders of the drain network, Salt Creek (SC), South Lagoon (SL), North Lagoon (NL) and Murray Estuary (ME) are indicated on the righthand y-axis.

3.3. Environmental drivers of movement and passage

Initiation of migration

In 2023, congolli initiated their downstream movement significantly earlier ($t_{43.138}$ = 3.244, p = 0.002; average date of movement = 23 June) than 2024 (6 July, Figure 8). Furthermore, in 2023, the distribution of initiation dates was significantly narrower (8 June to 19 July) compared to 2024 (6 June to 27 July; variance ratio: 0.355, $F_{23,26}$ = 0.355, p = 0.014). The model best explaining spatio-temporal variation in the daily likelihood of initiating downstream migration included an interactive smooth term for day of year (DOY) and distance (Table 2a). Fish were more likely to have initiated downstream movement as time progressed through winter and more likely on a given day if they were residing lower down in the drain network (Figure 9).

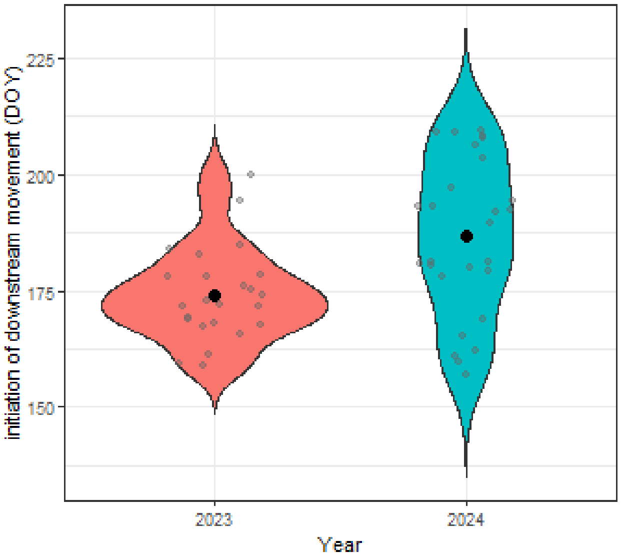

Figure 8. Violin plot of the timing of downstream movement initiation for congolli in the drain network in 2023 and 2024. The shape of each violin represents the density distribution of data (light grey points) and the solid black point is the group mean. DOY: day of the year.

Table 2. Selection results for models comparing the effects of a) spatio-temporal factors and b) spatio-temporal and environmental factors on the initiation of downstream migration. Models are ranked by ΔAICc, with the best highlighted in bold. The terms 's' and 't2', respectively, represent a smoother or tensor product smoother fitted to continuous covariates. All models included Year as a categorical parametric term for design reasons. df = degrees of freedom and DOY = day of year. For part 'b' of analysis, the best five models are presented.

Model	**log likelihood**	**AICc**	**ΔAICc**	**df**
a) Spatio-temporal model				
Year + t2(DOY, Distance)	**-199.3**	**416.6**	**0**	**9**
Year + s(DOY)	-206.9	423.89	7.3	5
Year + s(DOY, Distance, by = Year)	-196.9	423.89	7.3	15
Year + s(DOY, by = Year)	-206.9	427.9	11.3	7
b) Spatio-temporal + enviro models				
Year + t2(DOY, Distance)	**-199.3**	**416.6**	**0**	**9**
Year + t2(DOY, Distance) + s(21d rainfall)	-198	418.2	1.6	11
Year + t2(DOY, Distance) + s(moonphase)	-199.2	418.4	1.8	10
Year + t2(DOY, Distance) + s(temperature change)	-199.1	420.2	3.6	11
Year + t2(DOY, Distance) + s(moonphase, by = Year)	-199.1	420.4	3.8	11

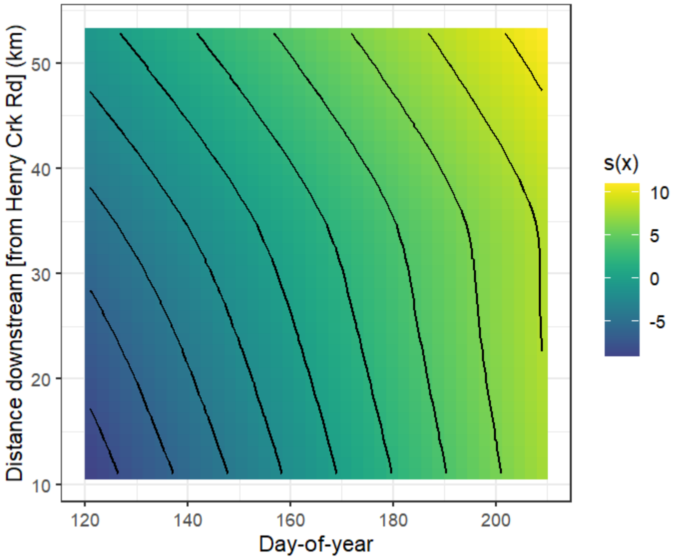

Figure 9. Interactive smooth plot for the effect of day-of year and distance upstream on the log odds of downstream congolli movement (colour ramp). S(x) indicates strength of positive or negative effect on the log odds of movement. More yellow colours indicate a greater likelihood of a congolli undertaking a downstream movement.

We next explored whether variation in rainfall, moon phase or water temperature could predict the odds of a congolli undertaking a downstream migration. We added additional smoothers for each environmental variable to our spatio-temporal model and also allowed for their effect to vary over space and years. There was strong co-linearity between daily and 7-day average water temperature with day of the year, and thus, these factors were not included in the same models. We also explored models where different combinations of DOY and distance were excluded to see if spatio-temporal dynamics of environmental variables could explain initiation. The addition of environmental predictors to the base spatio-temporal model, or the replacement of DOY and distance with environmental predictors, did not improve model fit (Table 2b). There was, however, some evidence (ΔAICc < 2) that 21-day rainfall and moon phase may contribute to the initiation time of congolli downstream movement with individuals more likely to move following periods of higher rainfall (smoother p = 0.04), and on the new moon (smoother p = 0.03, Figure 10).

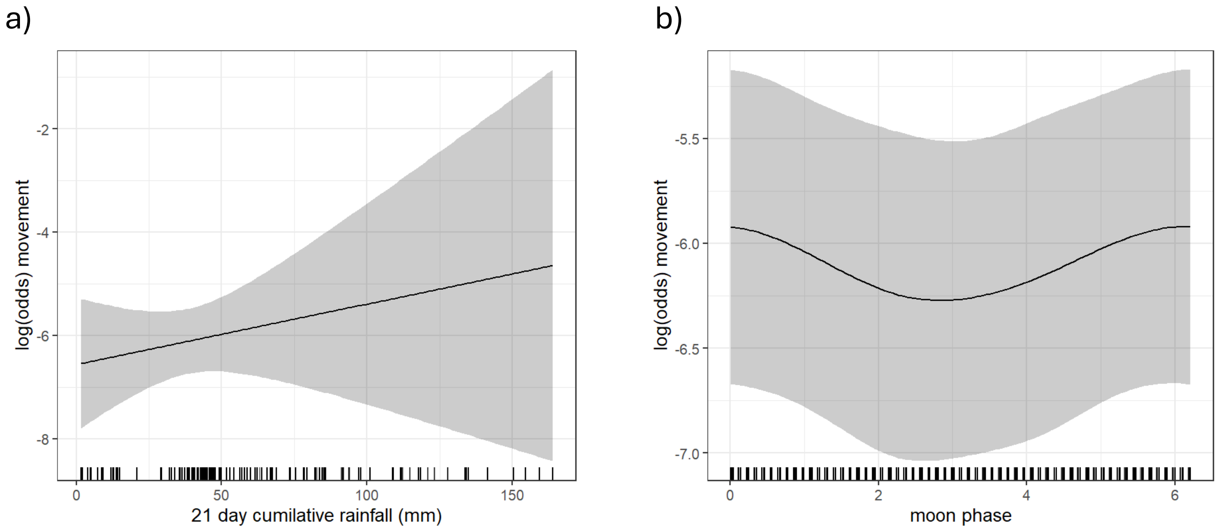

Figure 10. Partial effects plot showing the odds of a congolli migrating downstream (on the log scale) as a function of a) cumulative rainfall over the preceding 21 days and b) moon phase. A moon phase of zero denotes the new moon, while a moon phase approximately 3.14 denotes the full moon. More positive log odds represent increased likelihoods of congolli migrating. Shaded areas are 95% confidence intervals. Short vertical lines on x-axis indicate observed movement events.

