INSTITUTE FOR MARINE AND ANTARCTIC STUDIES
UNIVERSITY OF TASMANIA

# UNDERSTANDING MOVEMENT PATTERNS OF KEY RECREATIONAL FISH SPECIES IN SOUTHEAST TASMANIA

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# Understanding movement patterns of key recreational fish species in southeast Tasmania

## Executive summary

In Australia, recreational fisheries generally target inshore coastal and estuarine fish species. The way that many of these species utilise and interact with their environment is often poorly understood. Understanding the way that a fish moves and behaves develops our knowledge of the ecology of fish. This information is important not only for sustainable fisheries management, but also provides fishers, in this case recreational fishers, with a greater understanding of the fish they target, including key factors such as species distribution, abundance and availability. This increased understanding conveyed in an effective and responsible manner has the potential to increase recreational fisher's stewardship of their fisheries.

In this study we investigate the movement and behaviour of three key recreational finfish species in popular waterways of southeast Tasmania. The study utilises an acoustic telemetry array of passive receiver stations deployed throughout the Derwent estuary and Norfolk and Frederick Henry Bays. The three target species, sand flathead, black bream and brown trout are morphologically and functionally distinct and represent three of the most commonly recreationally caught species in Tasmania.

Despite the differences between the three species several common traits were observed in their movement and behaviour. Of the 50 individuals across all three species that were tagged in the Derwent estuary, all remained within the estuary for the duration of the study, with the exception of a single brown trout and one sand flathead both of which were detected after leaving the estuary in Frederick Henry Bay. While the home ranges of the three species differed in size, all individuals tagged in the Derwent remained resident around the mid-estuary where the majority of fish were tagged. Each of the species also displayed seasonal migrations, presumably linked to spawning. The timing of the beginning of these migrations was well synchronised both within and between species, starting in late spring/early summer. This suggests that environmental factors such as water temperature and day length may play an important role in cueing spawning behaviour for each of the species.

Sand flathead tagged in the Derwent estuary displayed small home ranges, limited movement for most of the year and hence strong site fidelity. The exception to the limited movement was a down-stream migration by four individuals to the mouth of Storm Bay. Each of the individuals returned to the area in the Derwent that they left from, highlighting the strong site fidelity of this species in the Derwent estuary.

Sand flathead tagged in the Norfolk bay appeared to have larger home ranges than the flathead tagged in the Derwent. The expanse of the bay and the low movement rates of sand flathead meant that the rate of detection in the area was significantly lower than for the

Derwent, making it difficult to draw conclusions on the behaviour of the species in this area. Flathead tagged and deployed within the detection range of the Vemco radio acoustic positioning system (VRAP) in Norfolk Bay provided some insight into the short term movement patterns of sand flathead. Tagged fish were detected in this system for up to two weeks with many displaying ‘burst’ movement behaviour over distances of 50 to 200 m interspersed with periods of relative inactivity. It is possible this behaviour is related to feeding as sand flathead are ambush predators. It was also observed from the VRAP system that sand flathead had a significantly higher detection rate during the day, implying greater activity during daylight hours than during the night.

Black bream also displayed home range affinity, but utilised a greater range of the estuary particularly during spring, summer and autumn. During winter however, the movement rates of many individuals decreased dramatically, suggesting potential over-wintering behaviour. During the warmer summer months 70% of the tagged black bream engaged in a strong and directed seasonal upstream migration, presumably related to spawning given the time of the year. Most of the individuals that embarked on this migration did so several times, returning to their home range between events. Five black bream also migrated from the mid-Derwent estuary upstream to Browns River and back. Site fidelity was also important for black bream with all fish returning to their home range after either upstream spawning migrations or the migration to Browns River.

The majority of brown trout that were tagged mid-estuary displayed a home range of approximately 3-4 km and moved throughout this range regularly during winter and spring. Five trout tagged further up river displayed more limited movement, with only occasional movements down river. Eight trout embarked on an upstream migration in early summer and one moved upriver in autumn to be beyond the extent of receiver array. The degree of synchronicity of this event, with the exception of the individual that migrated in August, was the highest of all three species with individuals migrating rapidly upriver within six days of each other. The downstream return was not observed until six months later when four of the individuals returned to the receiver array, including the fish that migrated upriver in August. This event was again highly synchronised with three of the individuals returning within 24 hours of each other and the other returning approximately 14 days earlier. All four individuals displayed strong site fidelity returning to their home ranges.

The results of this study provide unprecedented insight into the behaviour of these three important recreational species in southeast Tasmania. The results also have implications for human health confirming that these species spend the majority of their time in the mid-Derwent estuary, an area which has a long history of metal pollution from industrialisation. The residency and behaviour of these fish in the estuary correlates well with the elevated mercury levels reported for these species from other studies. It is also important to note that each of the species undergo seasonal migrations where a proportion of these potentially contaminated fish move into areas where contamination has not been highlighted as an issue.

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## Introduction

Understanding movement patterns of marine organisms is an important component of fisheries management (e.g. Metcalf and Arnold 1997; Brill *et al.* 1999; Watson *et al.* 1999; Zeller 1999). Fisheries researchers in the past relied on traditional tagging techniques that only provide data on release and capture location. Radio and satellite telemetry are valuable tools in movement studies, however they can only be applied to marine organisms that break the water surface. Consequently, we have a poorer understanding of movement patterns of marine and estuarine species that remain submerged. The paucity of detailed movement information for fish species is primarily a consequence of the level of effort required to obtain reliable estimates of movement over a meaningful range of spatial and temporal scales using traditional tagging methods. The development of acoustic telemetry technology has overcome these difficulties, providing a means of remotely tracking fish movement over a broad range of spatial and temporal scales, without the need to recapture tagged animals (see Heupel *et al*. 2006).

Acoustic monitoring – the use of passive acoustic monitors capable of recording the presence of multiple animals tagged with acoustic transmitters – has become an increasingly popular research tool (see Heupel *et al*. 2006 for a review). Acoustic monitoring of fish can reveal important information about fish behaviour, including habitat usage, migration or movement patterns, interactions with other species and con-specifics, cyclic variation in fisheries catch rates etc. Such information is important from a management perspective, as well as being informative to fishers in terms of understanding patterns of distribution, abundance and availability.

Movement data can also be examined in relation to environmental variables collected concurrently via co-instrumentation or retrospectively from other sources. Commonly used variables examined include tidal state, water depth, day length, water temperature, and salinity (e.g. Klimley *et al*. 1998; Bégout and Lagardère 1995; Bégout Anras *et al*. 1997; Arendt *et al.* 2001; Cote *et al*. 2003; Sakabe and Lyle 2010; Semmens *et al.* 2010). Continuous information about the environment allows the visitation pattern of the animals to be placed in a wider context. Based on longer-term deployment of receivers, annual or seasonal patterns of movement can be examined and factors that affect changes in habitat use or distribution can be elucidated (e.g. Arendt *et al*. 2001; Heupel and Hueter 2001; Egli and Babcock 2004; Heupel *et al*. 2004; Semmens *et al.* 2010).

This study targets one of the most heavily recreationally fished regions of Tasmania, the Derwent estuary and adjacent Norfolk-Frederick Henry Bay (Lyle *et al.* 2009). The Derwent estuary is an important ecosystem that is heavily urbanised, with approximately 40% of Tasmania's population living around its margins (Whitehead *et al.* 2010).

In this study we examine the movement and behaviour of three key recreational species: sand flathead (*Platycephalus bassensis*), black bream (*Acanthopagrus butcheri*) and brown trout (*Salmo trutta*) (Lyle *et al.* 2009). These three species have also been identified as having varying degrees of mercury contamination within and around the Derwent estuary (McPherson 2007; Verdouw 2008; Verdouw *et al*. 2011).

Sand flathead spawn around Tasmania from September through to February in coastal bays (Jordan 2001). The availability of this species can vary seasonally and between years but it is unclear whether this is due to dispersal from inshore areas and/or behavioural factors (e.g. reduced activity in winter). It is the most popular fish targeted by Tasmanian recreational fishers due to its high abundance and relative ease of capture, representing almost two-thirds of the total finfish catch numbers, with an estimated 1.07 million kept and 0.74 million released during 2007/08 (Lyle *et al.* 2009).

Black bream are most commonly found in estuaries and lower reaches of rivers, predominantly on the East Coast of Tasmania. They have the ability to cope with a wide range of salinity levels, and may sometimes be found in totally fresh water. Bream are becoming one of Tasmania's most popular sport angling species, with several fishing competitions targeting this species annually. An estimated 13,000 were kept and 35,000 released during 2007/08 (Lyle *et al*. 2009).

Brown trout are also one of the most popular species, with 157,000 kept and 105,000 released during 2007/08 (Lyle *et al*. 2009). Although primarily found in fresh water systems, lakes and rivers, some individuals periodically move into marine waters where they are known as sea-run trout.

Through this study valuable information about distributional patterns, habitat usage, and links between biological status (e.g. spawning or life history stage) and movement of these key recreational fish species will be established. With reliable information on the movement dynamics issues such as availability and vulnerability of the species will be better understood.

# Methods

## Study region

The study was conducted between February 2008 and October 2009 in the inshore waters of southeast Tasmania (Fig. 1). Passive acoustic receiver arrays were established in the Derwent estuary (Fig. 1a) and Norfolk/Frederick Henry Bays (Fig. 1b). Both are shallow waterways (< 44 m) characterised by soft sand/silt substrate. The southern shoreline of Norfolk Bay also has extensive seagrass beds. The two areas can be discriminated by their geomorphology and the degree of anthropogenic influence to which they are subject. The upper reaches of the Derwent estuary are narrow, with the lower reaches broadening before flowing into Storm Bay. The entire system is influenced by freshwater run-off from the Derwent catchment. Hobart, the capital city of Tasmania is situated mid-river resulting in a high degree of urbanisation and industrialisation, including a paper mill and zinc smelter along the estuary (Whitehead *et al.*, 2010). In contrast, the Norfolk/Frederick Henry Bay area is a broad coastal embayment, with a low degree of urbanisation and no significant industrialisation within the area. Freshwater inflows represent only a aminor enivronmental factor within the bays.

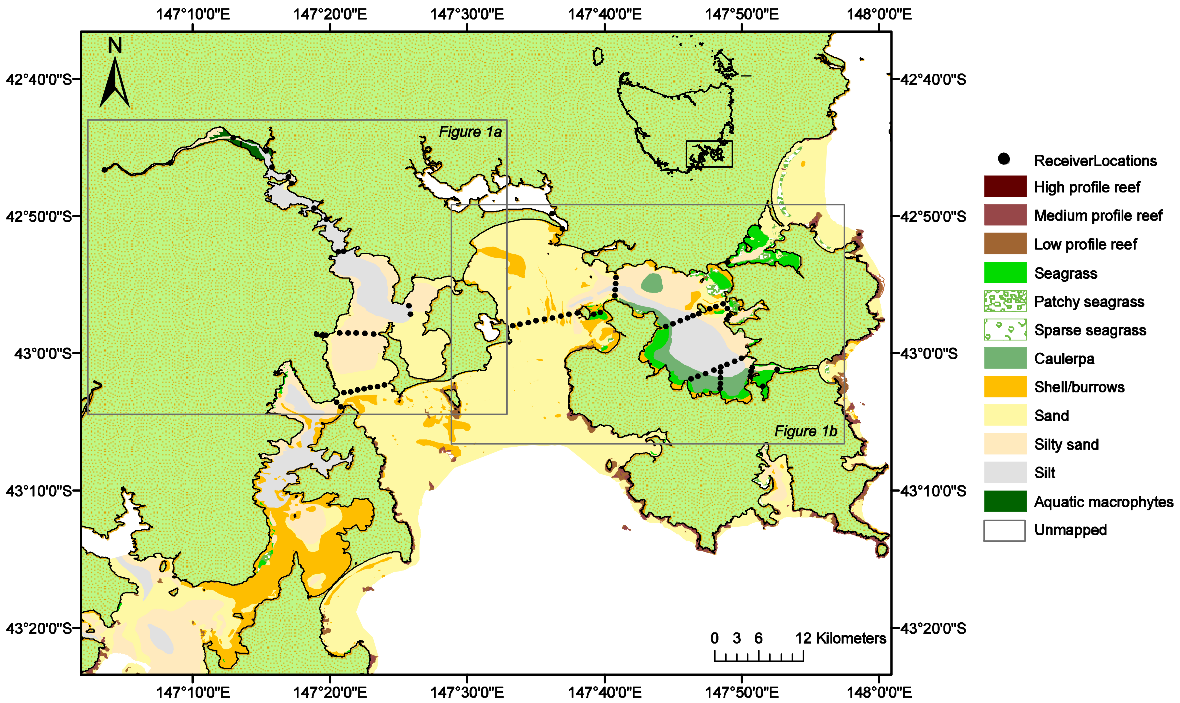


Fig. 1. Map of southeast Tasmania showing the extent of the acoustic receiver array. Colours throughout the waterways indicate habitat type as defined in the legend and locations of receivers are indicated by the dots.

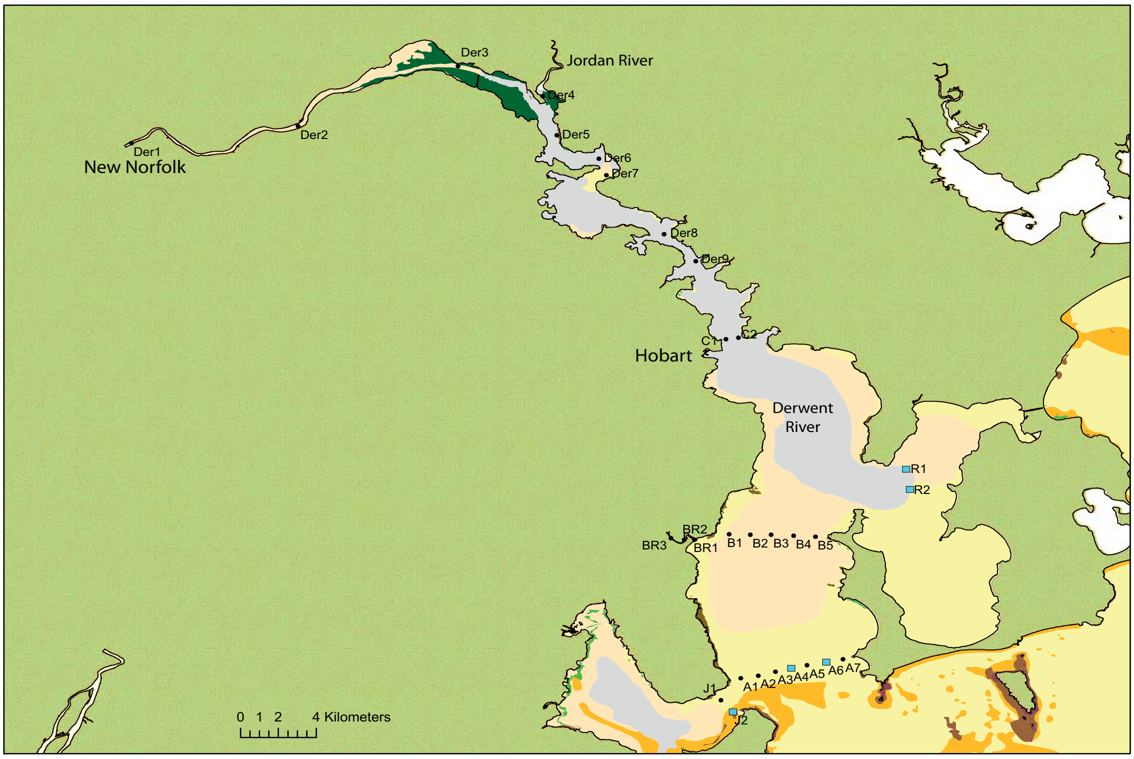


Fig. 1a. Map of the Derwent estuary showing receiver locations. Blue symbols indicate that these receivers were not in place or functioning for the entire duration of the study.

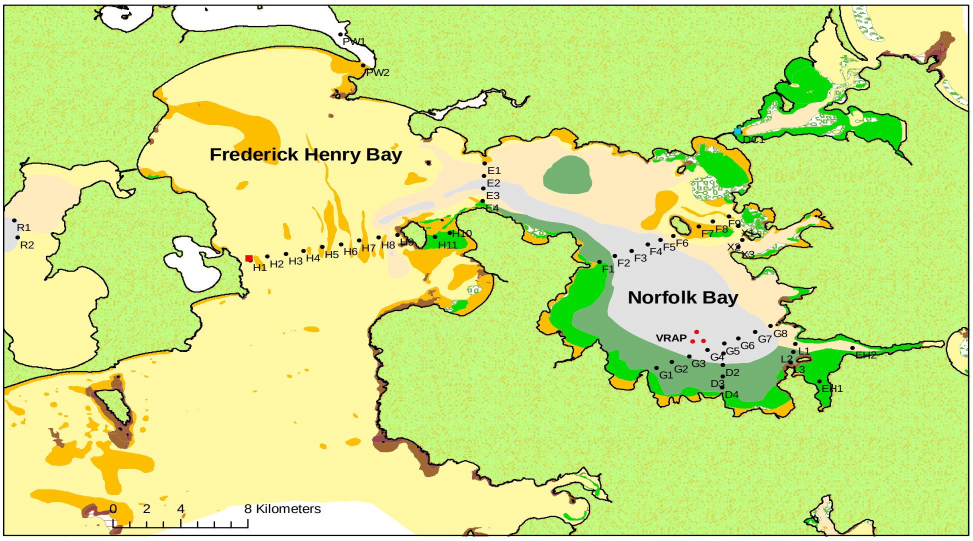


Fig. 1b. Map of Frederick Henry and Norfolk Bays showing receiver locations. Blue symbols indicate that these receivers were not in place or functioning for the entire duration of the study and red symbols indicate receiver failure for the duration of the study.