Regulator passage

Thirty-two of the 49 (~65%) congolli that approached the Morella Regulator in 2023 and 2024 successfully passed through this structure. In 2023, successful passage occurred between 12 June and 25 July, and in 2024, between 11 June and 17 August. In 2023, congolli spent an average of 1.9 days in the immediate vicinity of the regulator before successful passage. In 2024, this increased to 10.9 days, but this difference was not significant ($t_{7.130}$ = 2.21, p = 0.06). The best model predicting successful passage through the Morella Regulator included just a smooth term for log-transformed discharge, with fish more likely to pass through the Morella Regulator during periods of higher discharge (Table 3 and Figure 11a). Other models to receive support included regulator/fishway operation, with passage more likely when both regulator gates and the fishway were operating (Table 3 and Figure 11b). Other models suggested high headwater level and head loss across the regulator also increased likelihood of passage (Table 3).

Table 3. Selection results for models comparing the effects of regulator/fishway operation and temporal factors on the passage of congolli through the Morella Regulator. Models are ranked by ΔAICc, with the best highlighted in bold. Shown are the top five models, based on AICc deviance from the best model. The term ‘s’ represents a smoother fitted to continuous covariates. df is degrees of freedom. Open pooled (0: neither fishway or regulator gates open, 1: either open, 2: both open) and Open either (0: neither fishway or regulator gates open, 1: either open) describe management options for the regulator.

Model	log likelihood	AICc	ΔAICc	df
s(log daily discharge)	**-77.3**	**162.7**	**0**	**4**
Regulator permeability	-77.6	163.2	0.5	4
s(Morella head loss) + regulator permeability	-75.7	163.6	0.9	6
s(Morella upstream water level) + regulator permeability	-75.9	163.9	1.2	6
s(log daily discharge) + Open either	-76.9	164	1.3	5

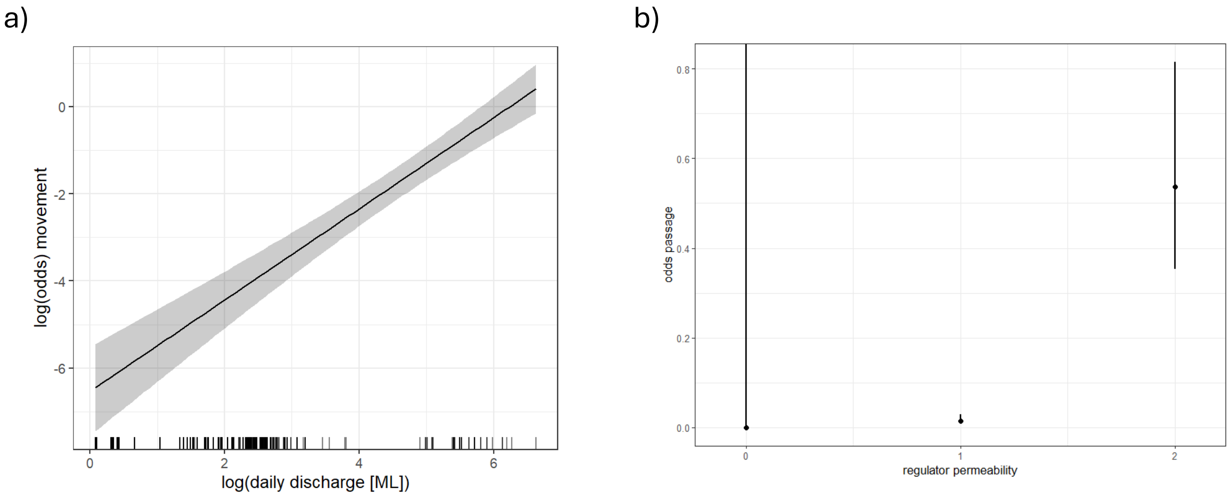

Figure 11. Predicted odds of congolli passage through the Morella Regulator (on the log scale) as a function of a) log daily discharge and b) regulator permeability. More positive log odds represent increased likelihoods of congolli passage. Shaded areas are 95% confidence intervals. Short vertical lines on x-axis indicate observed movement events. In plot b, permeability of zero is when both gates and fishways are closed, 1 is when either is open, and 2 is when both gates and fishway are open.

Of 32 congolli that passed the Morella Regulator, 31 (97%) also passed the Salt Creek Regulator. In 2024, however, time spent traversing from Morella to Salt Creek was significantly greater than in 2023 (8.2 vs. 1.8 days, $t_{7.165} = 2.655$, $p = 0.032$). The best model predicting the successful passage included just the term Year (Table 4), with the odds of a fish moving beyond the Salt Creek Regulator on a given day greatest in 2023 (Figure 12). The operation of the Salt Creek regulator did not have a discernible impact on fish passage.

Table 4. Selection results for models comparing the effects of regulator/fishway operation and temporal factors on the passage of congolli through the Salt Creek Regulator. Models are ranked by ΔAICc, with the best highlighted in bold. Shown are the top five models, based AICc deviance from the best model. The term ‘s’ represents a smoother fitted to continuous covariates. df is degrees of freedom. DOY = day of year.

model	log likelihood	AICc	ΔAICc	df
Year	**-61.2**	**128.6**	**0**	**3**
s(upstream water level)	-61.7	131.8	3.2	4
s(DOY) + Year	-60.6	131.8	3.2	5
s(downstream water level)	-61.9	132.3	3.7	4
s(upstream water level) + Year	-61	132.6	4	5

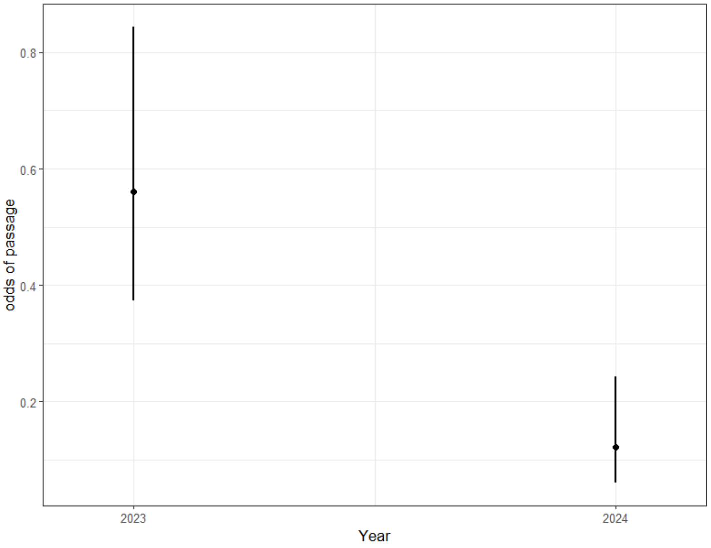

Figure 12. Predicted odds of congolli passage through the Salt Creek Regulator as a function of sample year. More positive odds represent increased likelihoods of congolli passage. Bars represent 95% confidence intervals.

Passage through the Coorong

In 2023, of 23 tagged congolli that entered the South Lagoon, 18 (78%) successfully passed into the North Lagoon and migrated towards the ocean. In 2024, only eight tagged congolli entered South Lagoon and just three (37.5%) successfully passed into the North Lagoon. In 2024, fish took considerably longer to traverse the South Lagoon (average 31.3 days) compared to 2023 fish (average 8.7 days), although this was not a significant difference ($t_{2.110} = 2.48$, $p = 0.13$, Figure 13). The model best predicting the successful exit of congolli from South Lagoon included just the model intercept, with no evidence that passage through the Coorong was influenced by salinity (daily and 7d average) salinity gradients (daily and 7d), water level (daily or 7d), moon phase, or even year (Table 5). We also found no evidence that the odds of exiting the South Lagoon could be predicted by migration days, a proxy for potential predation exposure. These results may reflect true underlying patterns or could be because of low sample sizes.