## Passive telemetry system – VEMCO VR2

A fixed array of 78 single frequency, omnidirectional VR2 receivers (Vemco, Canada) were deployed within the study domain, of which 30 were located in the Derwent estuary (Fig. 1a) and 48 were deployed throughout Norfolk and Frederick Henry Bays (Fig .1b). Receivers were deployed in both ‘curtain’ and ‘gate’configurations. The distance between receivers within a curtain was arbitarily set based on limited range testing at 800m centres. Gates were deployed in narrow areas where the maximum shore-to-shore distance was approximately 650m. Each receiver was attached to a mooring on the seafloor. The receivers were attached so that the hydrophone was pointing towards the surface and was approximately 1 – 2 m above the seafloor.

Receivers were deployed to the Derwent estuary and Norfolk/Frederick Henry Bay between November 2007 and February 2008, prior to the commencement of tagging. An additional receiver was deployed into the Derwent estuary (Der4) on the 4th of July 2008 coincident with the tagging of brown trout. Three receivers were deployed in Browns River on the 20th of March 2008. Finally, a further two receivers were deployed in Ralphs Bay (R1 and R2) on the 4th of September 2008. The project was terminated in May 2009 with all receivers retrieved by the 27th May 2009.

The battery life of receivers was either eight or fifteen months depending on receiver model. Accordingly, batteries were changed within the period of expected battery life. Data was downloaded at the time of battery change.

During the course of the study, data was not retrieved from five receivers due to either receiver failure or loss. Two of these receivers were located in the Derwent estuary (A4 and A6; failed date range = 29/11/2007 – 14/07/2008), one at the northern entrance to the D’Entrecasteaux Channel (J2; failed date range = 12/01/2008 – 07/07/2008) , one in the southern end of Norfolk Bay (G2; failed date range = 30/11/2007 – 08/07/2008) and one at the entrance to Frederick Henry Bay (H1; failed date range = 20/11/2007 – 20/05/2009).

A bayesian state-space model was constructed to provide probabilistic location estimations based on the detection of fish on receivers located in the Derwent estuary. The model calculates and then utilises species specific movement rates and detection efficiencies to estimate the position of a fish at times when it is not directly detected on a receiver. For further details on the model development see Appendix 2.

## Range Testing

Prior to the deployment of the VR2 array the detection range of the VR2 receivers was tested at four locations in the Derwent estuary. Tests were conducted at two sites where individual receivers were to be deployed as gates, including an upper estuary site (Der2) and a mid-estuary site (Der8). Using the planned receiver location as a centroid, tests were conducted at increments along a direct line to the nearest shore in both directions providing an estimate of the receiver’s effectiveness as a gate. The other two tests were conducted in the vicinity of the planned curtain locations A and B. At curtain B range tests were incrementally performed parallel and perpendicular to the coast.

For each test a VR2 was temporarily moored approximately 1.5-2.0 m above the substrate and then an acoustic transmitter (hereafter referred to as the ‘test tag’) with the same power output (146 db re 1 µPa @ 1 m) as the study transmitters and a fixed off-time of 5 s was lowered to within 1m above the substrate at a set distance from the receiver for a known time period.  The detections received at each test deployment were expressed as a percentage of the total number of detections expected in the time period, referred to as the ‘detection efficiency’.

### Ground truthing

To determine the detection range and efficiency over an extended time period, four tags were moored approximately 1m off the substrate at various distances from Der7 from 4$^{th}$ July 2008 to 15$^{th}$ August 2008 (Fig. 2 & Table 3). The tags used in this test had the same specification as the study tags. The study tags don’t have a fixed off period, therefore an average off time of 90 seconds was used in the calculation of receiver efficiency.

### Passive telemetry system – VRAP (VEMCO radio-acoustic positioning system)

Fine scale movement of sand flathead was monitored in the southwest corner of Norfolk Bay at a depth of approximately 16 m using a VEMCO™ Radio Acoustic Positioning System (VEMCO Ltd., Halifax, Canada). The system consists of three buoys deployed in an equilateral triangular array and a computer controlled base station.  Each buoy is anchored to the sea floor and has an inverted omnidirectional hydrophone attached which is positioned approximately one meter under the water surface.  The buoys triangulate the position and time co-ordinates of individual animals at a resolution of approximately two meters for fully resolved detection (where all three receivers detect the animal at a given time).  The VRAP system also reports unresolved detections where a transmission from an individual transmitter was not detected by all three receivers.  While this information does not provide high resolution positional data it does indicate that the transmitter is still in the general vicinity of the VRAP array.

The VRAP buoys were positioned 400 m apart (Buoy1: -43°00.269, 147°45.828, Buoy2: -43°00.471, 147°45.724, Buoy3: -43°00.438,  147°46.012), creating a triangle area of 0.069 km$^2$. By using fixed position transmitters (sentinal tags) within the VRAP array we were able to test the precision of the location estimates, which was consistently high with each sentinal tag reported within a one meter radius throughout the duration of the study.

### Environmental data collection

Water quality measurements were taken using a YSI-6600 V2 sonde anchored 1m off the sea floor adjacent to receiver Der 7. The sonde measured temperature (°C), salinity (ppt) and turbidity (ntu) and was deployed from 8$^{th}$ July 2008 to 13$^{th}$ August 2008. Water quality measurements were logged every five minutes, the mean of these readings were taken to provide an average per day.  Rainfall data was obtained from the Bushy Park weather station operated by the Bureau of Meteorology. The Bushy park weather station is the closest weather station upstream of the study area. River flow data from the Tyenna River was obtained from the Water Information System of Tasmania (http://water.dpiw.tas.gov.au/wist/ui). The Tyenna was chosen as a proxy for the Derwent as it had the most complete data set over the period of interest.

## Tagging protocol

All transmitters were surgically implanted into the peritoneal cavity of individual fish through a 1 cm incision in the ventral surface, between the pelvic fin insertions and the anus. All equipment that came into contact with the fish was washed with Nycex™ antifungal solution ($3g{\cdot}L^{-1}$) and Vidalife™ to reduce stress and abrasions during the handling process and ultimately reduce the risk of post-operative mortality. Prior to surgery each fish was anaesthetised in a bath of Aqui-S™ ($0.03\ ml{\cdot}L^{-1}$) until sufficiently subdued (when the fish could be handled without response). Throughout the surgical procedure a dilute solution ($0.015\ ml{\cdot}L^{-1}$) of Aqui-S™ was gently pumped across the fish's gills via the mouth to maintain an anaethitised state. The implantation site was washed with Betadine™ Iodine antiseptic solution ( $10\ ml{\cdot}L^{-1}$) prior to and after surgery to prevent infection. After the tag was inserted the incision was closed with dissolving sutures and a dose of antibiotic oxytetracycline hydrochloride ($50\ mg{\cdot}kg^{-1}$ $0.05\ mg{\cdot}g^{-1}$) was administered intramuscularly. Finally an external T-bar tag (Hallprint, Australia) was inserted into the dorsal surface of the fish to aid in identification if re-captured. The entire surgical process was completed in approximately 1½ minutes. Post-surgery, the fish were placed in an aerated seawater tub until they had fully recovered from the anaesthetic (approximately 5 – 10 minutes), prior to being released.

## Sand flathead (*Platycephalus bassensis*)

A total of 31 sand flathead were captured using baited hook and line. Twelve of these were caught on the 21st of February 2008 close to the VRAP system in Norfolk Bay and were implanted with V9-2H ultrasonic transmitters, which emitted a unique coded signal at a random interval of between 60 – 180 seconds and had an estimated life of 185 days. A further ten fish were caught between the 27th of February and the 2nd of March 2008, five in the vicinity of receiver 'Der6' and five in the vicinity of receiver 'Der8', in the Derwent estuary. Each of these fish were implanted with V9-2L ultrasonic transmitters, which emitted a unique coded signal at a random interval of between 50 – 130 seconds and had an estimated life of 370 days. Nine fish were caught on the 12th of March 2008 in the vicinity of receiver D1 in Norfolk Bay and were implanted with V9-2L ultrasonic transmitters, which had the same specifications as those deployed in the Derwent estuary.

## Black bream (*Acanthopagrus butcheri*)

A total of 20 black bream were caught using a combination of baited hooks and soft plastic lures using rod and line. Fish were caught in the Derwent estuary by competitors in the Tasmanian state leg of the Australian Bream Tournament fishing competition on the 1st and 2nd of March 2008. Fish were retrieved from the live display tank at the end of each day's competition, tagged and then released at one of four sites where the majority of fish were caught. Five fish were released in the vicinity of each receiver 'Der3' and 'Der5', another five fish were release in the vicinity of 'Der7' and the final five fish were released in the vicinity of 'Der8'. Although sampling fish from the live display tank did not allow us to return individuals to their exact capture location, it did allow for the selective sampling of a wide range of sizes. Each fish was implanted with a V9-2L ultrasonic transmitter, which emitted a unique coded signal at a random interval of between 50 – 130 seconds and had an estimated life of 370 days.

### Brown trout (*Salmo trutta*)

A total of 20 brown trout were caught using plastic lures and tagged and released in the Derwent estuary (Table 8). Six individuals were caught on the 17$^{th}$ of June 2008, four of which were caught and released in the vicinity of 'Der7', and one each were caught and released in the vicinity of receivers 'Der5' and 'Der6'. Eight fish were caught on the 24$^{th}$ of July 2008, five of which were caught and released in the vicinity of receiver 'Der6' and the remaining four were caught and released in the vicinity of 'Der5'. A further six fish were caught and released on the 3$^{rd}$ of September 2008 in the vicinity of receiver 'Der2'. Each brown trout was implanted with aV9-2L ultrasonic transmitters, which emitted a unique coded signal at a random interval of between 50 – 130 seconds and had an estimated life of 370 days.

# Results and Discussion

## Range testing

Pre-deployment range testing indicated that at receiver A5 the detection range running perpendicular to the coast (towards the direction of receiver A4) was greater than 400m with the detection efficiency at this distance from the receiver at 73%. A similar result was shown for receiver B7 with 100% detection efficiency at 400m running perpendicular to the coast towards receiver B6. An anomaly was, however, reported in the detection efficiency at 350 m with the estimate dropping to 38%. When the detection range of B7 was tested running parallel to the coast, the detection efficiency at 200 and 250 was greater than 85%, by 300m the detection efficiency dropped to 45% and by 350m the detection efficiency had dropped to 0%. This indicates that the maximum detection range running parallel to the coast is approximately 300m (Table 1). These results indicate that deploying the curtains with 800m centres provides a high probability of detection overlap.

Table 1. Range testing of curtain locations in the Derwent estuary indicating detection efficiencies at various distances and orientation from test receivers. The centroids for testing were receiver location A5 and B7 for curtain A and B respectively estuary (refer to Fig. 1a for locations).

| Distance from centroid (m) | Curtain A (Perpendicular to coast) | Curtain B (Parallel to coast) | Curtain B (Perpendicular to coast) |
|---|---|---|---|
| 200 | - | 88 | 70 |
| 250 | 85 | 85 | - |
| 300 | 66 | 45 | 80 |
| 350 | - | 0 | 38 |
| 400 | 73 | 4 | 100 |

Range testing at the planned site of receiver Der8, which was located in a predominately saline environment, indicated that the detection range was greater than 300 m. Specifically, range testing showed a ~85% detection efficiency out to 200m and 70% at 300m heading in a direct line to the closest land in either direction (Table 2). For the test at the location of Der2, located in a predominately freshwater environment, 100% detection efficiency was recorded at 100m from the receiver heading to the shoreline to the south of the receiver. Heading to the shore to the north of the receiver had 100% detection efficiency at 50m but at 100m it had dropped to ~40% (Table 2).

Table 2. Range testing of gate (single receiver) locations in the Derwent estuary (refer to Fig. 1a for locations). Tests were conducted across river to assess the efficiency of the receiver as a gate.

| Distance from centroid (m) | Der8 (Heading SW) | Der8 (Heading NE) | Der2 (Heading N) | Der2 (Heading S) |
|---|---|---|---|---|
| 50 | - | - | 100 | 100 |
| 100 | 97 | 94 | 39 | 100 |
| 150 | 97 | - | - | - |
| 200 | 95 | 83 | - | - |
| 250 | 97 | - | - | - |
| 300 | 70 | 69 | - | - |

## Ground truthing

### *Anchored tags at Receiver Der 7*

The four anchored tags deployed in defined locations in the vicinity of receiver Der7 provided a means to assess variations in detection efficiency through time. The effect of various environmental factors on detection rates was of particular interest. Given the complex bathymetry in the region of receiver Der7 the stationary tags also provided a means to assess the difference in detection efficiency if a fish were located within a deeper channel, in this case a channel that was approximately 10 meters deeper than the surrounding area (Fig. 2).

Tags three and four, located 180 m upstream and 200 m adjacent to river flow respectively (Fig. 2) had similar average detection efficiencies of 72 and 71% (Table 3). In general the total number of detections was consistent across the 41 days that they were deployed. The exception to this were declines in detection efficiency on the 5$^{th}$ – 7$^{th}$ July (no environmental data logged), 22$^{nd}$ of July, 24$^{th}$ of July, 13$^{th}$ and 14$^{th}$ of August (Fig. 3A). In each case, where environmental data was available, the declines appear to be attributed to significant rainfall events (Fig. 3E). The decrease in detection efficiency was more pronounced on tag four, located adjacent to receiver Der7.

The average detection efficiency of tags one and two was 16 and 11% respectively (Table 3). These tags were further away from receiver Der7 than tags three and four which is the likely cause of the decreased detection efficiency. Interestingly however, tag one which was 50m further away from the receiver than tag two had consistently higher detection efficiency. This would suggest that the deployment of tag two in the bottom of the channel had a significant negative effect on the detection efficiency. Therefore a fish that was associating with the deeper areas within the channel would have a lower probability of detection than a fish associating with the shallower habitat.

The detection efficiency of tags one and two was more variable through time than tags three and four (Fig. 3A). Rainfall again had a negative effect on the detection efficiency of these two tags (Fig. 3E). The effect, however, was much less severe than for tags three and four.

Turbidity, salinity and water temperature did not appear to have a significant influence on detection efficiency.

Table 3. The distance of fixed tags from receiver Der7 and the mean detection efficiency of each tag (± standard error) (refer to Fig. 2 for locations).

| Tag | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Distance from Der7 (m) | 300 | 250 | 180 | 200 |
| Mean detection efficiency (%) | 16.15 | 11.29 | 72.10 | 71.17 |
| Standard error of mean detection efficiency (%) | 0.54 | 0.40 | 0.85 | 1.02 |

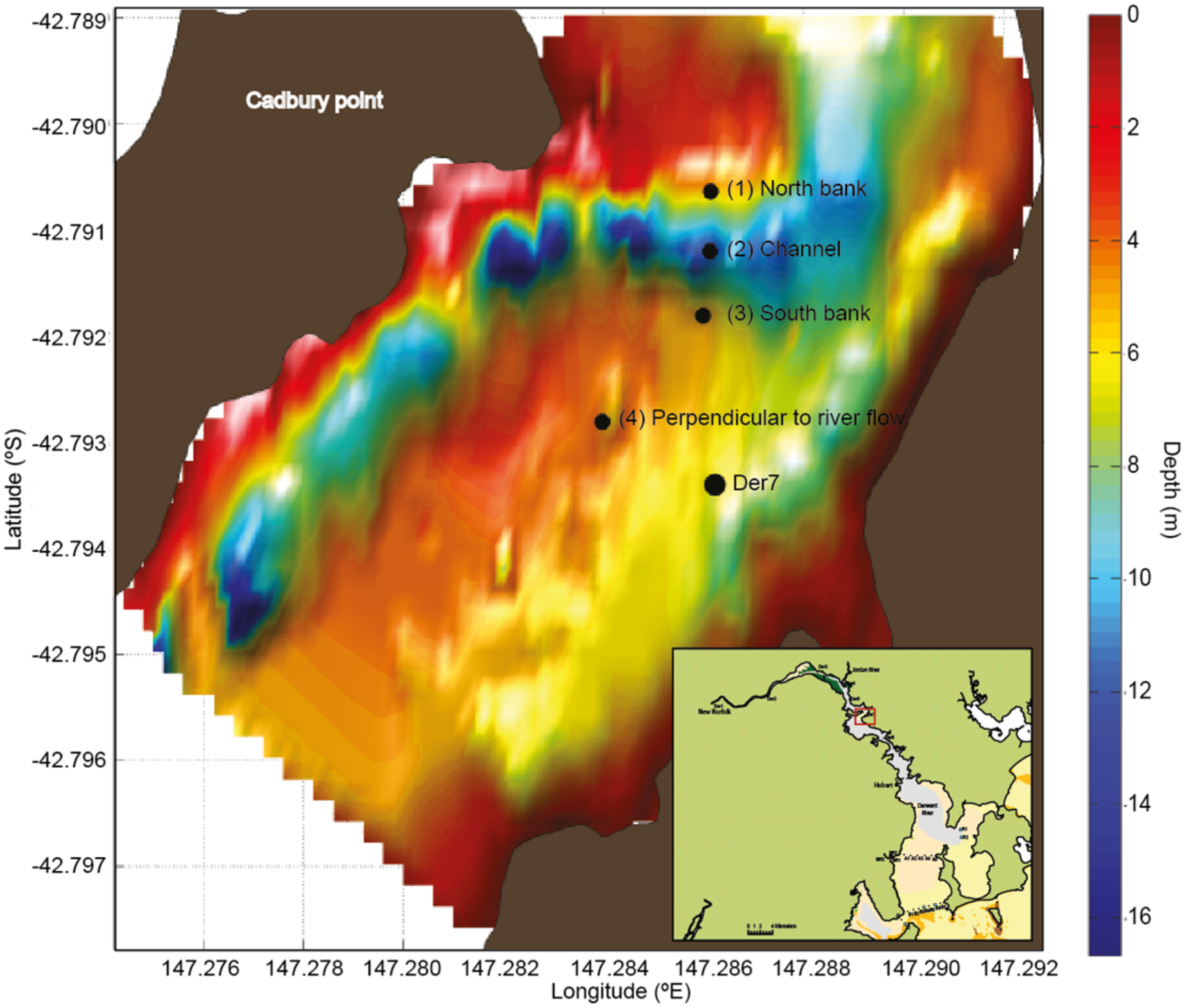


Fig. 2. Map of Cadbury point in the Derwent estuary showing the location of receiver Der7 and the four fixed location tags used to test the temporal variance in detection range. The coloured background represents the bathymetric profile of the area.

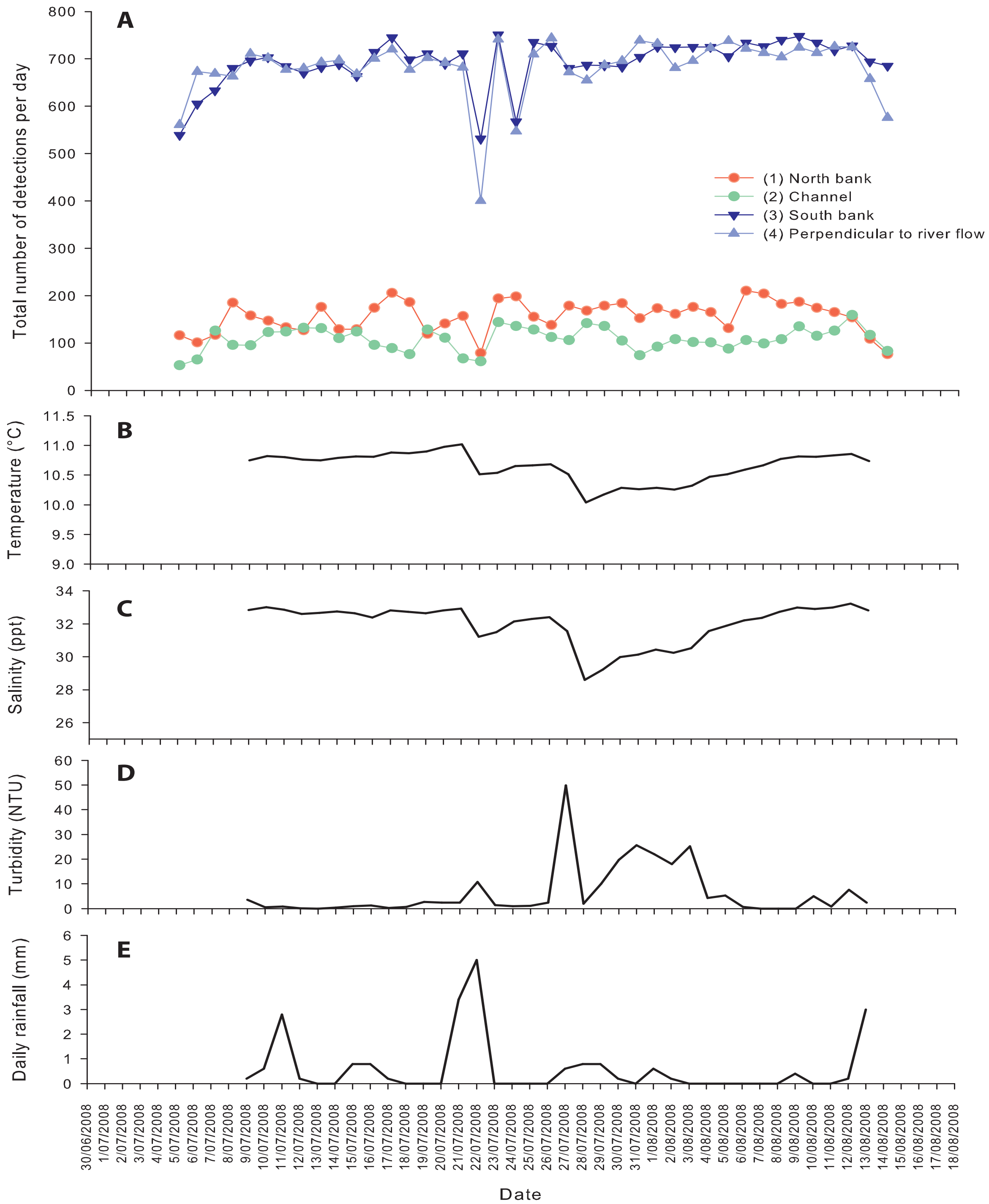


Fig. 3. (A) Total number of detections from 4 tags anchored around receiver 'Der7' (refer to Fig. 2 for map showing tag and receiver locations). Environmental parameters were as follows: (B) average water temperature per day, (C) average salinity per day, (D) average turbidity per day, and (E) cumulative rainfall per day.

### State-space model movement rate and detection efficiency outputs

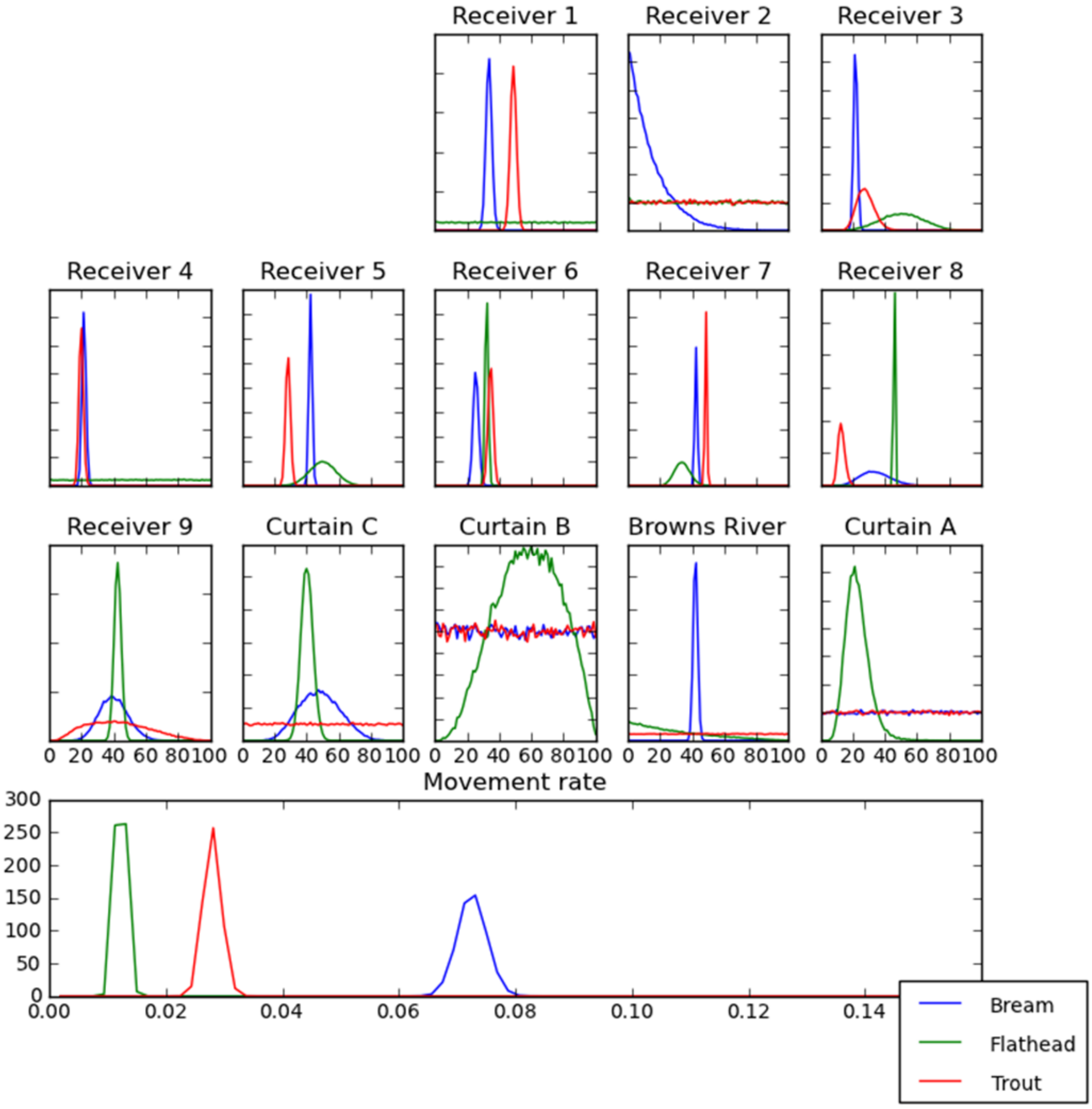


Fig 4. Detection and movement rates for the receivers as estimated by the model described in Appendix 2.

A Bayesian state-space model was developed that simultaneously estimates species-specific detection probabilities for each receiver and movement rates. This model is described in Appendix 2 and presents a significant step forward in the analysis of acoustic telemetered.

For each receiver the probability density (y axis) of the detection rate (x axis) for each species is shown. The peak of each curve indicates the most likely detection probability. For example at receiver 7, the detection probability was approximately 20% for Bream and Trout and approximately 10% for Flathead. The height/spread of the curve shows how certain the model is about the detection probability at that receiver for that species. For example at receiver 7, the model is highly certain about the detection probability for Bream and Trout and less certain about Flathead. The extreme example of this is for Flathead in the upper Derwent, particularly Receivers 1-5 where the model is highly uncertain about the detection probability – this is because Flathead rarely moved into this area.

## Sand flathead (*Platycephalus bassensis*) – Derwent estuary

The ten sand flathead caught in the mid- Derwent estuary (Fish ID's: 113 – 122) ranged in length from 270 to 355 mm FL (mean ± SE = 304 ± 8.4 mm FL) (Table 5). The total number of detections ranged from 639 to 167,195 per individual (Table 5). The total detection periods ranged from 149 to 377 days.

Table 5. Summary of *Platycephalus bassensis* tagged in the Derwent estuary between 27/2/2008 – 2/3/2008. TP= Total detection period in days; DD = Total number of days detected; DI = detection index (DD/TP).

| Fish ID | TL (mm) | Release date | Nearest receiver at deployment | Total detections | No. of receivers | TP (d) | DD (d) | $D_I$ |
|---|---|---|---|---|---|---|---|---|
| 113 | 325 | 27-Feb-08 | Der8 | 61319 | 11 | 353 | 249 | 0.71 |
| 114 | 295 | 27-Feb-08 | Der8 | 11434 | 4 | 315 | 93 | 0.30 |
| 115 | 290 | 27-Feb-08 | Der8 | 5471 | 3 | 297 | 70 | 0.24 |
| 116 | 270 | 27-Feb-08 | Der8 | 46506 | 2 | 377 | 241 | 0.64 |
| 117 | 305 | 27-Feb-08 | Der8 | 167195 | 1 | 380 | 282 | 0.74 |
| 118 | 285 | 27-Feb-08 | Der6 | 889 | 4 | 118 | 8 | 0.07 |
| 119 | 335 | 27-Feb-08 | Der6 | 639 | 7 | 348 | 40 | 0.11 |
| 120 | 355 | 27-Feb-08 | Der6 | 9466 | 10 | 374 | 207 | 0.55 |
| 121 | 300 | 02-Mar-08 | Der6 | 11299 | 10 | 316 | 61 | 0.19 |
| 122 | 280 | 02-Mar-08 | Der6 | 6249 | 3 | 149 | 28 | 0.19 |

These sand flathead displayed limited home ranges, strong site fidelity and limited movement for the majority of the study period, with the exception of relatively short periods of downstream movement before returning to the vicinity of the release site. All ten tagged fish remained for protracted periods in the vicinity of receivers 'Der6' and 'Der8'where they were tagged and released (Fig. 5) and all but one remained exclusively within the Derwent estuary throughout the study period. The highest number and most consistent detections were from those fish captured, tagged and released within the detection range of receiver 'Der8' (Fig. 6) – individuals 113 – 117 (Table 5). There were no detections of these individuals further up river from this receiver during the course of the study. Individuals 113, 116 and 117 had high detection index scores ($D_I$) and were detected consistently from early March to mid-November 2008, most frequently on receiver 'Der8', and a few intermittent detections on 'Der9' for individuals 113 and 116. The high $D_I$ of these individuals indicates that they were regularly within the detection range of a receiver and provides a high degree of confidence in the assertion that these individuals were highly site attached. Individuals 114 and 115 were also released at 'Der8' but had low $D_I$ scores (Table 5). However, when detected it was most commonly at 'Der8' and for individual 114 between June and November 2008 intermittently at 'Der9'. The absence of hits at alternative receivers further up or down river suggests that these individuals had a limited home range in the area around 'Der8' and 'Der9', but spent a significant amount of time outside of the detection ranges of the receivers, hence less detections were recorded. Individual behaviour profiles are reported in Appendix 1 and visualised in Figure 7.

The sedentary behaviour of sand flathead has previously been reported (Dix *et al*. 1975; Jordan 2001), however there are anecdotal reports suggesting that the catchability of the species decreases over the winter months giving rise to the the suggestion that they may move out of the estuaries at this time. The results of this study suggest that this is not the case and that the decrease in catchability, over the winter period, must be attributed to other factors.

An observed exception to the limited movement displayed by sand flathead for most of the year was a directed migration downriver. Six of the ten tagged fish made this migration (Fig. 7) Two moved at least as far down river as Curtain C (Tasman bridge) while four were detected as far down river as Curtain A, a distance of approximately 32 km for fish tagged at Der 6 and 25 km for fish tagged at Der 8. Individual 121 began the migration to curtain A in mid-June, four months earlier than the other three fish that moved that moved to Storm Bay. This individual was, however, the only fish that left the Derwent estuary, being detected in Frederick Henry Bay in early August before moving back into the Derwent in late August (Appendix 1 & Fig. 7). For the other three fish that migrated to curtain A the timing of the migration was highly synchronized. Two of the three fish left their 'home' receivers (noting one was from Der6 and the other from Der8) within two days of each other, while the third fish left 10 days later. The migration began in late October- early November. While variability has been reported in the spawning season for sand flathead (Jordan 2001; Bani and Moltschaniwskyj 2008; Bani *et al.* 2009), peak spawning is reported to occur between October and December in southeast Tasmania (Jordan 2001). Therefore it is highly likely that these fish were migrating to Storm Bay to spawn. These were also the three largest specimens tagged in the Derwent estuary ranging in size from 325 – 355 mm TL, well above the reported size at 50% maturity for this species of 220 mm and 255 mm for males and females, respectively (Bani and Moltschaniwskyj 2008).

The return migration was also highly synchronized with two individuals last detected on curtain A on the same day ($10^{th}$ December) while the third fish was last detected eight days later. Upon returning to the mid-Derwent estuary all three fish again took up residency within the detection range of the receiver from which they left. All three were first detected back at their home receiver within 14 days of each other. This is strong evidence of site fidelity of sand flathead. Fish species displaying a high degree of site fidelity such as this are generally more susceptible to localised depletion from targeted fishing effort (Spedicato *et al.* 2005; Semmens *et al.* 2010).

The syncronisation of the timing of this spawning migration would suggest that extraneous cues are influencing the timing of the migration. The initiation of the migration occurred at a time when river flow had significantly decreased and there was a marked warming of the waters within the river (Fig. 8A & 8B). A significant rainfall event also corresponded with the arrival of two of the three individuals at 'Curtain A' (Fig. 8A & 8B).

The general sedentary behaviour of sand flathead has implications for bio-accumulation of heavy metals (Verdouw *et al.* 2011), particularly for fish inhabiting the mid and upper

Derwent estuary which has a long history of metal pollution associated with industrial processing along its banks (Whitehead *et al.* 2010). Sand flathead are benthic feeders (Jordan 2001) and as such feed on prey that is often exposed to higher metal levels. Mercury in particular is a concern in the Derwent estuary. Bio-monitoring of mercury concentrations in the muscle tissue of sand flathead has occurred since the mid-1970's (Dix *et al*. 1975; Ayling *et al.* 1975; Ratkowsky *et al.* 1975; Langlois *et al.* 1987; McPherson, 2007). The existence of these long term data sets provide evidence of environmental loadings in sand flathead exceeding maximum permitted levels as prescribed by Food Standards Australia and New Zealand (Maximum Permitted Limit; 0.5 mg $kg^{-1}$). More recent measurements of heavy metals in sand flathead showed concentrations of mercury far in excess of ANZAAS guidelines (Verdouw *et al*. 2011), and led to public health warnings being released in April 2008. While many people who fish and consume sand flathead in the Derwent estuary are aware of the contamination of sand flathead in the upper and mid estuary it must also be considered that a proportion of fish that inhabit this highly metal contaminated area migrate down to the mouth of the estuary (Storm Bay region) during the spring/summer period to spawn. This coincides with the period of highest catches of sand flathead in Storm Bay by recreational fishers.

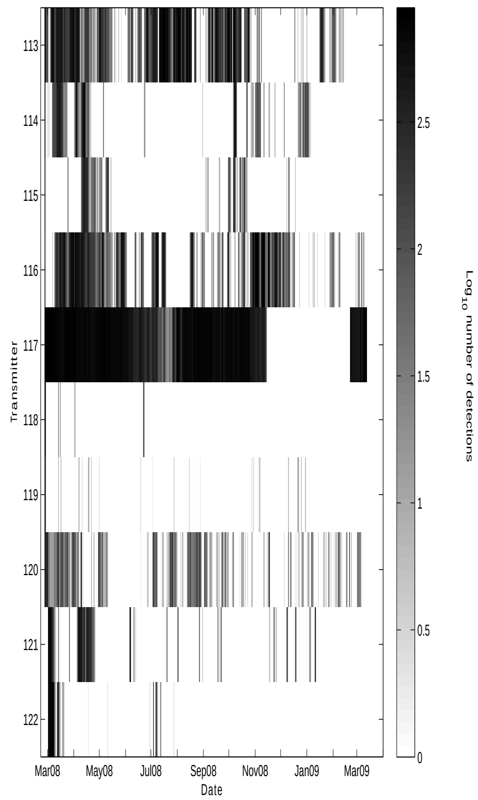


Fig. 5. Detection profiles of individual sand flathead (*Platycephalus bassensis*) tagged in the Derwent estuary.