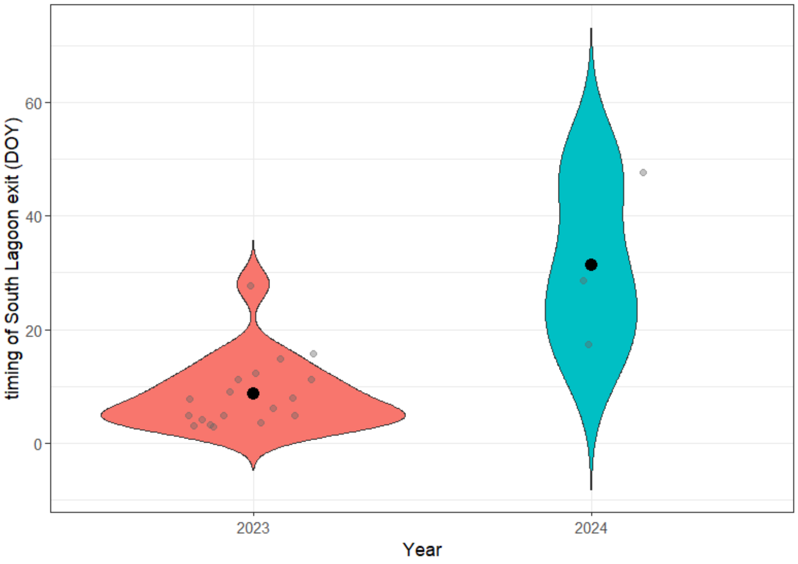

Figure 13. Violin plot of the timing of congolli exit from South Lagoon. The shape of each violin represents the density distribution of data (light grey points) and the solid black point is the group mean. DOY: day of the year.

Table 5. Selection results for models comparing the effects of environmental variables on the successful exit of congolli from the South Lagoon. Models are ranked by ΔAICc, with the best highlighted in bold. Shown are the top five models, based AICc deviance from the best model. The term 's' represents a smoother fitted to continuous covariates. df is degrees of freedom.

model	log likelihood	AICc	ΔAICc	df
intercept only	**-54.4**	**112.9**	**0**	**2**
Year	-54.3	114.9	2	3
s(moonphase)	-54.4	115	2.1	3
s(days migrating)	-53.9	116.2	3.3	4
s(moonphase) + Year	-54.3	117.1	4.2	4

We next explored whether environmental conditions could predict how long it took congolli to exit the South Lagoon after moving through the Salt Creek Regulator. We focused on 7-day environmental variables as these better covered the time fish spent moving through the South Lagoon. We did not explore whether any environmental patterns differed across years as we only had three observations in 2024. The best model predicting the time congolli spent moving through the South Lagoon included a smoother term for the 7-day average salinity gradient (Table 6). Here, migrations were quickest at intermediate salinity gradient values, but increased when the gradient disappeared, or when the South Lagoon was much saltier than the North Lagoon (Figure 14).

Table 6. Selection results for models comparing the effects of environmental variables on the duration of migration of congolli through South Lagoon. Models are ranked by ΔAICc, with the best highlighted in bold. The term 's' represents a smoother fitted to continuous covariates. df is degrees of freedom.

model	**log likelihood**	**AICc**	**ΔAICc**	**df**
s(salinity gradient 7 days)	**-67.2**	**146**	**0**	**4.3**
s(water level 7 days)	-69	150.6	4.6	4.6
Year	-72	151.4	5.4	3
s(log salinity 7 days)	-71.2	155.3	9.3	4.7
intercept only	-79.9	164.5	18.6	2

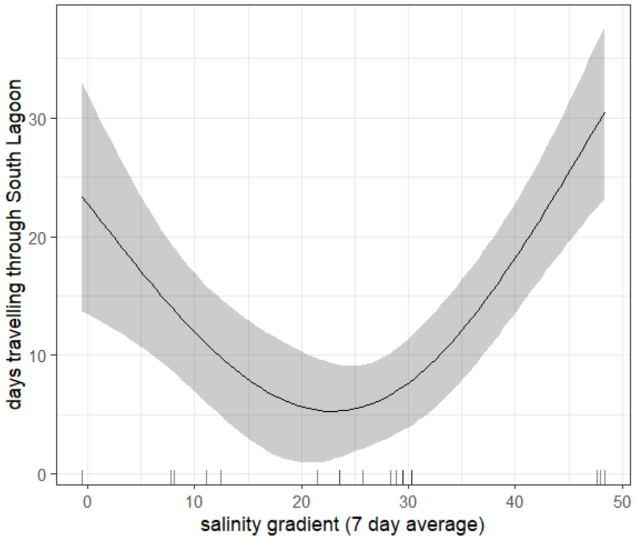

Figure 14. Predicted duration of congolli travel through South Lagoon as a function of 7 day average salinity gradient. Shaded areas are 95% confidence intervals. Short vertical lines on x-axis indicate observed movement events.

4. DISCUSSION

Patterns of movement demonstrated by adult female congolli tagged in the SEFRP Drain were generally consistent with findings from previous studies, including sedentary behaviour in freshwater habitats in autumn followed by rapid nocturnal downstream migrations in winter, and in many cases, transition through the estuary and into the ocean (Crook et al. 2010, Bice et al. 2018b). Importantly, the two years of the current study were characterised by substantially different climatic and hydrological conditions, namely: high rainfall, discharge, drain water level and connectivity, and relatively low salinities within the Coorong in 2023; and low rainfall, discharge, drain water level and connectivity, and relatively high salinities within the Coorong in 2024. In association, ~40% of detected fish successfully reached the Murray Mouth in 2023 and just 3% in 2024. These diverse conditions and migratory outcomes provided critical new knowledge on the movement ecology of congolli in the USE and Coorong, including the influence of key environmental variables and management actions on specific aspects of migration (e.g. passage from the SEFRP Drain to the Coorong).

Most detected fish (85%) initiated driven downstream movements in the direction of water flow and towards the Coorong during winter, while few fish moved in a south-easterly (‘upstream’) direction toward Henry Creek Road. Passage to the ocean may, at times, be provided via the Blackford Drain at the southeastern end of the SEFRP Drain, but passage via this route was unlikely to be possible during either 2023 or 2024 due to operation of the flow-regulating structure on the Blackford Drain. Data collected in the study indicate that Salt Creek is likely the primary route taken by female congolli out migrating from the SEFRP Drain.

The strongest predictors of initiation of downstream migration were day of year and distance upstream. Association of downstream migration with time of year (average dates 23 June–5 July immediately following the winter solstice) was expected given the generally well-defined and consistent timing previously reported for the species across its range (Crook et al. 2010, Bice et al. 2018b). It is likely that a combination of low water temperature and short photoperiod (manifesting as DOY) broadly define the migration season. Fish tagged relatively further downstream were also likely to initiate migration sooner. Reasons for this are unclear, but these individuals, by virtue of their location, may perceive certain cues (e.g. increasing water level) earlier than their upstream counterparts, and these cues may not have been detected in our analyses. There was also some support for high drain discharge (using 21d rainfall as a proxy) and moon-phase (new moon) as proximate cues. Increased discharge was also found as a proximate cue of congolli migration in western Victoria (Crook et al. 2010) and the downstream migrations of other catadromous (e.g. Australian Bass, *Macquaria novemaculeata*; Reinfelds et al. 2013) and amphidromous fishes (Australian grayling, *Prototroctes maraena*; Koster et al. 2018) in southeastern Australia. The lack of a strong flow signal in this study may be because rainfall only approximated in-channel flows experienced by congolli. Initiation of migration on a new moon and its associated dark nights may indicate a preference for migration during periods of lower predation risk from piscivorous fishes (e.g. the predation risk allocation hypothesis; Lima and Bednekoff 1999).

A key step in continuing downstream migrations was passage over the Morella Regulator, with differing operation between years greatly influencing successful passage. Passage was most likely during higher discharge, when headwater levels were relatively high and when both the regulator gates and fishway were operated simultaneously. During June–August 2023, total discharge (gates and fishway combined) from the Morella Regulator was typically >200 ML.day^{-1}, and headwater levels were >3.96 m AHD, allowing simultaneous operation of regulator gates and the fishway; 96% of female congolli detected within the vicinity of the regulator successfully passed and on average passage occurred <2d following first detection in the upstream vicinity of the regulator. During June–August 2024, due in part to the preceding drawdown and subsequent need to refill Morella Basin, discharge over the Morella Regulator was generally <25 ML.day^{-1}, whilst headwater levels were <3.84 m AHD until 28 July, precluding operation of the fishway till after this date, when all discharge was subsequently passed through the fishway. In this year, only 30% of female congolli detected within the vicinity of the regulator successfully passed, and for those that did, successful passage, on average, took 11d to occur. Nonetheless, successful passage events occurred both prior to (n = 4) and after fishway operation commenced (n = 4), suggesting both the regulator and fishway are at times viable migration routes. Despite passage occurring over the regulator gates prior to the fishway operating, the large number of fish that did not pass, and migratory delay for those that did, suggest that when discharge over the regulator gates is <25 ML.day^{-1} and headwater levels are <3.84 m, the regulator represents a partial barrier to downstream passage.