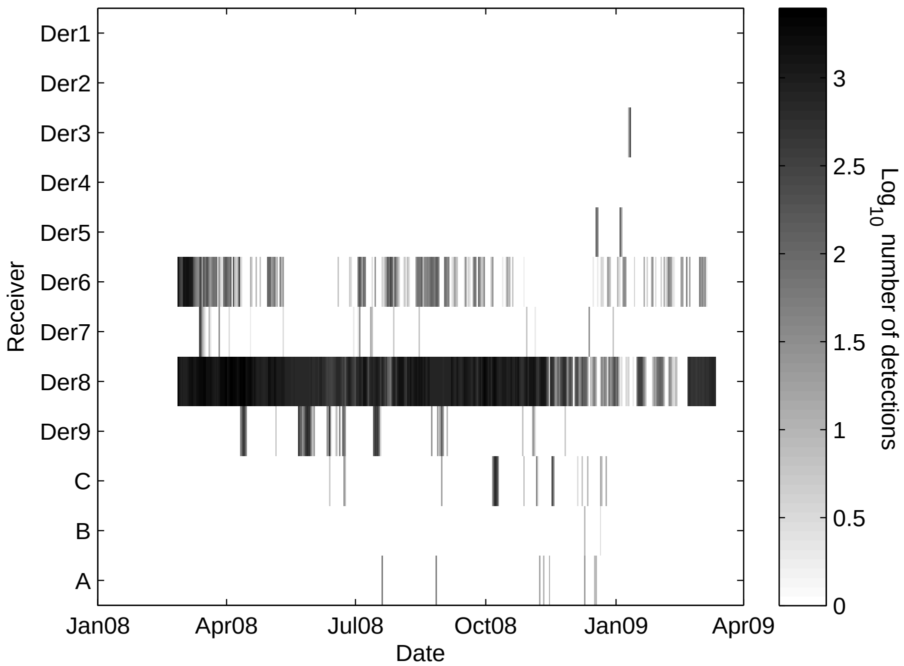


Fig. 6. Aggregated detection profile of sand flathead (*Platycephalus bassensis*) tagged in the Derwent estuary.

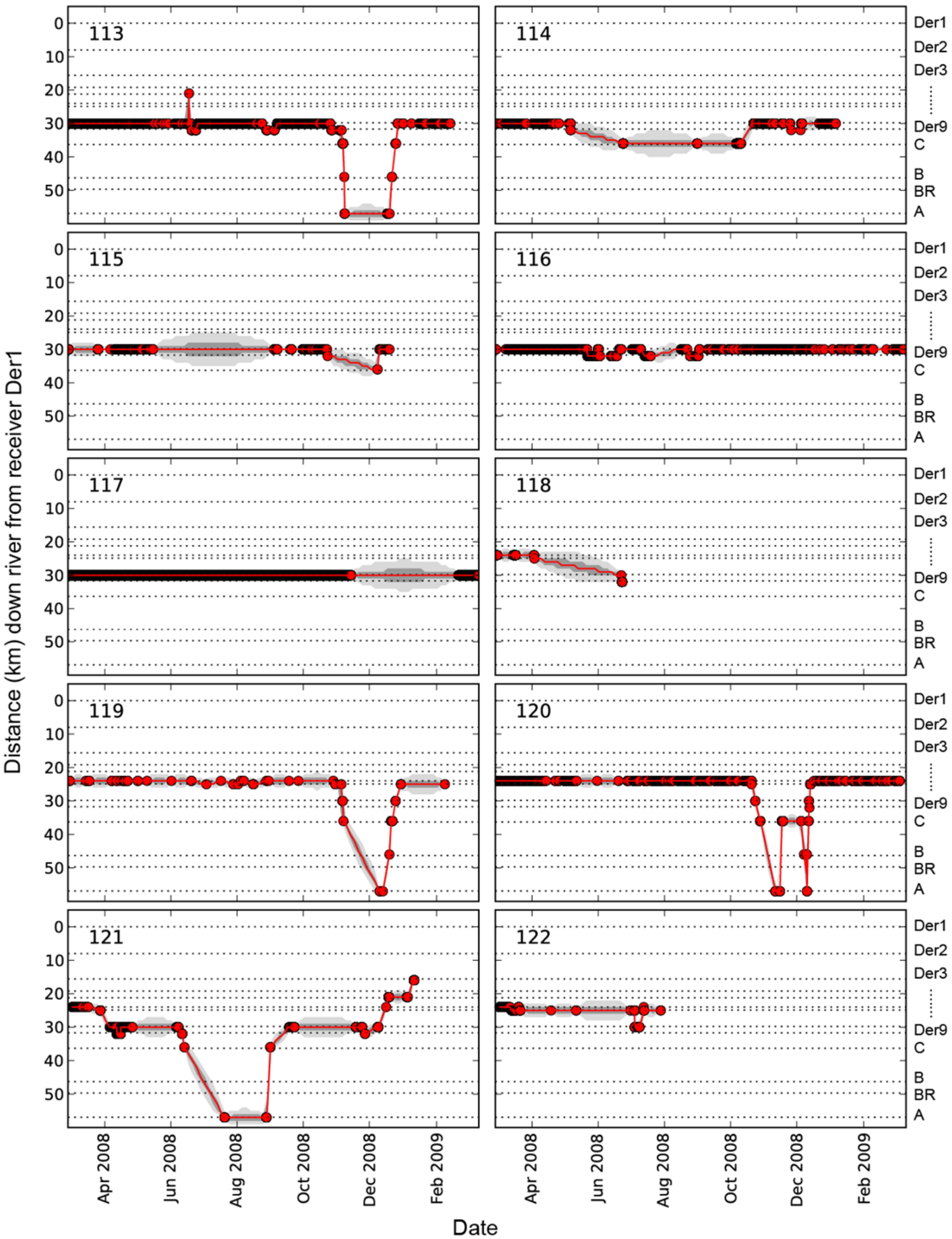


Fig. 7. State-space model outputs showing the predicted movement profiles of individual sand flathead (*Platycephalus bassensis*) tagged and released in the Derwent estuary. The red points indicate detections and the red line shows the median expected trajectory. The dark grey shading indicates the 50% probability range while the light grey shading indicates the 95% probability range.

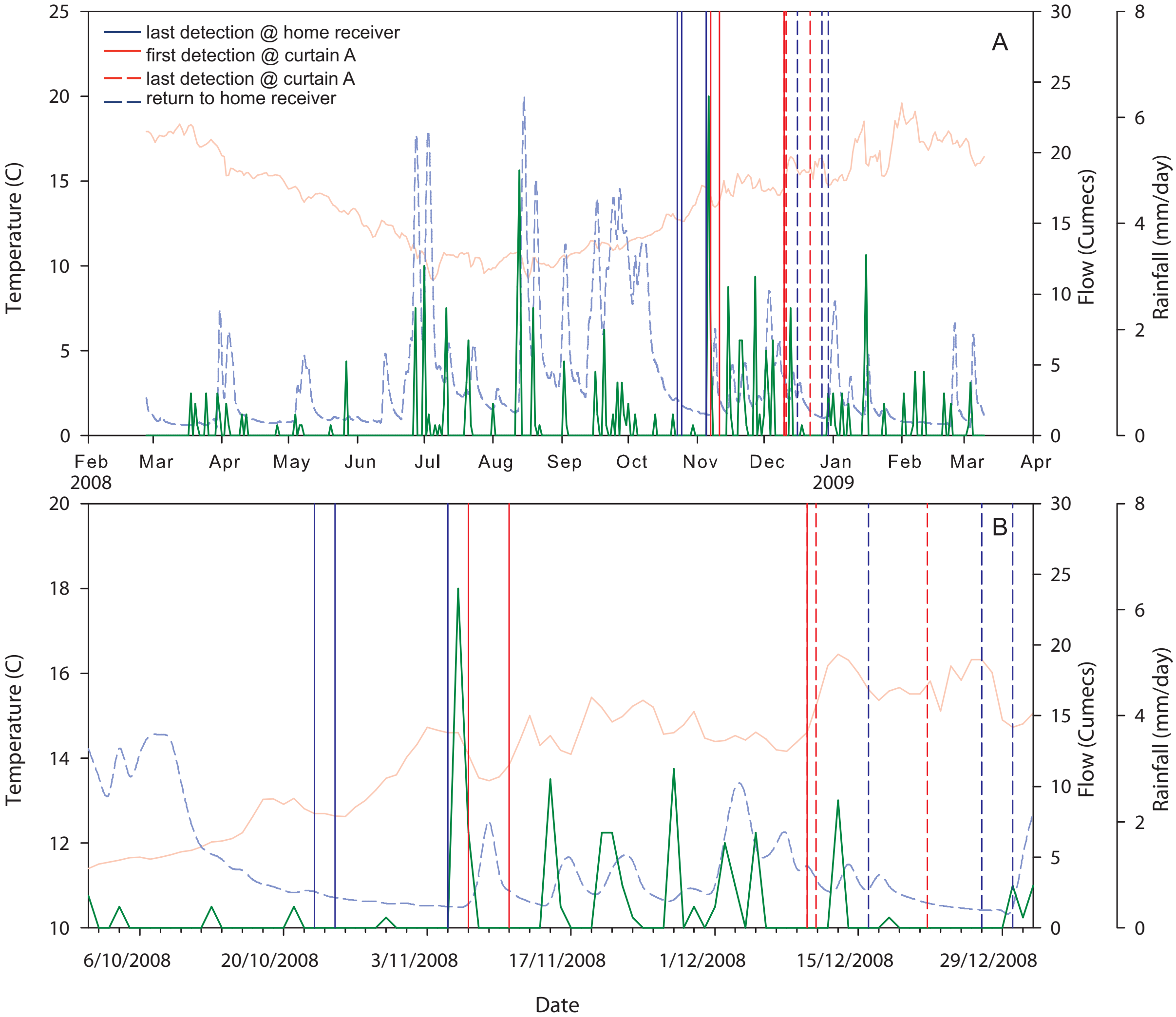


Fig. 8. The timing of the seasonal migration of three sand flathead from their home region to curtain A. The solid green line indicates the daily rainfall as recorded at the Hobart Bureau of Meteorology weather station. The dashed blue line indicates the river flow through the Tyenna River (which flows into the Derwent estuary). The solid red line indicates the water temperature recorded in situ at receiver 'Der7'. The vertical lines are described in the figure legend. Figure A shows the timing of the migration within a year while figure B focuses on the temporal period of interest.

## Sand flathead (*Platycephalus bassensis*) – Frederick Henry and Norfolk Bays

The twenty-one sand flathead caught in Norfolk Bay (Fish ID's: 101 – 112 & 123 – 131) ranged in length from 270 to 410 mm FL (mean ± SE = 328 ± 8.5 mm FL) (Table 6).

Individuals 101 – 112 were captured and released within the VRAP system (discussed in the next section). The number of detections of these fish in the VR2 array range from 0 to 2249 per individual (Table 6). The total detection period ranged from 0 to 216 days.

Individuals 123 – 131 were released at receiver D1. The number of detections of these fish in the VR2 array ranged from 335 to 54,706 per individual (Table 6) and the total detection period ranged from 2 to 263 days.

Table 6. Summary of *Platycephalus bassensis* tagged in Norfolk bay between the 21/2/2008 – 12/3/2008. TP= Total detection period in days; DD = Total number of days detected; DI = detection index (DD/TP).

| Fish ID | TL (mm) | Release date | Nearest receiver at deployment | Total detections | No. of receivers | TP (d) | DD (d) | $D_I$ |
|---|---|---|---|---|---|---|---|---|
| 101 | 340 | 21-Feb-08 | VRAP | 0 | 0 | 0 | 0 | 0.00 |
| 102 | 315 | 21-Feb-08 | VRAP | 0 | 0 | 0 | 0 | 0.00 |
| 103 | 320 | 21-Feb-08 | VRAP | 2249 | 4 | 68 | 20 | 0.29 |
| 104 | 295 | 21-Feb-08 | VRAP | 255 | 1 | 57 | 22 | 0.39 |
| 105 | 300 | 21-Feb-08 | VRAP | 35 | 4 | 117 | 4 | 0.03 |
| 106 | 335 | 21-Feb-08 | VRAP | 143 | 4 | 39 | 4 | 0.10 |
| 107 | 360 | 21-Feb-08 | VRAP | 510 | 2 | 95 | 14 | 0.15 |
| 108 | 360 | 21-Feb-08 | VRAP | 1526 | 5 | 216 | 24 | 0.11 |
| 109 | 275 | 21-Feb-08 | VRAP | 0 | 0 | 0 | 0 | 0.00 |
| 110 | 355 | 21-Feb-08 | VRAP | 12 | 1 | 2 | 2 | 1.00 |
| 111 | 270 | 21-Feb-08 | VRAP | 0 | 0 | 0 | 0 | 0.00 |
| 112 | 355 | 21-Feb-08 | VRAP | 5 | 3 | 4 | 4 | 1.00 |
| 123 | 410 | 12-Mar-08 | D1 | 1287 | 10 | 263 | 47 | 0.18 |
| 124 | 400 | 12-Mar-08 | D1 | 52035 | 1 | 77 | 77 | 1.00 |
| 125 | 370 | 12-Mar-08 | D1 | 47357 | 1 | 77 | 77 | 1.00 |
| 126 | 360 | 12-Mar-08 | D1 | 335 | 4 | 2 | 2 | 1.00 |
| 127 | 310 | 12-Mar-08 | D1 | 349 | 9 | 6 | 5 | 0.83 |
| 128 | 275 | 12-Mar-08 | D1 | 53698 | 1 | 77 | 77 | 1.00 |
| 129 | 315 | 12-Mar-08 | D1 | 7794 | 10 | 179 | 38 | 0.21 |
| 130 | 290 | 12-Mar-08 | D1 | 54706 | 2 | 77 | 77 | 1.00 |
| 131 | 330 | 12-Mar-08 | D1 | 13373 | 2 | 77 | 77 | 1.00 |

### *Key movement traits of sand flathead in Frederick Henry and Norfolk Bays*

The frequency of detections for sand flathead tagged in Norfolk bay were far less frequent than recorded from the Derwent estuary. This was most likely due to the expanse of the bay area compared to the relatively narrow mid-estuary in the Derwent and the resultant lower coverage by receivers. The home ranges of sand flathead tagged in Norfolk Bay were greater than fish tagged in the Derwent estuary, with fish moving greater distances within the bay system.

All sand flathead were tagged and released either into the VRAP array or at the intersection of curtains G and D. These locations were approximately central to the southern quadrant of Norfolk Bay. Six of the 13 sand flathead that were detected on the VR2 array were detected at G1, a receiver located in a habitat dominated by *Caluerpa* and a distance of approximately 2.5 km from their release location. Several individuals also moved directly south again into habitat dominated by *Caluerpa*, in the detection range of receivers D3 and D4. One individual moved to curtain L at the mouth of Eaglehawk neck.

No tagged individuals were detected outside of the array in Norfolk and Frederick Henry Bay. One individual (ID 129) did, however, made a significant migration moving out into Frederick Henry Bay before returning back into Norfolk Bay.

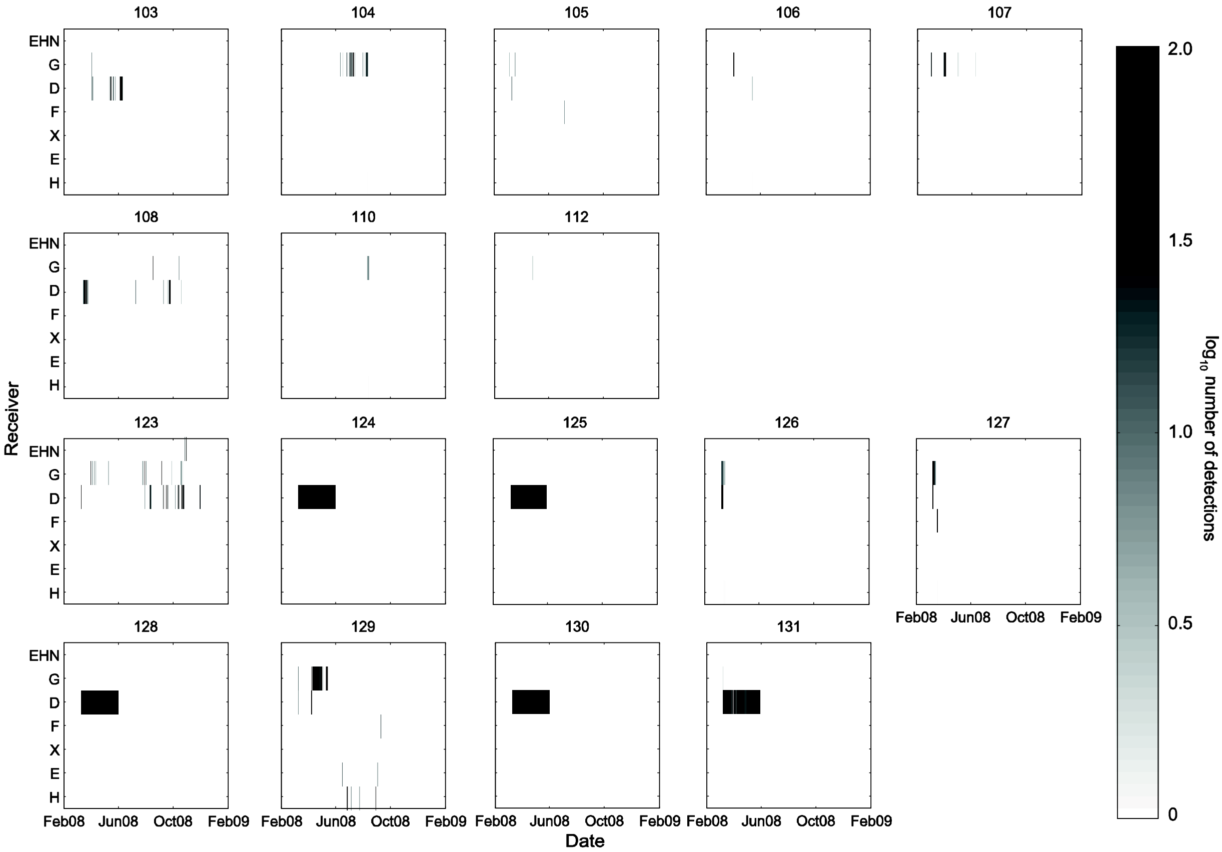


Fig. 9. Detection profiles of individual sand flathead (*Platycephalus bassensis*) tagged and released in Norfolk Bay.