Passage past the Salt Creek Regulator was not impeded in either year, with 97% of all fish that passed Morella, also passing Salt Creek. Like the Morella regulator, from June–August 2023, discharge through the Salt Creek regulator was relatively high and the regulator gates and the fishway operated simultaneously. In 2024, regulator gates and the fishway operated simultaneously from June–August, except for 15 July–15 August when all flow passed via the fishway; all but one passage event occurred when both regulator gates and fishway were operating. The function of the Salt Creek Regulator differs from that of Morella, in that it is used to manage flow and regulate water levels in a relatively short (~3 km) creek compared to the extensive basin and drainage network upstream of Morella. As such, only minimal discharge from Morella is required to maintain headwater levels at the Salt Creek Regulator high enough to allow fishway and gate operation. Subsequently, under most conditions, the structure is unlikely to represent a barrier to the downstream movements of congolli.

Fish that entered the Coorong, transitioned directly from brackish (7–11 $g.L^{-1}$) to hypermarine salinities (2023 = 45–60 $g.L^{-1}$, 2024 = 60–104 $g.L^{-1}$, daily mean at Woods Well). In both years, some individuals successfully completed their seaward migrations, demonstrating the broad salinity tolerance of the species (Hortle 1978, McNeil et al. 2013). After entering the South Lagoon, individuals followed a reverse salinity gradient (high salinity to low salinity) toward the Murray Mouth. This is atypical for the downstream migrations of catadromous fishes, which generally occur across a gradient from low to high salinity as individuals move from freshwater to marine habitats. A downstream gradient of increasing salinity is commonly posited as a cue for orienting downstream migrations in diadromous fishes (Hedger et al. 2008), yet navigation of a reverse salinity gradient suggests cues other than increasing salinity (e.g., innate compass navigation, Dodson 1988) may guide migration through the Coorong.

Salinities and water levels in the Coorong lagoons varied greatly between the migration periods of 2023 and 2024, and we investigated if higher salinities and lower water levels experienced in 2024 may have resulted in fewer individuals transitioning between South and North lagoons and reaching the Murray Mouth. The specific salinity tolerance of adult female congolli is unknown, but laboratory trials suggest that juveniles begin to be directly impacted at salinities ranging from 80–100 $g.L^{-1}$ (McNeil et al. 2013); salinities in this range were common in the South Lagoon in 2024. Additionally, the transition area between the South and North lagoons, particularly in the vicinity of the Needles, exhibits shallow bathymetry (e.g. bed elevation commonly >0 m AHD), and while low water levels in the Coorong (as observed in 2024) do not hydrologically disconnect the lagoons, these conditions result in an expansive area of shallow water that must be navigated. Such an area could impede migration due to heightened predation risk, locally increased water temperatures due to solar radiation, or other behavioural aversions to swimming through shallow water. Our models, however, suggested no evidence for these effects, although the small sample size of fish that successfully made this transition in 2024 (*n* = 3) likely hampered analyses. Interestingly, additional analyses indicated migration rates through the South Lagoon were fastest during intermediate salinity gradient between the North and South lagoons, and slowest during low and high gradients. While interpretation of this result is difficult, it does suggest a potential role of salinity in migration outcomes once individuals enter the Coorong.

Several individuals in 2023 (*n* = 6) and 2024 (*n* = 2) passed the South Lagoon but did not reach the Murray Mouth. These fish were last detected in the North Lagoon or Murray Estuary. Each was undertaking a rapid and driven migration, and it is possible that some of these individuals may have missed detection on receivers at the Murray Mouth and transitioned to the ocean. An alternative explanation is that downstream migrating individuals were preyed upon. Within the Coorong, congolli are a food resource for large piscivorous fishes (e.g., mulloway, *Agyrosomus japonicus*), birds (e.g., great cormorant, *Phalacrocorax carbo*) and long-nosed fur seals (*Arctocephalus forsteri*) (Giatas and Ye 2015; SARDI unpublished data, Goldsworthy et al. 2019), and distinct circa-annual migrations of fishes, like that of congolli, commonly attract large numbers of predators (Gende et al. 2002). Additionally, these individuals may have been captured by fishers in the Lakes and Coorong Commercial Fishery.

The current study provides important information on the outmigration of female congolli during years of contrasting hydrology and connectivity in the SEFRP drain network, and salinity and water level in the Coorong. Nevertheless, several questions remain regarding the species ecology in the South East Drainage Network. Chief among these are: 1) the fate and longevity of individuals that aborted downstream migrations in 2024; and 2) the dynamics of upstream migration of juveniles into the drainage network. Regarding the first question: similar instances when the species downstream migrations have been obstructed for one or more years in the Lower Lakes during the Millenium Drought (2007–2010) and Lake George from 2017–2025 may provide insight. In those instances, length measurements and opportunistic ageing of adult females suggested the survival of fish that were obstructed grew to larger sizes and ages than typical during downstream migrations in connected systems (Giatas et al. 2024; SARDI Unpublished Data). Nonetheless, in the case of Lake George, prolonged obstruction has also been associated with declines in abundance. Regarding the second question: during sampling for the current study, all congolli captured were large adults >196 mm TL, although low numbers of juvenile congolli have been detected passing upstream into the SEFRP Drain from the Coorong via the Salt Creek and Morella fishways (Ye et al. 2022, Ye et al. 2024). This suggests that juveniles were only present in low abundance, or that significant recruitment/movement events into the SEFRP Drain may be sporadic in nature and juveniles may have been using alternative habitat in the USE Drainage Network other than those sampled in the current study. Additionally, juveniles migrating upstream from the ocean may, at times, access the system from other parts of the South East Drain Network (e.g. the Blackford Drain). Nonetheless, due to the large number of flow regulating structures throughout the network, broader-scale hydrological connectivity is only facilitated sporadically during periods of high discharge (Mark de Jong, South Australian Limestone Coast Landscape Board, pers comm.).

5. CONCLUSIONS AND RECOMMENDATIONS

In the current study, adult female congolli demonstrated aspects of the catadromous life history typical of the species, characterised by a rapid downstream spawning migration during winter. Acoustically tagged fish migrated in the direction of water flow toward the Coorong, and in many cases, through the Coorong, against a reverse salinity gradient, toward the ocean. Successful passage through the Morella Regulator was critical to ultimate destination and success of migrations. Conditions within the South Lagoon may have also influenced migration outcomes, but analyses were not definitive.

Results of the current and similar studies (Crook et al. 2010, Bice et al. 2018b) suggest that while discharge in the drain and moon phase may act as proximate environmental cues to stimulate movement, migrations are likely to predictably occur annually around the winter solstice. If the passage of adult female congolli is an objective of management of the SEFRP Drain, we suggest the following for the period June–August:

1) Maintaining water levels in the Morella Basin >3.84 m AHD and Salt Creek >0.95 m AHD to facilitate fishway function. This allows for water to be discharged through the fishways and maintains a minimum water depth of 0.1 m at the fishway exit.
2) Providing additional discharge through regulator gates to enable simultaneous operation of fishways and gates. A specific threshold is not apparent from the study, but the lower end of discharges experienced during 2023 (200 ML.day^{-1}) provide a guide.

The water level regime experienced in 2024 was, in part, a result of low rainfall, but also a drawdown of the Morella Basin that was a deliberate management action to achieve specific ecological objectives (i.e. to expose mudflat habitat and provide food resources for waterbird populations). The timing of drawdowns may subsequently influence diadromous fish migrations due to a need to refill the basin prior to reaching water levels that enable regulator and fishway discharge. As such, the achievement of different ecological objectives may represent trade-offs in certain years.

While statistical relationships between environmental conditions and passage through the South Lagoon were limited to migration rates, the comparatively greater success demonstrated by individuals in 2023 suggests periods of higher water levels and lower salinity are more conducive to successful migration. Such conditions are largely reliant on freshwater discharge from the

Murray Barrages. While migration of congolli from the SEFRP drain is unlikely to be an objective of large volume barrage releases, the physico-chemical conditions in the Coorong provide a context for expected outcomes of migration in given years.

Regarding further improvements to understanding of movement ecology of congolli in the region, key knowledge gaps include:

1) The fate and longevity of adult female congolli retained within the SEFRP Drain;
2) Interaction of individuals between the USE and LSE Drainage systems; and
3) The frequency of recruitment events in the SEFRP Drain and spatial source of recruits.

Investigations focused on these questions would improve the ecologically sensitive operation of the South East Drainage Network that recognises the unique life histories of diadromous fishes.

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7. APPENDICES

7.1. Appendix A

Table A1. Details of adult female congolli captured and tagged in the Tilley Swamp Drain system in 2023 including tagging date, location, total length (mm), weight (g). number of acoustic detections, displacement from tagging location (km, +/- refer to upstream/downstream displacement), and indication if individuals entered the Coorong (1 = yes, 0 = no) and ocean (1 = yes, 0 = no).