## Sand flathead (*Platycephalus bassensis*) - Vemco radio acoustic positioning system (VRAP)

The number of resolved detections for an individual sand flathead tagged in the vicinity of the VRAP system ranged from 0 to 223. The longest period of resolved detections for an individual was 33 days and the most days that a fish was detected was 14 (Table 7). The number of unresolved detections for an individual ranged from 527 to 30884 (noting the tag implanted in fish 109 failed). The maximum detection period for an individual was 61 days and the most days that an individual fish was detected on was 60 (Table 7).

Table 7. Summary table of Vemco Radio Acoustic Positioning (VRAP) study of sand flathead (*Platycephalus bassensis*) in Norfolk Bay, southeast Tasmania. TP(d) = Total detection period in days, DD(d)= Number of individual days detected.

| Fish ID | Resolved detections | Resolved TP (d) | Resolved DD (d) | Unresolved detections | Unresolved TP (d) | Unresolved DD (d) | Resolution efficiency |
|---|---|---|---|---|---|---|---|
| 101 | 0 | 0 | 0 | 527 | 40 | 13 | 0 |
| 102 | 70 | 11 | 5 | 21336 | 61 | 60 | 0.0033 |
| 103 | 101 | 30 | 14 | 10202 | 33 | 33 | 0.0099 |
| 104 | 66 | 5 | 4 | 1710 | 35 | 20 | 0.0386 |
| 105 | 192 | 9 | 9 | 2544 | 36 | 14 | 0.0755 |
| 106 | 153 | 33 | 13 | 12945 | 41 | 36 | 0.0118 |
| 107 | 14 | 8 | 3 | 4164 | 11 | 11 | 0.0034 |
| 108 | 6 | 1 | 1 | 2063 | 21 | 17 | 0.0029 |
| 109 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 110 | 103 | 33 | 12 | 6679 | 20 | 20 | 0.0154 |
| 111 | 7 | 6 | 4 | 30884 | 61 | 60 | 0.0002 |
| 112 | 223 | 14 | 10 | 6641 | 61 | 19 | 0.0336 |

The resolution efficiency for all sand flathead tagged in the vicinity of the VRAP system was poor, ranging from 0 to 0.075 (Table 7). Four out of 11 tags were unsuccessful in resolving more than 15 detections over the time the VRAP system was deployed. Although the unresolved detections suggest that these individuals remained in the vicinity of the VRAP system for at least 11 days and up to 61 days (Fig. 10). For the majority of individuals all resolved detections were within the VRAP triangle, exceptions being individuals 111 (Fig. 15A) and 112 (Fig. 16A). Both these individuals had single hits outside the VRAP triangle although it is possible these were false detections. The other exception was individual 106 which had two active movement periods where several detections were recorded outside the VRAP triangle (Fig. 14A).

All individuals that had greater than 15 resolved detections displayed similar behaviour. This involved a period of relative inactivity followed by a period of ‘burst’ activity generally within a small area but covering a distance of up to approximately 200 m (Fig. 11 to 16B). Individual 106 displayed an anomalous period of activity moving over a far greater area than displayed by other individuals and covering a minimum distance of 1500 m within a 12 hour period (Fig. 14B). The number of resolved detections increased while individuals were active and for all individuals, the greatest proportion of detections were recorded during daylight hours (643 compared with 292 during the night) (Fig. 17), implying that sand flathead are more active during the daytime.

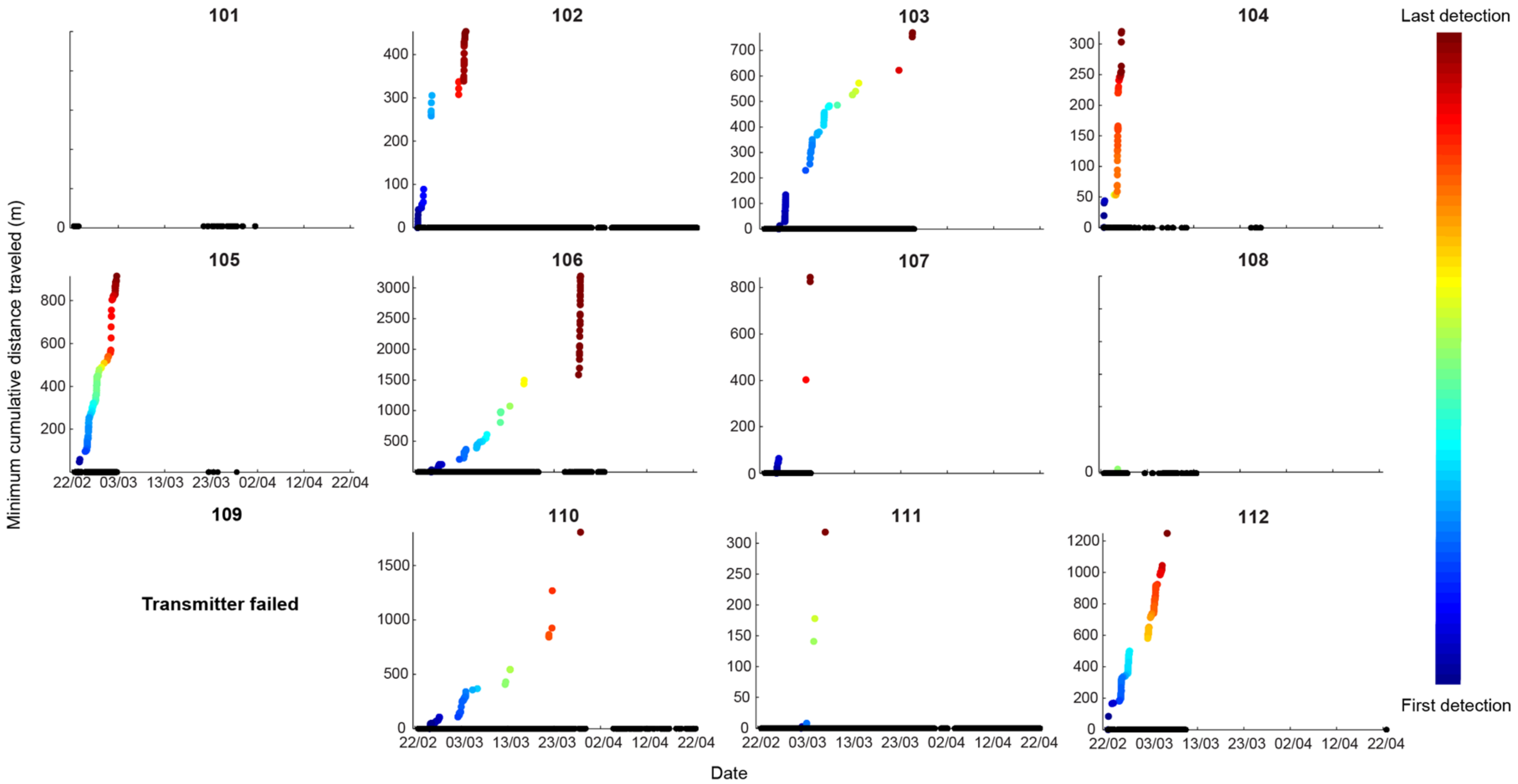


Fig. 10. Detection profiles of sand flathead (*Platycephalus bassensis*) from a VRAP system deployed in Norfolk Bay, southeast Tasmania. Coloured points indicate resolved detections, while black points (on the x-axis) indicate an unresolved detection (see text for definition of resolved vs unresolved detections).

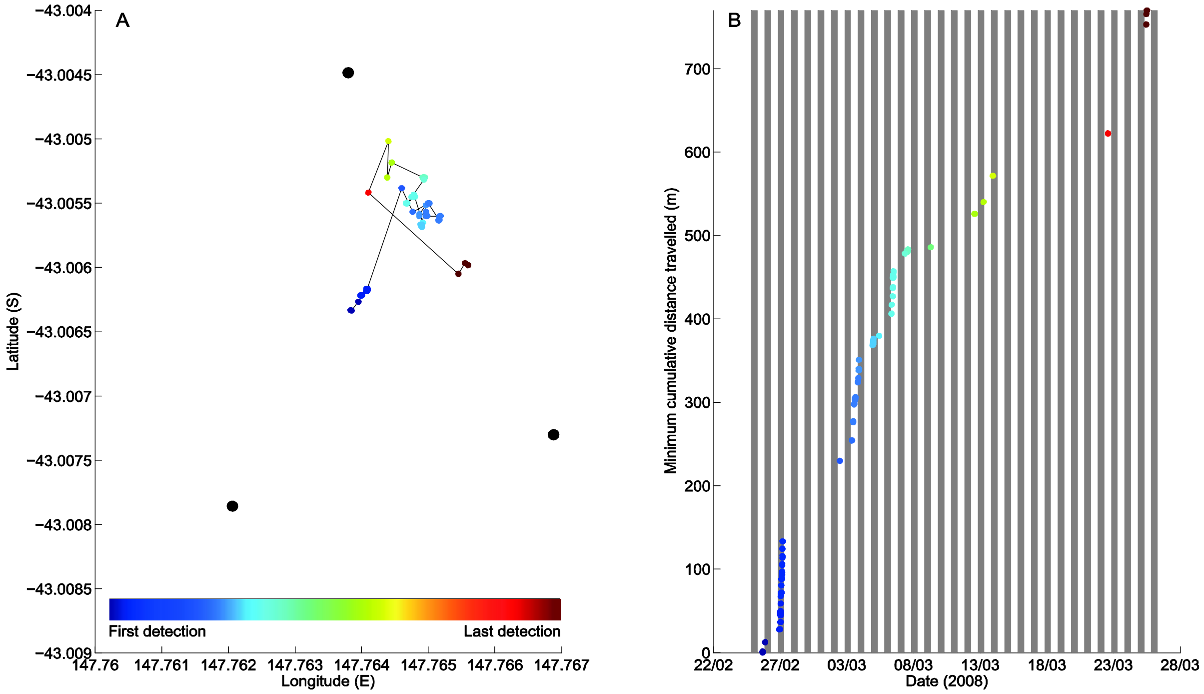


Fig. 11. (A) Location of resolved detections by the VRAP system of sand flathead (*Platycephalus bassensis*) individual number 103. The large black points indicate the location of the VRAP receivers. (B) The cumulative minimum distance travelled of individual 103 determined from resolved VRAP detections. Shaded columns indicate night time.

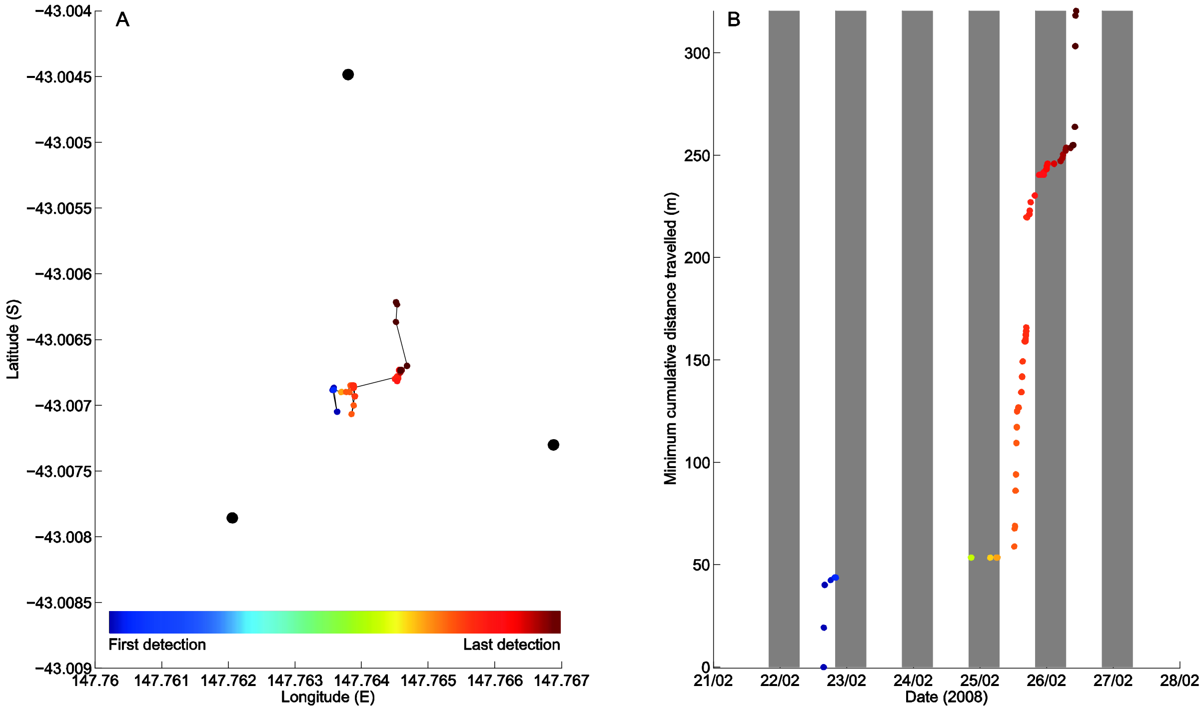


Fig. 12. (A) Location of resolved detections by the VRAP system of sand flathead (*Platycephalus bassensis*) individual number 104. The large black points indicate the location of the VRAP receivers. (B) The cumulative minimum distance travelled of individual 104 determined from resolved VRAP detections. Shaded columns indicate night time.

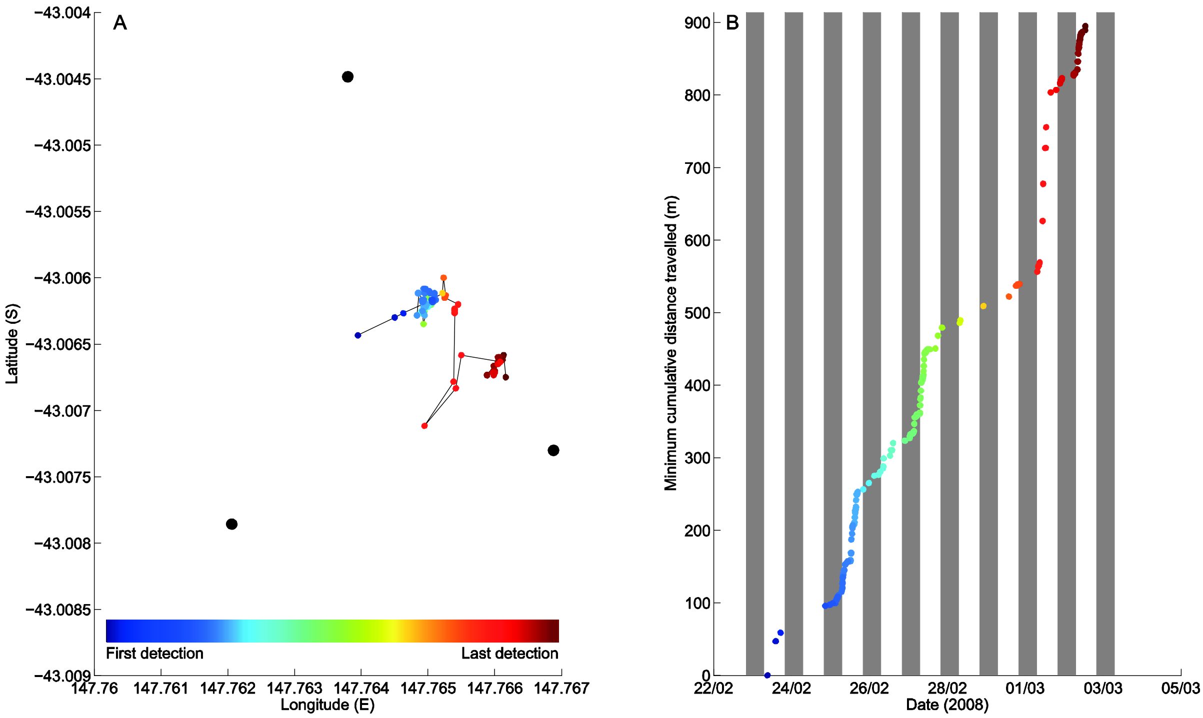


Fig. 13. (A) Location of resolved detections by the VRAP system of sand flathead (*Platycephalus bassensis*) individual number 105. The large black points indicate the location of the VRAP receivers. (B) The cumulative minimum distance travelled of individual 105 determined from resolved VRAP detections. Shaded columns indicate night time.

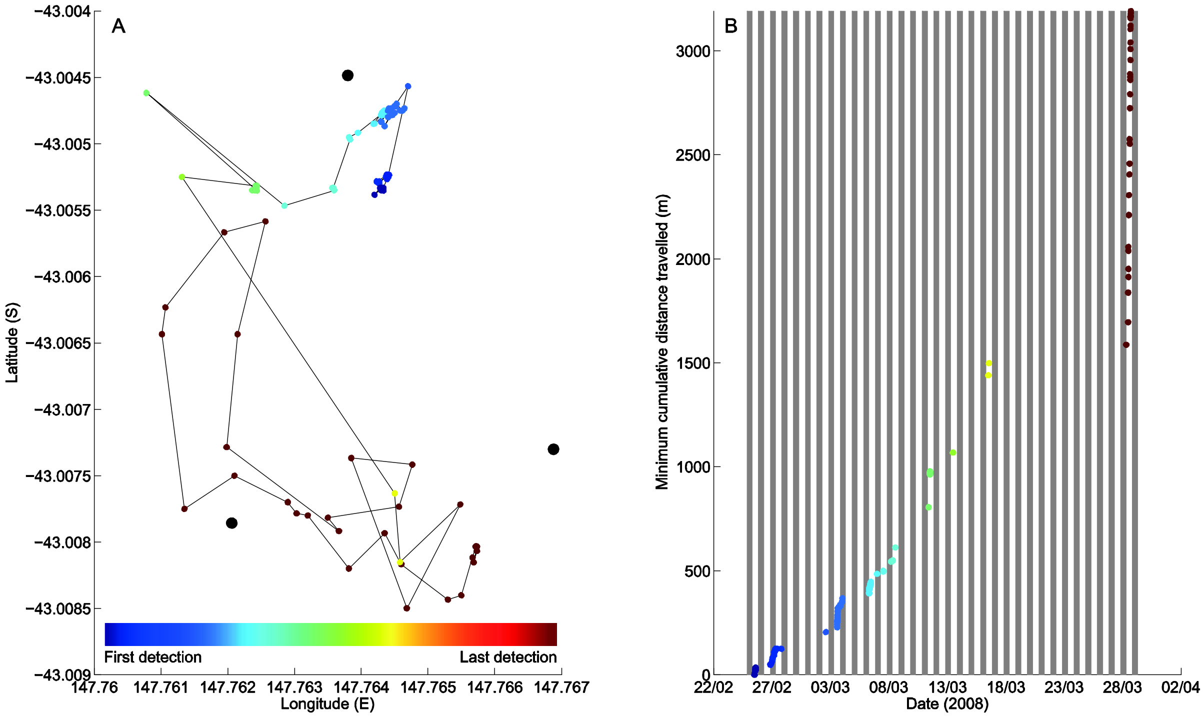


Fig. 14. (A) Location of resolved detections by the VRAP system of sand flathead (*Platycephalus bassensis*) individual number 106. The large black points indicate the location of the VRAP receivers. (B) The cumulative minimum distance travelled of individual 106 determined from resolved VRAP detections. Shaded columns indicate night time.

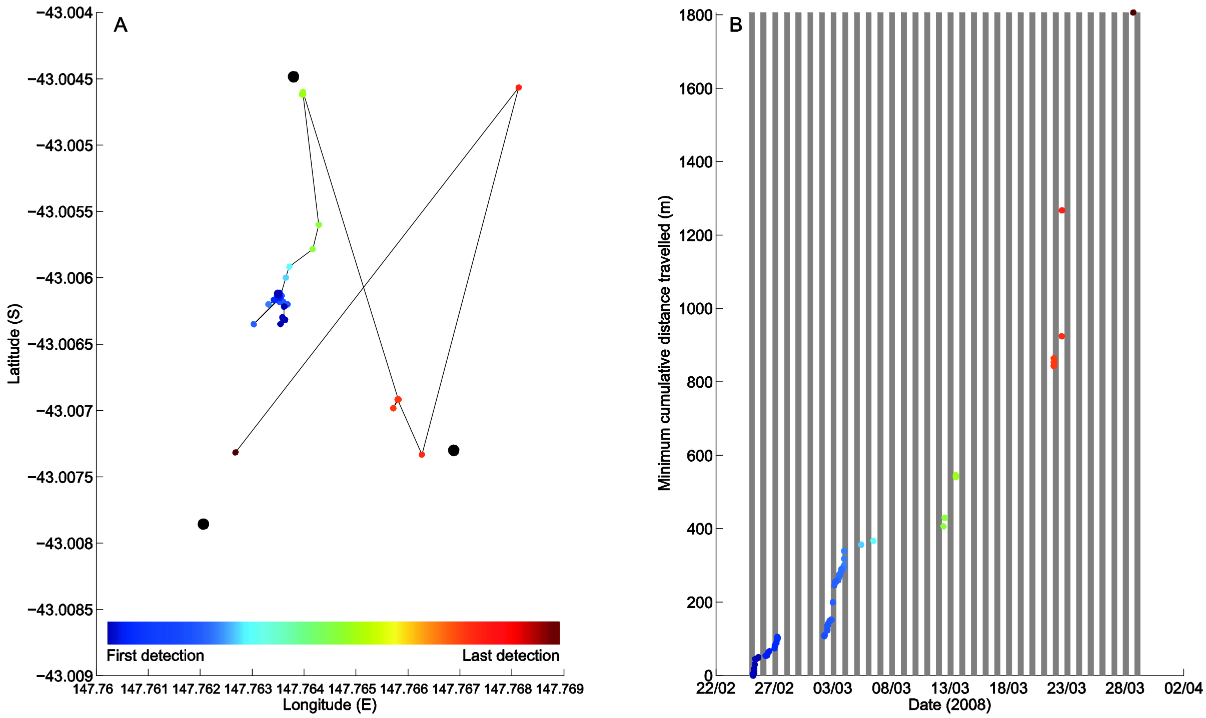


Fig. 15. (A) Location of resolved detections by the VRAP system of sand flathead (*Platycephalus bassensis*) individual number 110. The large black points indicate the location of the VRAP receivers. (B) The cumulative minimum distance travelled of individual 110 determined from resolved VRAP detections. Shaded columns indicate night time.

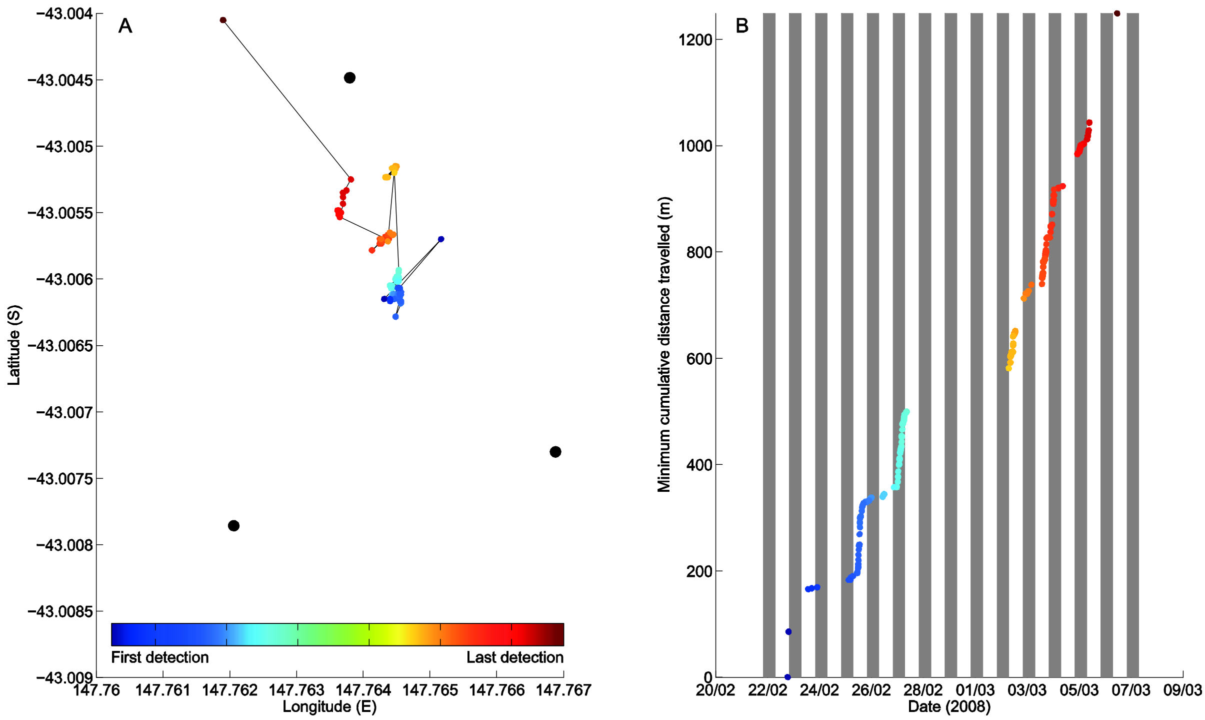


Fig. 16. (A) Location of resolved detections by the VRAP system of sand flathead (*Platycephalus bassensis*) individual number 112. The large black points indicate the location of the VRAP receivers. (B) The cumulative minimum distance travelled of individual 112 determined from resolved VRAP detections. Shaded columns indicate night time.

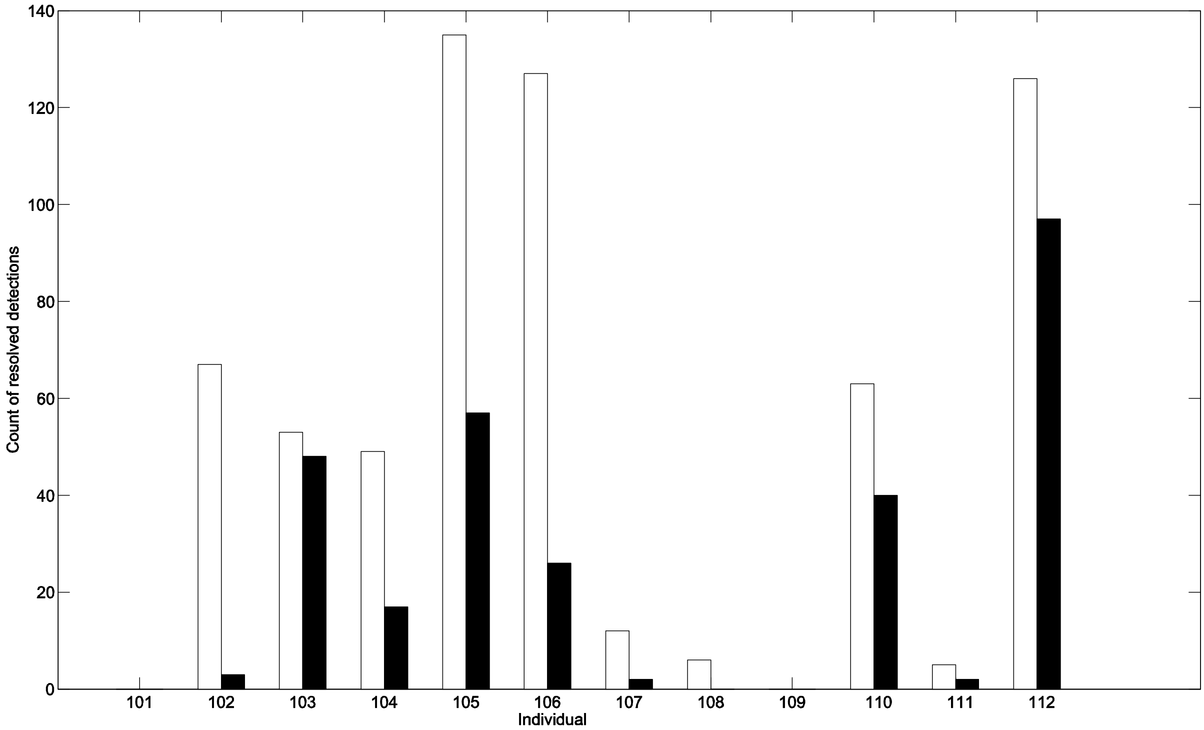


Fig. 17. The number of resolved detections from individual sand flathead reported from the VRAP system in Norfolk Bay, southeast Tasmania. The hollow bars indicate the number of detections during the day while the shaded bars indicate the number of detections during the night.

## Black bream (*Acanthopagrus butcheri*) – Derwent estuary

A total of twenty black bream were tagged and released in the Derwent estuary, ten each on the 1st and 2nd of March 2008 respectively (Table 7). The range of fish sizes was (295 – 428mm FL; mean ± SE = 363 ± 6.3 mm FL). The total detection period ranged from 113 days to 380 days with all but one fish (#15) being detected on multiple receivers in the Derwent estuary during the study (Table 7 & Figs. 18 and 19). All twenty fish were above the size at which bream attain maturity - approximately 215 mm or two years old (Sarre and Potter 1999).

Table 7. Summary of tagged *Acanthopagrus butcheri* in the Derwent estuary including details of acoustic detections. TP= Total detection period in days; DD = Total number of days detected; DI = detection index (DD/TP).

| Fish ID | TL (mm) | Release date | Nearest receiver at deployment | Total detections | No. of receivers | TP (d) | DD (d) | $D_I$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 380 | 01-Mar-08 | Der6 | 115 | 5 | 113 | 23 | 0.20 |
| 2 | 248 | 01-Mar-08 | Der6 | 11151 | 4 | 292 | 206 | 0.71 |
| 3 | 360 | 01-Mar-08 | Der6 | 1194 | 7 | 373 | 69 | 0.18 |
| 4 | 380 | 01-Mar-08 | Der6 | 14337 | 8 | 336 | 43 | 0.13 |
| 5 | 345 | 01-Mar-08 | Der6 | 6033 | 10 | 341 | 100 | 0.29 |
| 6 | 355 | 01-Mar-08 | Der3 | 2804 | 7 | 333 | 146 | 0.44 |
| 7 | 355 | 01-Mar-08 | Der3 | 8752 | 9 | 331 | 113 | 0.34 |
| 8 | 365 | 01-Mar-08 | Der3 | 8698 | 5 | 371 | 160 | 0.43 |
| 9 | 390 | 01-Mar-08 | Der3 | 1379 | 12 | 356 | 89 | 0.25 |
| 10 | 350 | 01-Mar-08 | Der3 | 1965 | 7 | 347 | 75 | 0.22 |
| 11 | 360 | 02-Mar-08 | Der7 | 8611 | 11 | 367 | 89 | 0.24 |
| 12 | 365 | 02-Mar-08 | Der7 | 531 | 8 | 369 | 51 | 0.14 |
| 13 | 375 | 02-Mar-08 | Der7 | 2065 | 10 | 363 | 86 | 0.24 |
| 14 | 385 | 02-Mar-08 | Der7 | 26920 | 10 | 358 | 160 | 0.45 |
| 15 | 360 | 02-Mar-08 | Der7 | 1281 | 1 | 152 | 12 | 0.08 |
| 16 | 360 | 02-Mar-08 | Der8 | 1874 | 7 | 346 | 96 | 0.28 |
| 17 | 365 | 02-Mar-08 | Der8 | 3439 | 5 | 116 | 39 | 0.34 |
| 18 | 295 | 02-Mar-08 | Der8 | 5679 | 8 | 379 | 146 | 0.39 |
| 19 | 390 | 02-Mar-08 | Der8 | 436 | 7 | 317 | 67 | 0.21 |
| 20 | 310 | 02-Mar-08 | Der8 | 2239 | 9 | 380 | 88 | 0.23 |

All 20 black bream remained in the Derwent estuary for the duration of the study, predominantly in the mid-estuary between receivers Der3 and Der7 with the highest concentration of detections occurring at Der6 and Der7 (Fig. 20). In fact 15 individuals were not detected further downstream than curtain C (Derwent Bridge), while five were observed to move further downstream and into Browns River, situated close to the entrance of the estuary (Fig. 20). The fidelity to the Derwent estuary was not unexpected as bream are believed to complete their entire life cycle within a given estuarine system (Potter and Hyndes 1999). This hypothesis is further supported by a low level of genetic interchange between adjacent estuaries (Burridge and Versace 2007).

The behaviour of the majority of black bream indicated a bi-modal seasonal pattern in their movements within the Derwent estuary. During the warmer summer months black bream were far more active and utilised a broader range of the mid and upper-estuary than the cooler winter months.

Beginning in early November, 16 of the 20 tagged individuals moved up-river to the vicinity of 'Der1' or 'Der2'. Of the four fish that were not observed migrating upstream their detection profiles suggest that there behaviour was anomalous. There are several possibilities for this including tag failure, unreported recapture or fish mortality. These fish are therefore not considered in further analysis (Fish#: 1, 2, 15 and 17). The migration correlates well with the known spring/summer spawning season for black bream in Australia (Newton 1996; Haddy and Pankhurst 1998; Sarre and Potter 1999; Sakabe *et al.* 2011), with peak gonad development occurring in November in Tasmania (Haddy and Pankhurst 1998; Sakabe *et al.* 2011). The upstream movement is also typical for black bream with the species observed spawning in the upper regions of several estuaries in south-eastern Australia, often in the vicinity of the salt wedge (Newton 1996; Walker and Neira 2001; Sakabe and Lyle 2010).

From November to mid-January the majority of tagged bream made multiple trips down river and back to the area around Der1 and Der2, which given the time of year may have been related to spawning activity (Fig. 20). As black bream are group synchronous multiple spawners (Sarre and Potter 1999), it is likely that individual black bream return to the spawning grounds multiple times throughout the spawning season.

Similar to sand flathead, black bream displayed a strong degree of synchronicity in upstream migration behaviour. The first migration event saw 3 tagged individuals arrive at 'Der1' within 24 hours of each other (Fig. 21B). The next event ~10 days later, saw another 8 individuals arrive within 4 days of one another (Fig. 21C). A further event was observed ~3 weeks later with 8 fish arriving within 4 days of each other (some for the second time) (Fig. 21D). The onset of spawning migratory behaviour occurred when flow rates had dropped significantly and the river had warmed by several degrees (Fig. 21A). All three of the synchronised migrations occurred shortly after rainfall events (Fig. 21A-E).