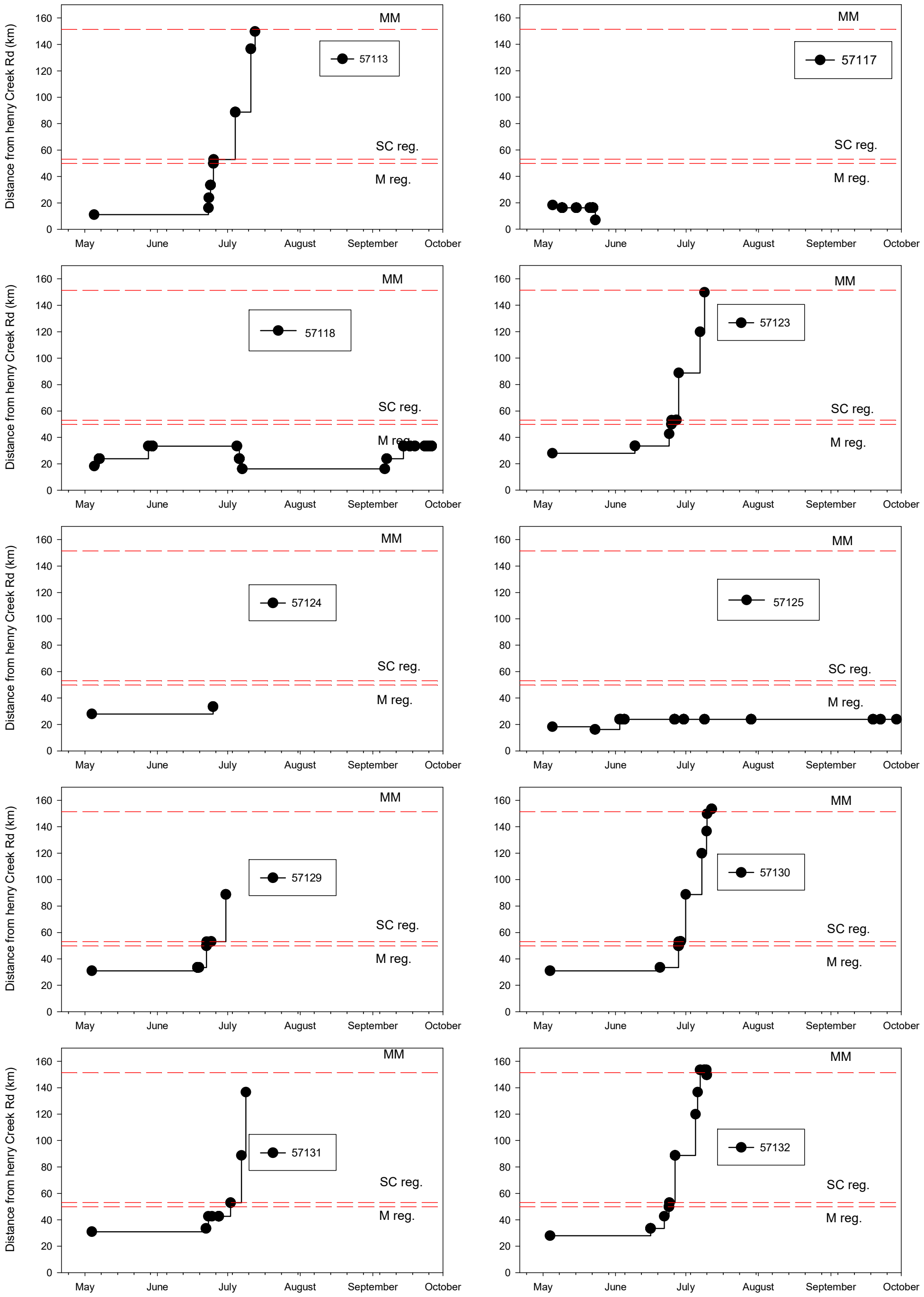
Fish no.	Date Tagged	Tagging Location	Total length (mm)	Weight (g)	Detections	Displacement	Enter Coorong	Enter ocean
1	2/05/2023	DS END MORELLA	285	235	1102	-39.75	1	0
2	2/05/2023	DS END MORELLA	273	212	114	-100.85	1	1
3	2/05/2023	US END MORELLA	331	294	0	-	-	-
4	2/05/2023	US END MORELLA	278	214	21	-44.15	1	0
5	2/05/2023	US END MORELLA	312	336	17	-44.15	1	0
6	2/05/2023	US END MORELLA	305	284	173	-107.2	1	1
7	2/05/2023	US END MORELLA	332	323	30	-5.32	0	0
8	3/05/2023	US NORTHERN OUTLET	285	234	226	-112.11	1	1
9	3/05/2023	US NORTHERN OUTLET	290	235	44	-99.01	1	0
10	3/05/2023	US NORTHERN OUTLET	308	282	28	-112.11	1	1
11	3/05/2023	US NORTHERN OUTLET	268	182	149	-99.93	1	0
12	3/05/2023	US NORTHERN OUTLET	280	225	0	-	-	-
13	3/05/2023	US NORTHERN OUTLET	277	189	5	-83.13	1	0
14	3/05/2023	DS SAFARI RD	293	229	0	-	-	-
15	3/05/2023	DS SAFARI RD	292	220	1	-17.95	0	0
16	3/05/2023	DS SAFARI RD	300	231	14	-101.75	1	0
17	4/05/2023	DS CANTARA RD (R3S4)	280	229	27	-127.86	1	1
18	4/05/2023	US SAFARI RD (R3S2)	265	178	11	-118.8	1	1
19	4/05/2023	US SAFARI RD (R3S2)	261	179	30	-122.47	1	1
20	4/05/2023	US SAFARI RD (R3S2)	254	156	13	-88.9	1	0
21	4/05/2023	US SAFARI RD (R3S2)	276	213	23	-122.47	1	1