Increases in water temperature often act as a trigger for initiating spawning activity in teleosts (Lam 1983) and this has been shown for other sparids (Kojima 1981; Scott and Pankhurst 1992). In Tasmania, bream have been shown to successfully spawn when river flow is low and salinity is greater than 15 ppt (Sakabe *et al.*2011). There is also evidence that when a flood of cold (9°C) fresh water enters an estuary that fish move downriver and gonadal sex steroid concentrations fall (Haddy and Pankhurst 1998). In this study fish were observed moving upstream immediately after rainfall events, however these events were minor and were not directly correlated with river flow due to the mechanical control of water discharge in the estuary. Furthermore the water temperature did not drop below 13°C during the spawning season.

Again, similar to the flathead, there is strong evidence to suggest a suite of environmental parameters control the timing of the spawning for black bream in the Derwent estuary. Climate change predictions for eastern Tasmania indicate a decrease in river flows in spring and an increase during summer, potentially increasing environmental variability between and within years (Viney *et al*. 2009). This has the potential to have implications for spawning success and subsequent recruitment of black bream (Sakabe *et al.* 2011), although the species has been shown to tolerate a wide thermal-haline range in other systems (Sarre and Potter 1999).

Five individuals were detected in Browns River some 25 km from where the majority of tagged bream spent the majority of the time in the mid-Derwent estuary (Der6 and Der7). Two bream (Fish#: 5 and 11) spent extended periods in this small river system, being detected regularly from July to November and May to November respectively, before both were detected again up in the mid-estuary. Fish# 20 was only detected in Browns River briefly in July before also returning to the mid-estuary. Two individuals (Fish#: 4 and 9) moved between the mid-estuary and Browns River on multiple occasions. These migrations were later in the year and coincided with the spawning season implying that these individuals were moving to Browns River to spawn. This may suggest that there are multiple spawning sites within the Derwent estuary.

While the bream tagged in this study spent the majority of time upstream of the zinc smelter, which is the main source of metal contamination in the Derwent estuary, mercury levels in this species are well as above the Food Standards Australia and New Zealand (FSANZ) maximum permitted level (ML) of 0.5 mg $kg^{-1}$ (Verdouw *et al.* 2011). The relatively high ages of black bream tested (X-Y years) and benthic feeding habit (Verdouw *et al.* 2011) coupled with fidelity to the system are likely to be factors contributing to the high mercury concentrations. In light of this a health advisory released in 2007 recommended that black bream from the Derwent should not be used for human consumption.

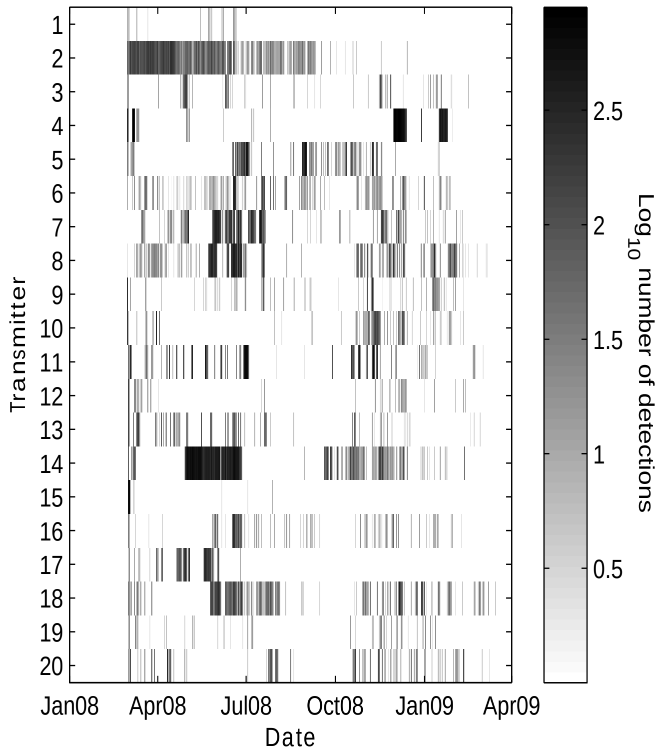


Fig. 18. Detection profiles of individual black bream (*Acanthopagrus butcheri*) tagged throughout the duration of study.

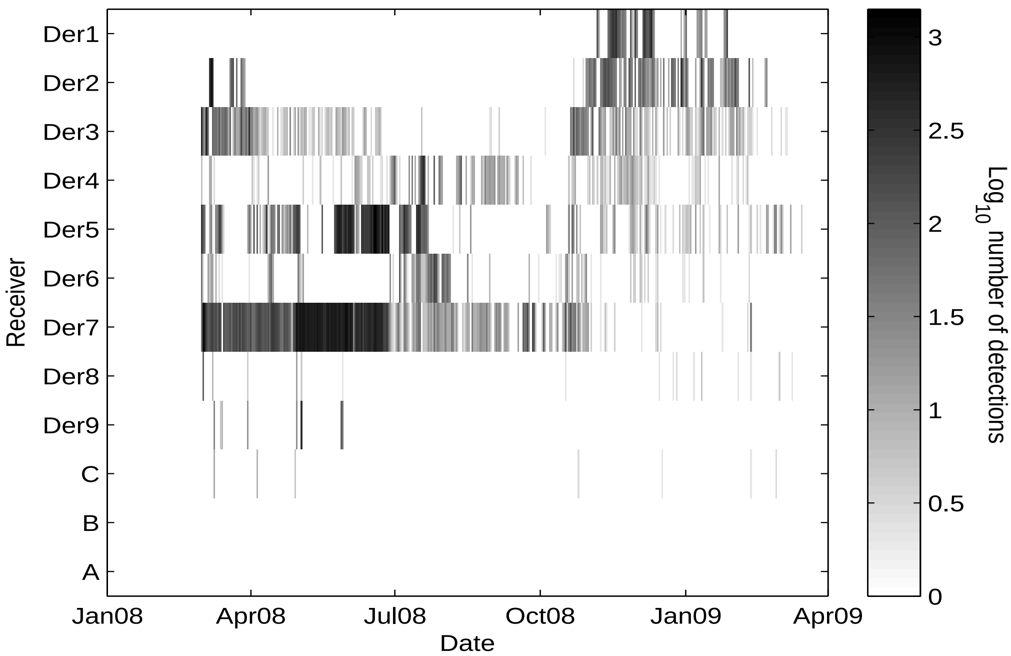


Fig. 19. Aggregated detection profile of the 20 black bream (*Acanthopagrus butcheri*) tagged in the Derwent estuary.

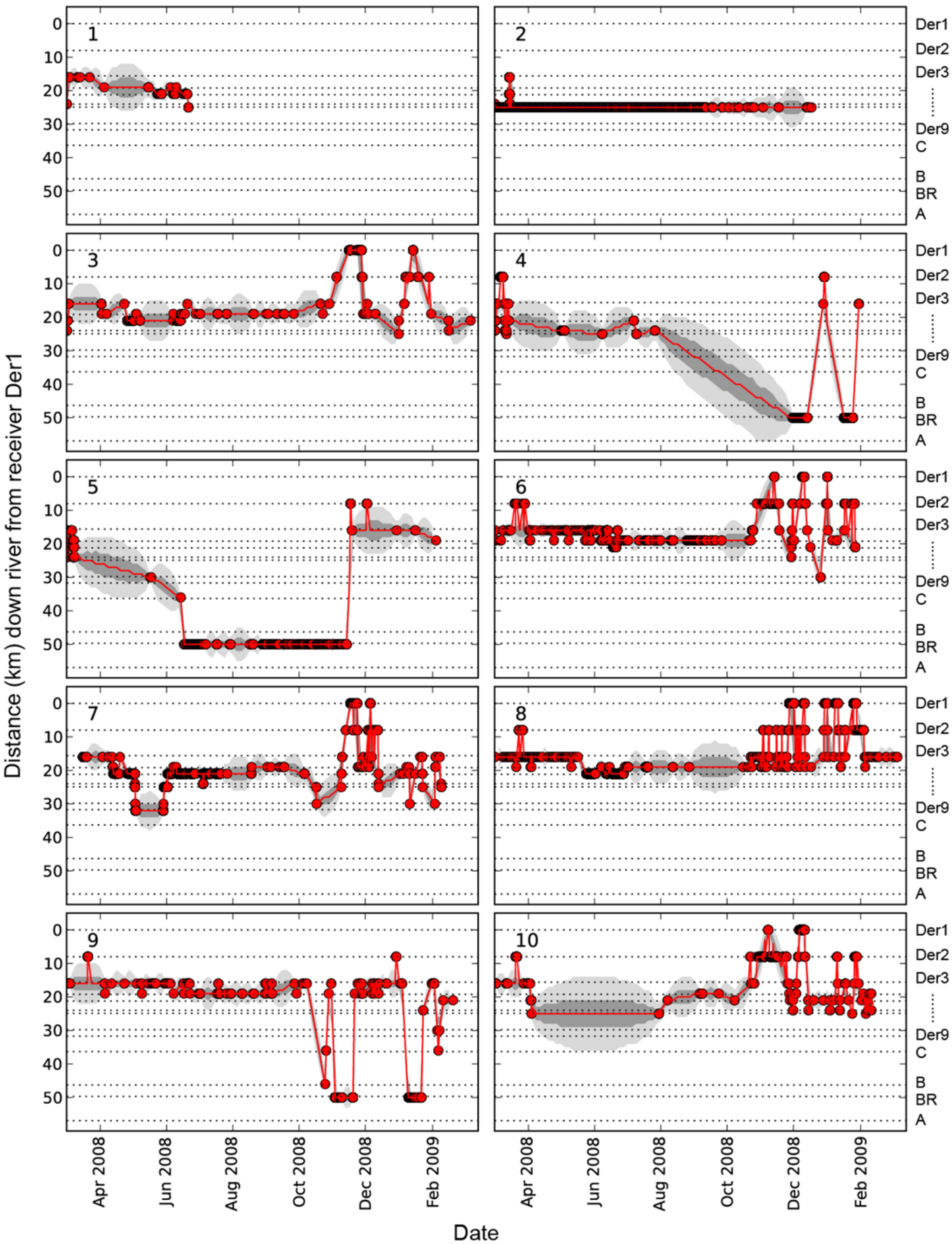


Fig. 20. State-space model outputs showing the predicted movement profiles of individual black bream (*Acanthopagrus butcheri*) tagged and released in the Derwent estuary. The red points indicate detections and the red line shows the median expected trajectory. The dark grey shading indicates the 50% probability range while the light grey shading indicates the 95% probability range.

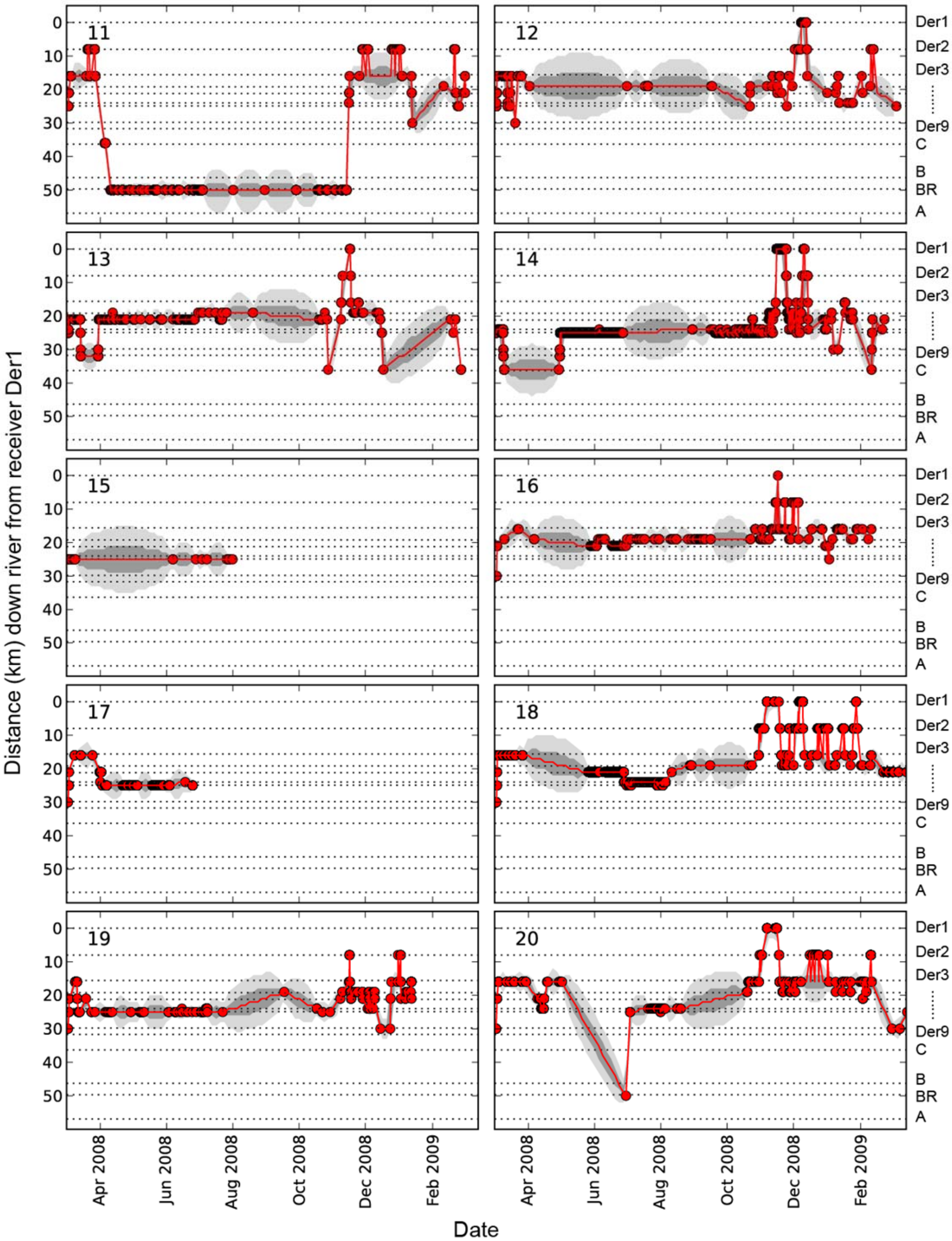


Fig. 20 continued. State-space model outputs showing the predicted movement profiles of individual black bream (*Acanthopagrus butcheri*) tagged and released in the Derwent estuary. The red points indicate detections and the red line shows the median expected trajectory. The dark grey shading indicates the 50% probability range while the light grey shading indicates the 95% probability range.

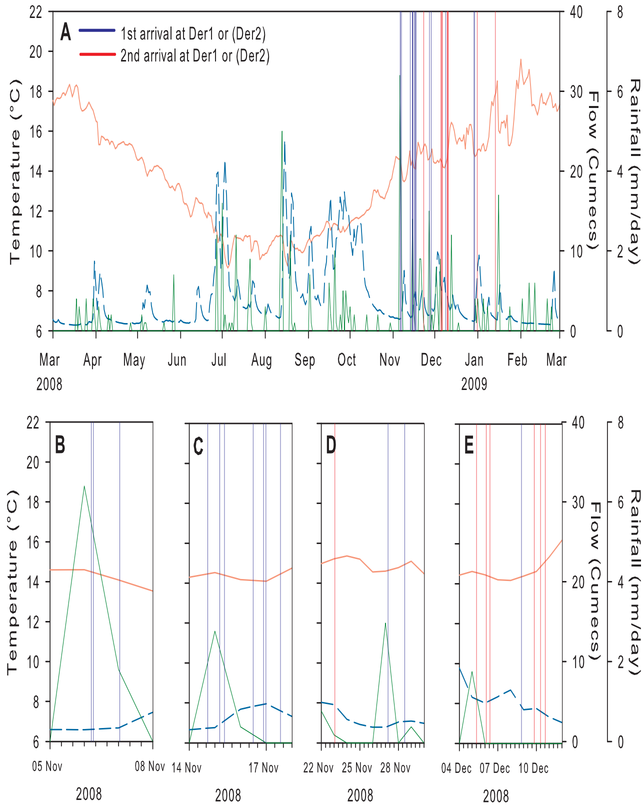


Fig. 21. The timing of the up-river seasonal migration of black bream. The solid green line indicates the daily rainfall as recorded at the Hobart Bureau of Meteorology weather station. The dashed blue line indicates the river flow through the Tyenna River (which flows into the Derwent estuary). The solid red line indicates the water temperature recorded in situ at receiver ‘Der7’. The vertical lines are described in the figure legend. Figure A shows the timing of the migration within a year while figure B-E focus on temporal periods of interest.

## Brown trout (*Salmo trutta*) – Derwent estuary

Twenty brown trout were caught and tagged in the upper Derwent estuary (Fish ID's: 201 – 220), ranging in length from 255 to 570 mm TL (mean ± SE = 417 ± 22 mm TL) (Table 8). The total number of detections ranged from 127 – 164,500 per individual, noting that individual 217 was not detected during the study, presumably due to tag failure (Table 8). The total detection period ranged from 9 days to 380 days.