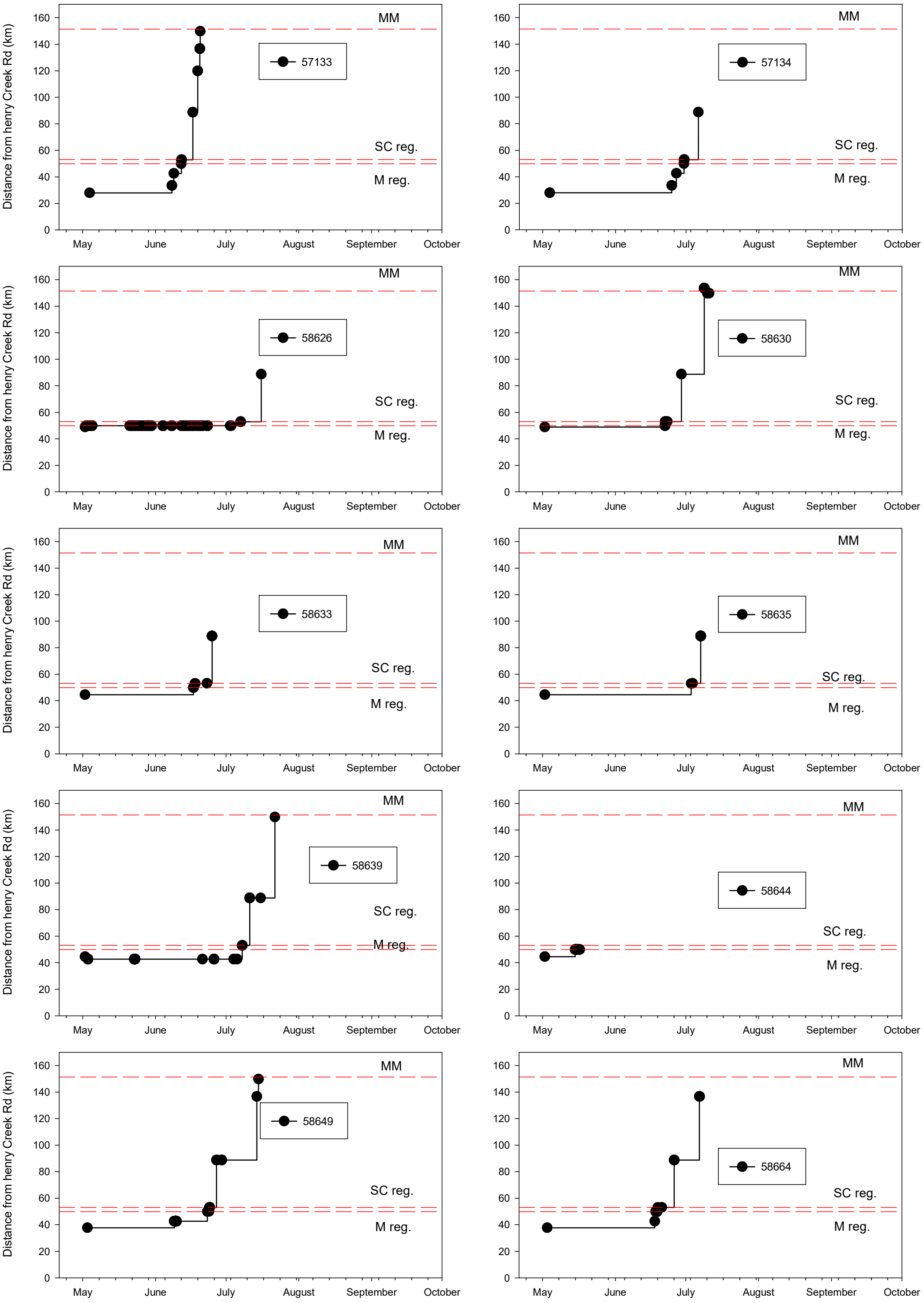
Fish no.	Date Tagged	Tagging Location	Total length (mm)	Weight (g)	Detections	Displacement	Enter Coorong	Enter ocean
22	4/05/2023	US SAFARI RD (R3S2)	300	230	12	-105.7	1	0
23	4/05/2023	US SAFARI RD (R3S2)	271	246	36	-57.7	1	0
24	4/05/2023	MID SAFARI RD - CANTARA RD (R3S3)	290	224	8	-60.7	1	0
25	4/05/2023	MID SAFARI RD - CANTARA RD (R3S3)	327	305	20	-121.8	1	1
26	4/05/2023	MID SAFARI RD - CANTARA RD (R3S3)	283	247	26	-121.8	1	1
27	4/05/2023	MID SAFARI RD - CANTARA RD (R3S3)	281	226	16	-121.8	1	1
28	4/05/2023	MID SAFARI RD - CANTARA RD (R3S3)	276	203	3	-5.46	0	0
29	5/05/2023	TILLEY SWAMP (R4S2)	317	291	22	-138.71	1	1
30	5/05/2023	US CANTARA RD (R4S1)	330	333	75	11.36	0	0
31	5/05/2023	US CANTARA RD (R4S1)	275	185	150	-17.22	0	0
32	5/05/2023	US CANTARA RD (R4S1)	260	162	67	-7.66	0	0
33	30/04/2024	US END MORELLA	282	200	24	-5.32	0	0
34	30/04/2024	US END MORELLA	270	195	68	1.95	0	0
35	30/04/2024	US END MORELLA	245	135	24	-92.15	1	0
36	30/04/2024	US END MORELLA	224	100	27	-92.15	1	0
37	30/04/2024	1ST OVERPASS	231	109	249	-11.25	1	0
38	30/04/2024	1ST OVERPASS	249	130	232	-8.02	0	0
39	30/04/2024	1ST OVERPASS	242	132	161	-11.25	1	0
40	30/04/2024	1ST OVERPASS	230	108	23	-107.95	1	1
41	30/04/2024	US NORTHERN OUTLET	227	98	0	-	-	-
42	30/04/2024	US NORTHERN OUTLET	208	70	0	-	-	-
43	30/04/2024	US NORTHERN OUTLET	269	172	0	-	-	-
44	30/04/2024	US NORTHERN OUTLET	244	129	61	29.9	0	0
45	1/05/2024	S-C 2	284	248	96	-3.23	0	0
46	1/05/2024	S-C 2	276	204	115	-22.87	1	0
47	1/05/2024	S-C 2	205	75	4	-12.37	0	0
48	1/05/2024	S-C 1	249	170	3	-3.26	0	0
49	1/05/2024	S-C 3	196	59	0	-	-	-
50	1/05/2024	DS SAFARI RD	239	144	141	1.49	0	0
51	1/05/2024	DS SAFARI RD	252	154	20	-7.65	0	0

Fish no.	Date Tagged	Tagging Location	Total length (mm)	Weight (g)	Detections	Displacement	Enter Coorong	Enter ocean
52	1/05/2024	DS SAFARI RD	239	115	151	-8.51	0	0
53	1/05/2024	DS SAFARI RD	250	154	991	-8.51	0	0
54	1/05/2024	DS SAFARI RD	336	365	181	0.63	0	0
55	1/05/2024	DS SAFARI RD	225	108	195	0.63	0	0
56	1/05/2024	DS SAFARI RD	221	93	123	0.63	0	0
57	1/05/2024	DS SAFARI RD	202	67	50	-8.51	0	0
58	2/05/2024	US CANTARA RD	204	59	13619	2.09	0	0
59	2/05/2024	US CANTARA RD	325	317	3532	2.09	0	0
60	2/05/2024	US CANTARA RD	234	134	120	-31.54	0	0
61	2/05/2024	US CANTARA RD	222	93	5746	2.09	0	0
62	2/05/2024	US CANTARA RD	250	159	1169	-34.77	1	0
63	2/05/2024	DS PETHERICK RD	286	208	257	-40.24	1	0
64	2/05/2024	DS PETHERICK RD	221	101	92	-3.38	0	0
65	2/05/2024	DS PETHERICK RD	215	95	228	-3.38	0	0
66	2/05/2024	DS PETHERICK RD	225	104	56	5.89	0	0
67	2/05/2024	DS PETHERICK RD	203	67	54	-11.04	0	0

7.2. Appendix B

Figure B1. Individual movement plots for adult female congolli tagged in 2023. The position of the Morella and Salt Creek regulators, and the Murray Mouth, are indicated by dashed red lines.




Distance from henry Creek Rd (km)
0
20
40
60
80
100
120
140
160
May
June
July
August
September
October
MM
SC reg.
M reg.
57133
57134
58626
58630
58633
58635
58639
58644
58649
58664

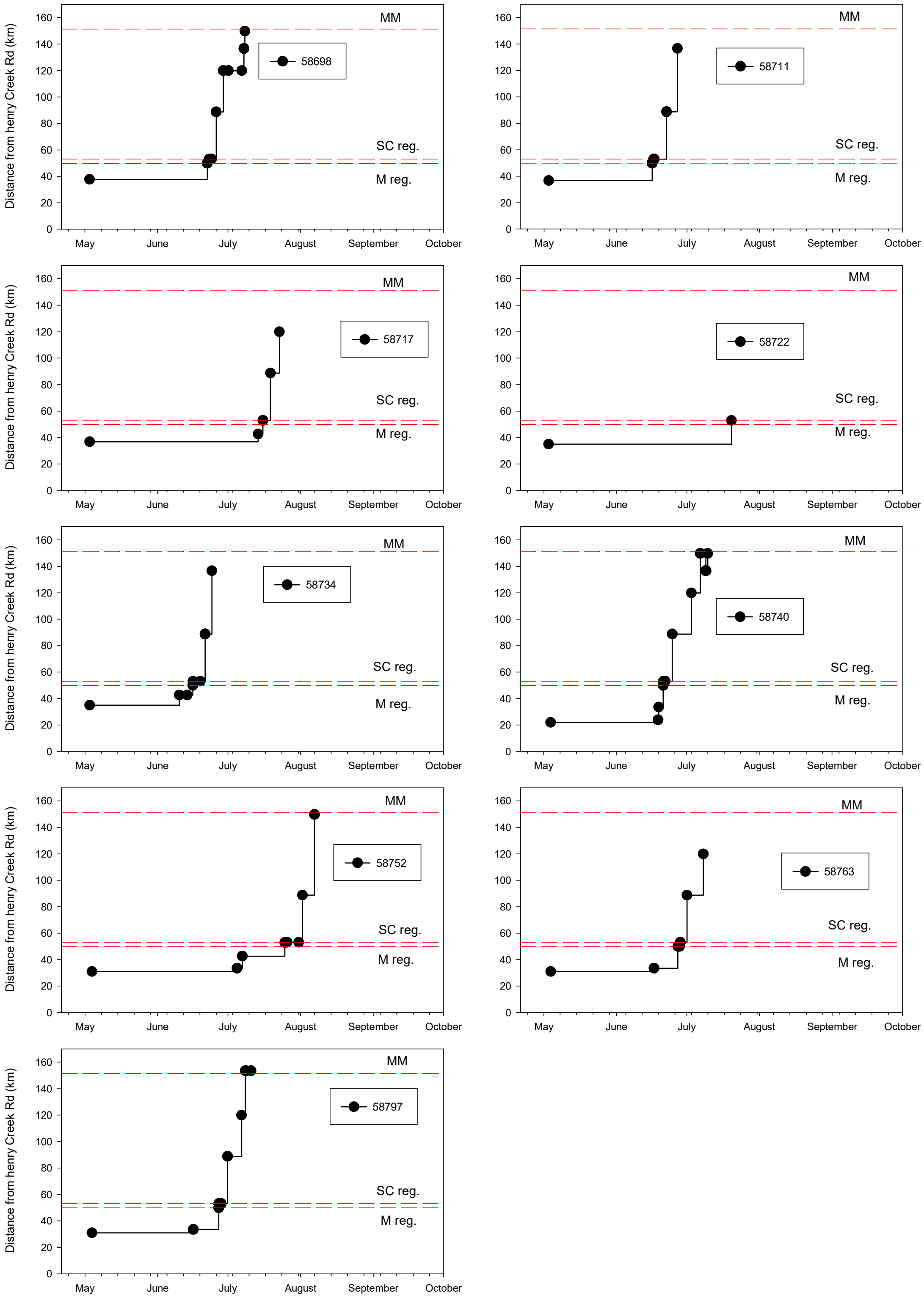
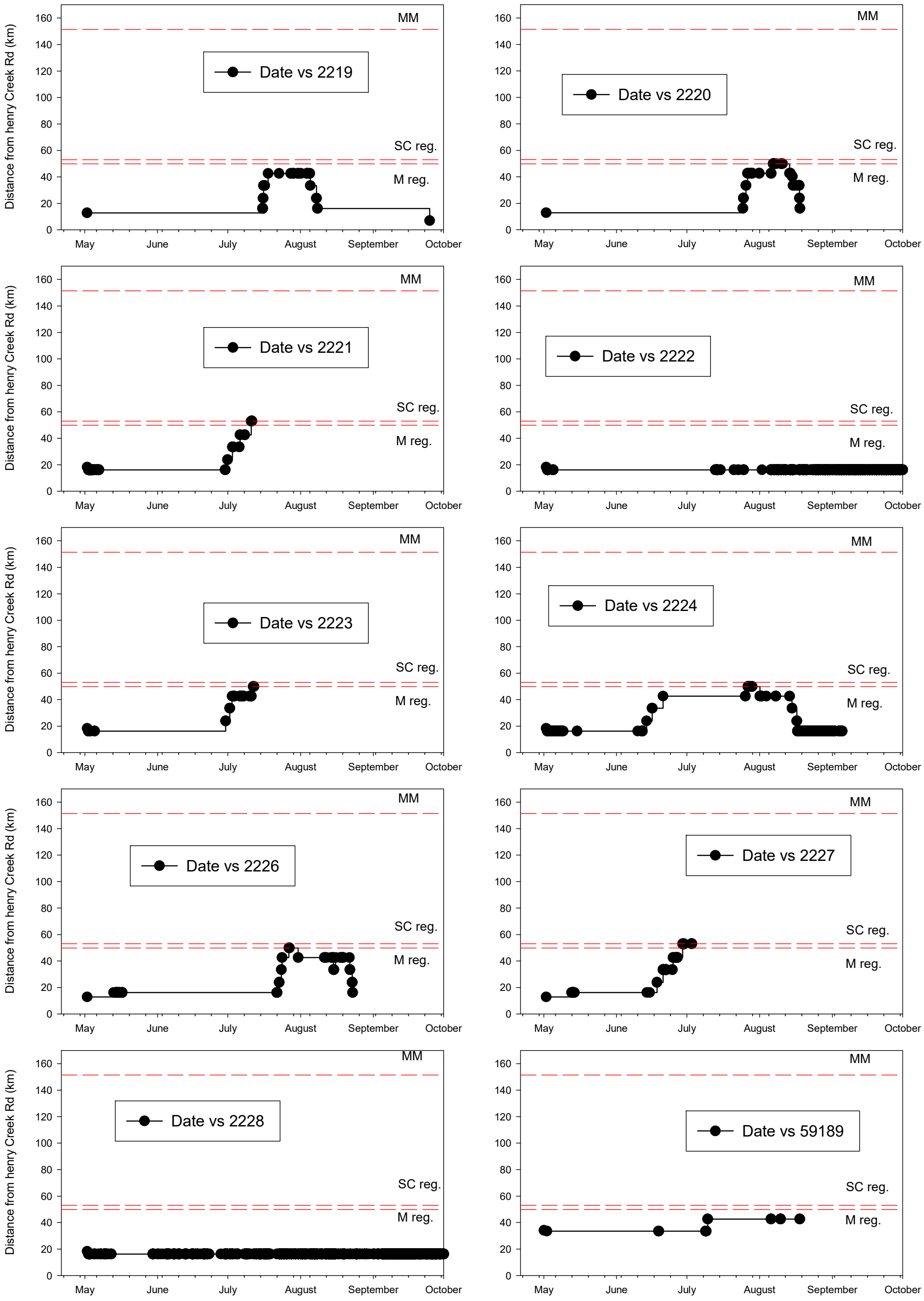
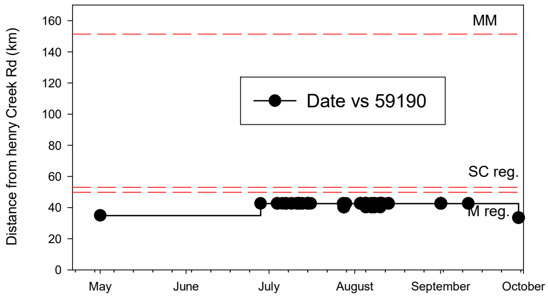
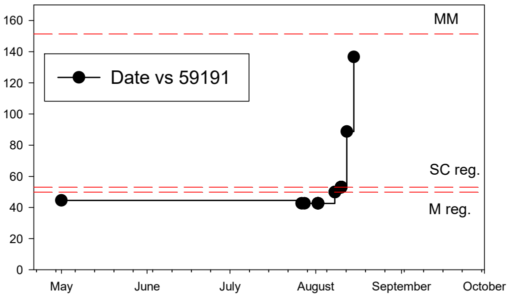

Distance from henry Creek Rd (km)
0
20
40
60
80
100
120
140
160
May
June
July
August
September
October
MM
SC reg.
M reg.
58698
58711
58717
58722
58734
58740
58752
58763
58797

Figure B2. Individual movement plots for adult female congolli tagged in 2024. The position of the Morella and Salt Creek regulators, and the Murray Mouth, are indicated by dashed red lines.




Distance from henry Creek Rd (km)
0
20
40
60
80
100
120
140
160
MM
Date vs 59190
SC reg.
M reg.
May
June
July
August
September
October


0
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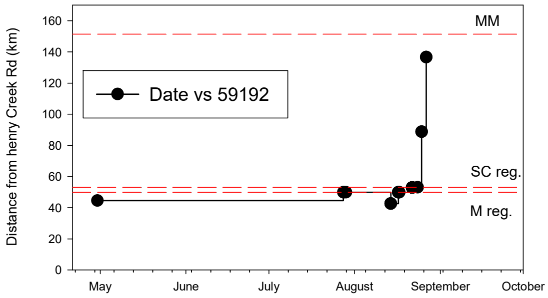
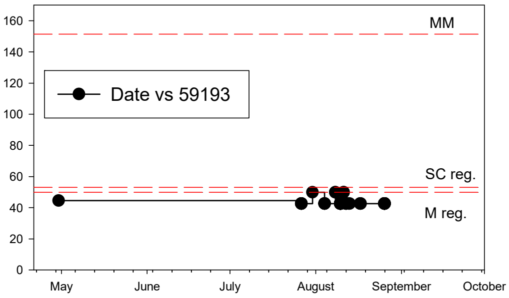
80
100
120
140
160
MM
Date vs 59191
SC reg.
M reg.
May
June
July
August
September
October


Distance from henry Creek Rd (km)
0
20
40
60
80
100
120
140
160
MM
Date vs 59192
SC reg.
M reg.
May
June
July
August
September
October


0
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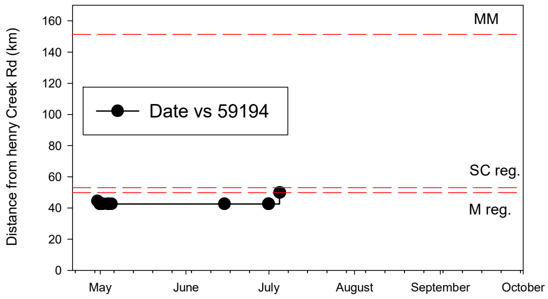
100
120
140
160
MM
Date vs 59193
SC reg.
M reg.
May
June
July
August
September
October


Distance from henry Creek Rd (km)
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40
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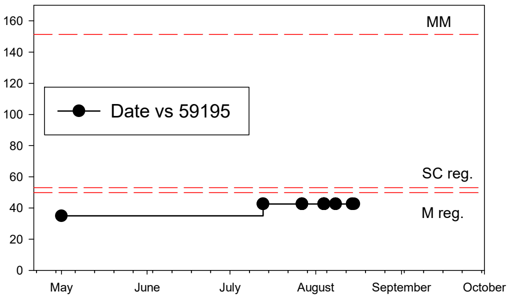
80
100
120
140
160
MM
Date vs 59194
SC reg.
M reg.
May
June
July
August
September
October


0
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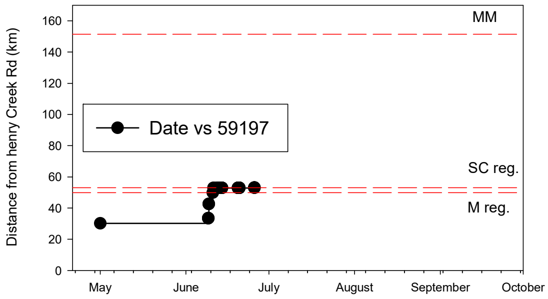
100
120
140
160
MM
Date vs 59195
SC reg.
M reg.
May
June
July
August
September
October


Distance from henry Creek Rd (km)
0
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40
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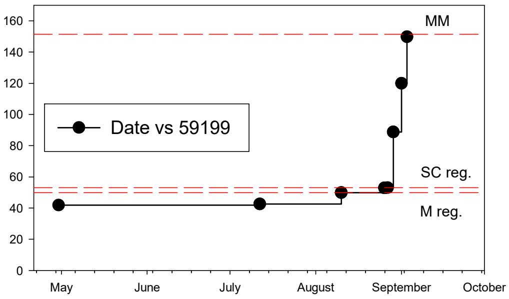
100
120
140
160
MM
Date vs 59197
SC reg.
M reg.
May
June
July
August
September
October


0
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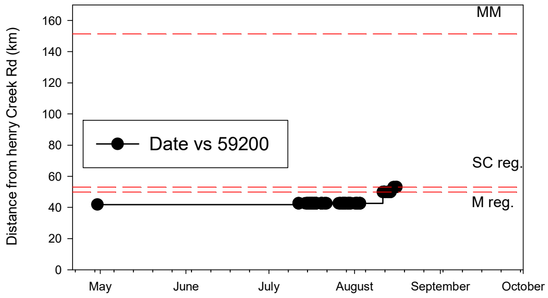
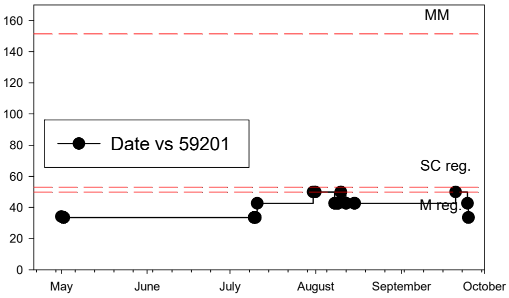
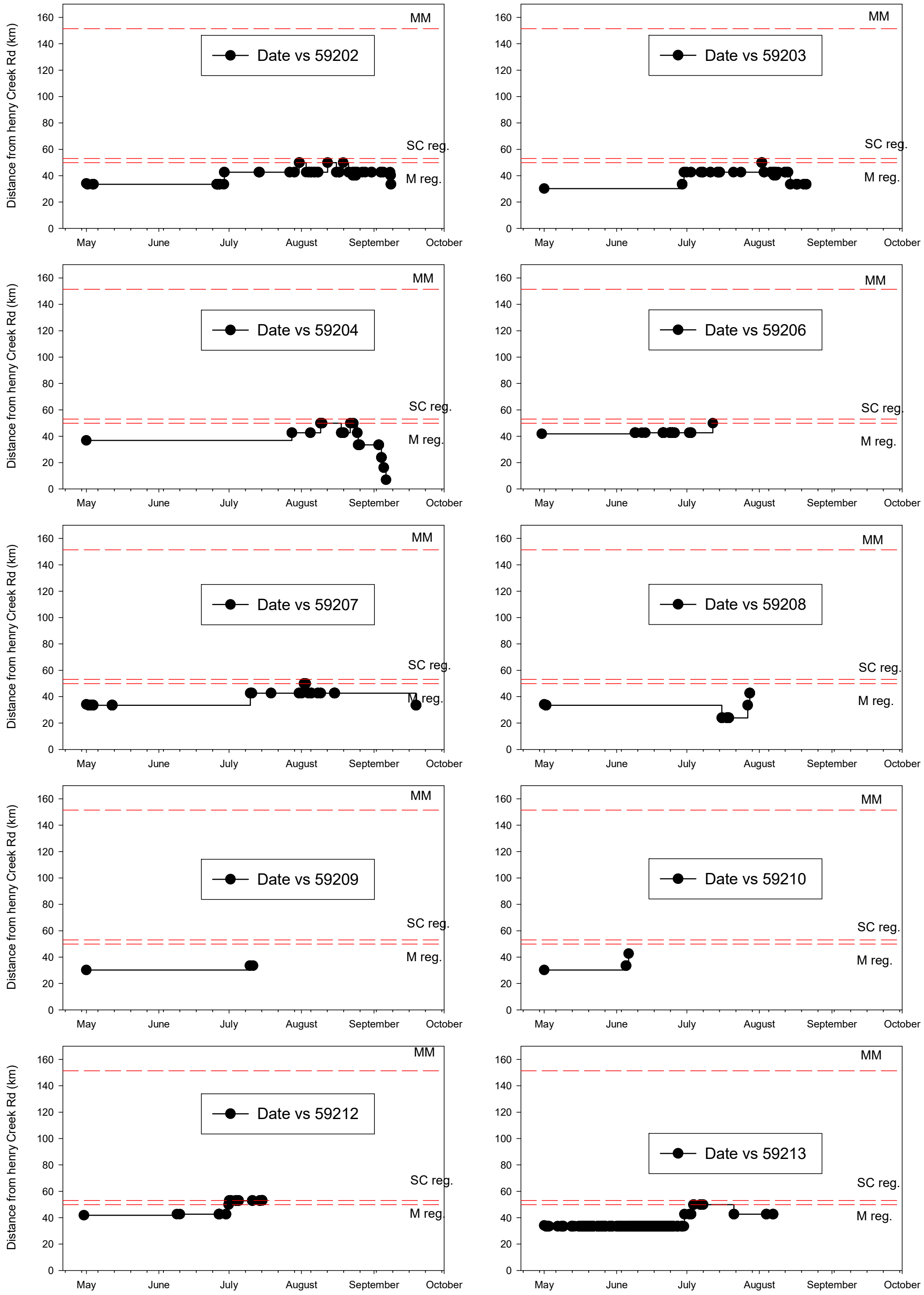
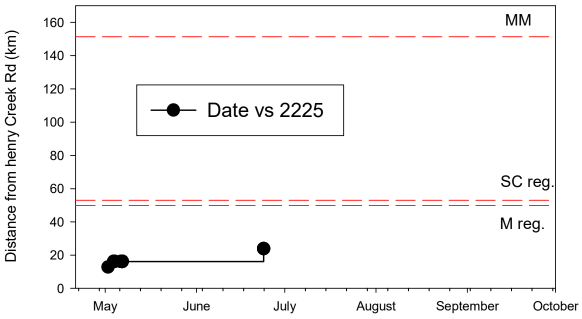
120
140
160
MM
Date vs 59199
SC reg.
M reg.
May
June
July
August
September
October


Distance from henry Creek Rd (km)
0
20
40
60
80
100
120
140
160
MM
Date vs 59200
SC reg.
M reg.
May
June
July
August
September
October


0
20
40
60
80
100
120
140
160
MM
Date vs 59201
SC reg.
M reg.
May
June
July
August
September
October


Distance from henry Creek Rd (km)
0
20
40
60
80
100
120
140
160
May
June
July
August
September
October
MM
SC reg.
M reg.
Date vs 59202
Date vs 59203
Date vs 59204
Date vs 59206
Date vs 59207
Date vs 59208
Date vs 59209
Date vs 59210
Date vs 59212
Date vs 59213


Distance from henry Creek Rd (km)
0
20
40
60
80
100
120
140
160
MM
Date vs 2225
SC reg.
M reg.
May
June
July
August
September
October