Table 8. Summary of *Salmo trutta* tagged in the Derwent estuary, between 17/6/2008 – 3/9/2008. TP= Total detection period in days; DD = Total number of days detected; DI = detection index (DD/TP).

| Fish ID | TL (mm) | Release date | Nearest receiver at deployment | Total detections | No. of receivers | TP (d) | DD (d) | $R_I$ |
|---|---|---|---|---|---|---|---|---|
| 201 | 420 | 17-Jun-08 | Der6 | 530 | 7 | 189 | 24 | 0.13 |
| 202 | 300 | 17-Jun-08 | Der7 | 8252 | 3 | 102 | 99 | 0.97 |
| 203 | 255 | 17-Jun-08 | Der7 | 164500 | 2 | 381 | 381 | 1.00 |
| 204 | 320 | 17-Jun-08 | Der7 | 855 | 6 | 132 | 25 | 0.19 |
| 205 | 430 | 17-Jun-08 | Der7 | 146 | 7 | 244 | 35 | 0.14 |
| 206 | 285 | 17-Jun-08 | Der5 | 299 | 1 | 43 | 18 | 0.42 |
| 207 | 285 | 24-Jul-08 | Der6 | 4217 | 5 | 207 | 85 | 0.41 |
| 208 | 545 | 24-Jul-08 | Der6 | 5322 | 7 | 380 | 37 | 0.10 |
| 209 | 330 | 24-Jul-08 | Der5 | 355 | 3 | 42 | 6 | 0.14 |
| 210 | 520 | 24-Jul-08 | Der5 | 455 | 4 | 155 | 32 | 0.21 |
| 211 | 430 | 24-Jul-08 | Der5 | 593 | 6 | 364 | 16 | 0.04 |
| 212 | 540 | 24-Jul-08 | Der6 | 4353 | 8 | 67 | 28 | 0.42 |
| 213 | 335 | 24-Jul-08 | Der6 | 2469 | 6 | 132 | 95 | 0.72 |
| 214 | 435 | 24-Jul-08 | Der6 | 1279 | 6 | 380 | 38 | 0.10 |
| 215 | 550 | 03-Sep-08 | Der2 | 30855 | 3 | 256 | 105 | 0.41 |
| 216 | 405 | 03-Sep-08 | Der2 | 39811 | 4 | 99 | 75 | 0.76 |
| 217 | 515 | 03-Sep-08 | Der2 | 0 | 0 | 0 | 0 | 0.00 |
| 218 | 460 | 03-Sep-08 | Der2 | 7628 | 6 | 109 | 46 | 0.42 |
| 219 | 415 | 03-Sep-08 | Der2 | 14948 | 2 | 337 | 76 | 0.23 |
| 220 | 570 | 03-Sep-08 | Der2 | 127 | 3 | 9 | 7 | 0.78 |

Fourteen of the trout were tagged mid-estuary in the vicinity of 'Der5-7', the remaining six were tagged up-river in the vicinity of 'Der2'. Throughout the study the tagged brown trout were detected almost exclusively upstream of receiver Der8 (Fig. 29). One exception to this was an individual (Fish#212) that travelled out of the Derwent estuary and was last detected near Wedge Island in Norfolk Bay during September 2008 (Appendix 1). The overall number of detections decreased over summer till the following winter (Fig. 28 and Fig. 29).

The behaviour of brown trout varied depending on where they were tagged. Ten of the fourteen fish tagged in the mid-estuary displayed a consistent pattern of movement throughout the mid-estuary predominantly between receivers 5 and 7 (distance of approximately 3.8 km) during winter and into spring, although the detection rate of these fish varied significantly between individuals. Of the six fish tagged in the upper estuary four displayed residency behaviour with a much lower degree of movement. For the other two fish one transmitter failed and the other had very few detections. Bridcut and Giller (1993) reported two types of movement for brown trout. They found some trout to be stationary, where the fish exhibited a limited home range, and other fish in the population were mobile, where the fish continually moved and did not show any site fidelity. The former movement mode is referred to as the 'restricted movement paradigm' (RMP) and was often thought to be the behaviour of choice for riverine and stream based brown trout when not engaging in a spawning migration. In some reports the home range of trout is reported as being as short as several hundred meters (Gerking 1959; Burrell *et al.* 2000). Later studies however, challenged this notion and the concept of two behavioural patterns in the movement of brown trout was more widely accepted (Bridcut and Giller 1993; Gowan *et al.* 1994).

A possible explanation that accounts for both types of movement is based on energetics. It has been proposed that while the cost of establishing a territory is energetically demanding, once established, a territory has an energetic advantage over more mobile behaviour (Puckett and Dill 1985). Pert and Erman (1994) suggested that more transient fish had either not established a territory, or, had abandoned it due to changing habitat and that in variable flow conditions, a more transient behaviour may be more beneficial than strong site fidelity.

From late spring into summer 16 of the 20 tagged trout (noting that there is a high probability that Fish#203 died, based on behaviour) were undetected; 13 were not detected again for the duration of the study, eight being last detected not far from their home range, while the remainder moved quickly upriver and were last detected at receiver Der1 (Fig. 24). A further three individuals also moved quickly up to Der1 at the same time, these fish were, however, detected again later in the study (see below). Fish# 214 also embarked on this rapid upstream migration but not until April 2009.

It is believed that the upstream migration was related to spawning and the synchronicity of this event was the strongest of each of the three species monitored. Six out of nine brown trout that displayed the seasonal migration passed by 'Der1' within 6 days of each other and four within 48 hours (Fig. 25). From there they are assumed to move further up-river and beyond the scope of the receiver array. The recapture of a tagged individual in the Styx River, approximately 25 km upriver from Der1, would tend to validate this assumption. For the four fish that returned downstream the timing of their first detection back at Der1 was also well synchronised, almost exactly 6 months later, 3 of the 4 fish again passed by 'Der1' within 24 hours of each other (the other passed by approximately 2 weeks earlier) (Fig. 25). The fish involved in the seasonal migration represented the majority of the largest fish tagged (415 - 545 mm FL).

Given that brown trout do not spawn until winter it is possible that the fish began migrating upriver in mid-December as a form of thermo-regulation or chasing a particular prey item that is seasonally abundant. The optimal and preferred temperatures for brown trout vary between populations (Reynolds and Caterlin 1979; Olsen *et al.* 1988), water temperature above 19°C can adversely affect growth (Elliot 1975). At the time when the majority of fish moved upriver the water temperature had increased to approximately 16°C. There were no obvious environmental cues associated with rainfall and/or river flow at the time of the migration upriver other than a general relaxed river flow. The return event however, was preceded directly by a significant rainfall event (Fig. 25).

All four individuals that were detected moving back down river after the spawning event returned to their original home range. Such strong site fidelity has been observed for brown trout previously (Meyers *et al.* 1992; Garrett and Bennett 1995).

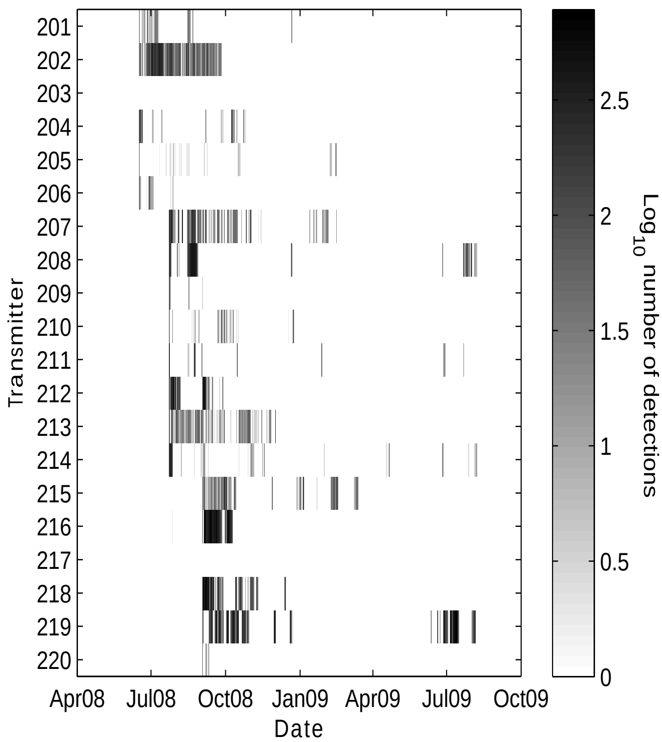


Fig. 22. Detection profiles of brown trout (*Salmo trutta*) throughout the duration of study.

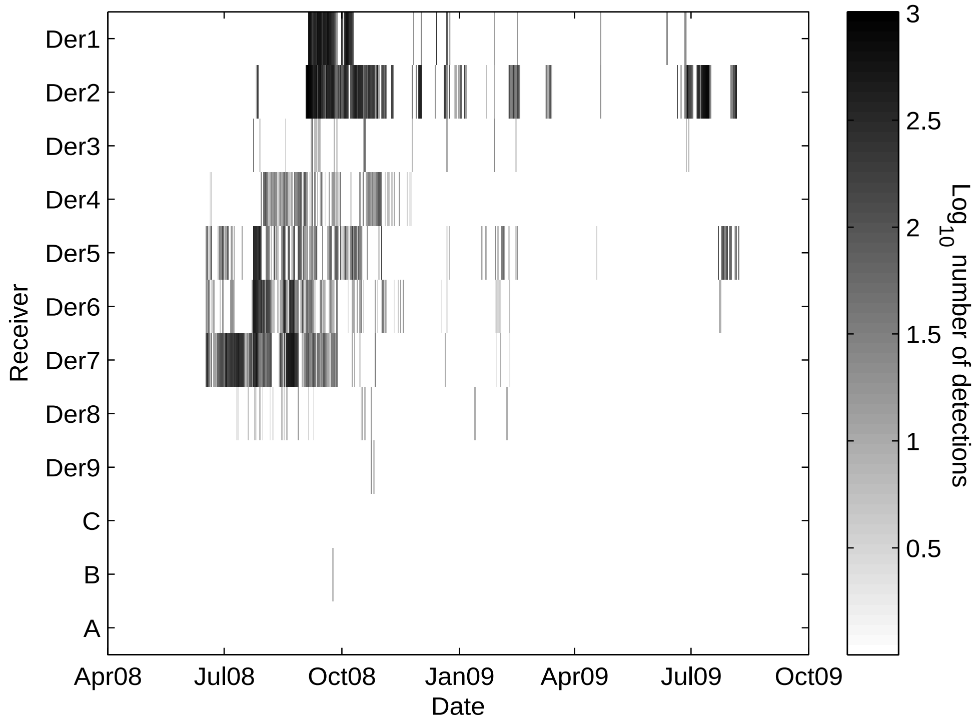


Fig. 23. Aggregated detection profile of the 20 brown trout (*Salmo trutta*) tagged in the Derwent estuary.

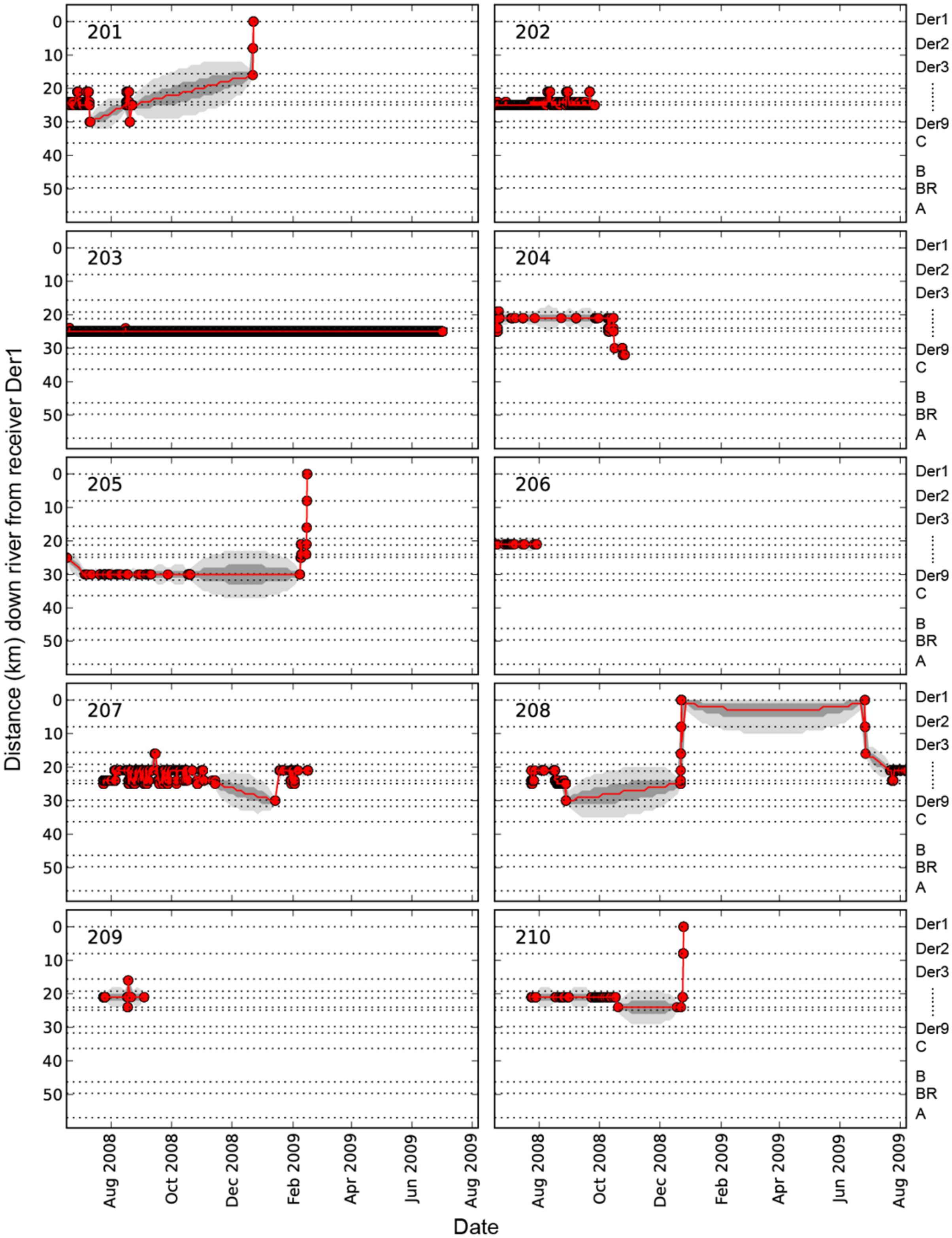


Fig. 24. State-space model outputs showing the predicted movement profiles of individual brown trout (*Salmo trutta*) tagged and released in the Derwent estuary. The red points indicate detections and the red line shows the median expected trajectory. The dark grey shading indicates the 50% probability range while the light grey shading indicates the 95% probability range.

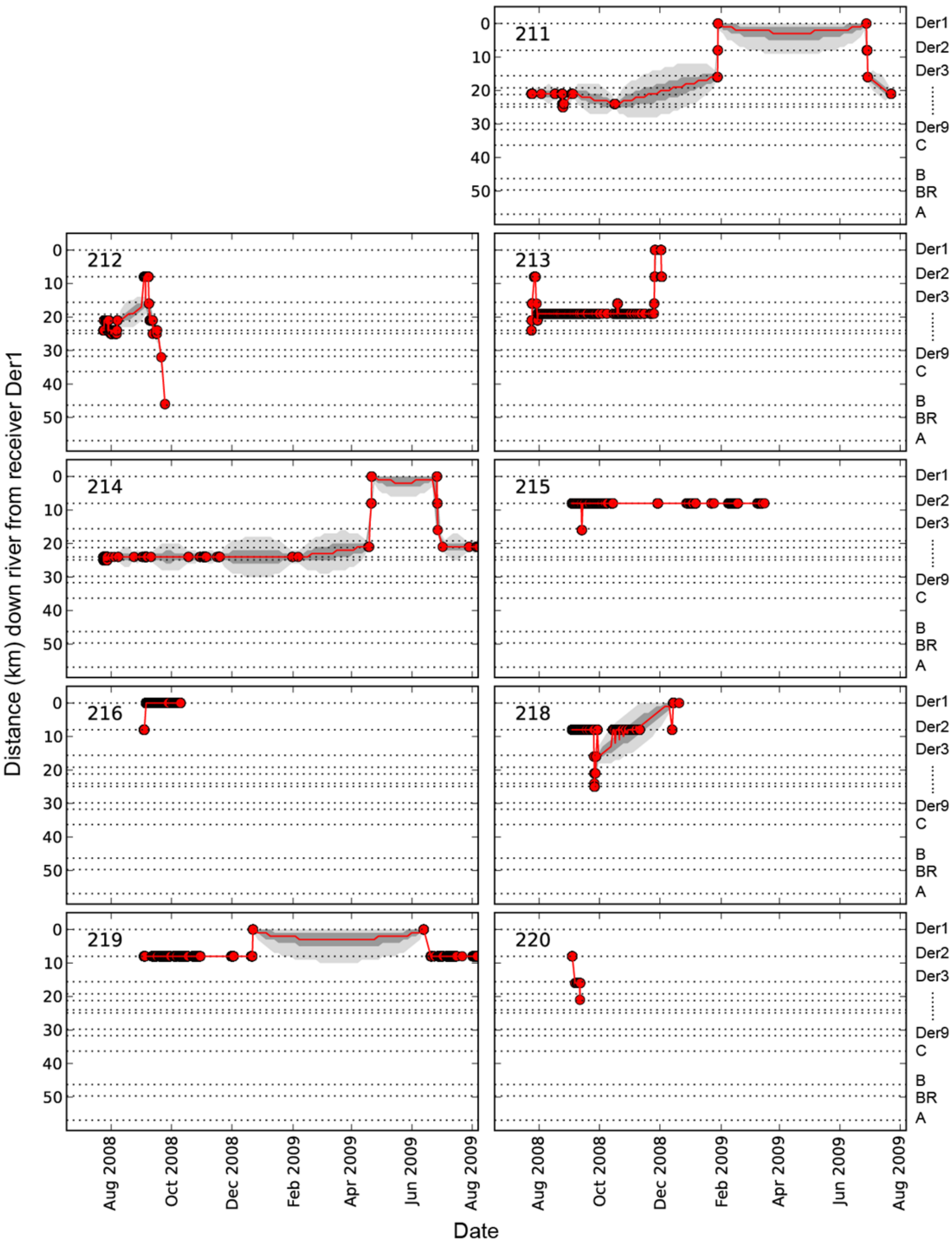


Fig. 24 continued. State-space model outputs showing the predicted movement profiles of individual brown trout (*Salmo trutta*) tagged and released in the Derwent estuary. The red points indicate detections and the red line shows the median expected trajectory. The dark grey shading indicates the 50% probability range while the light grey shading indicates the 95% probability range.

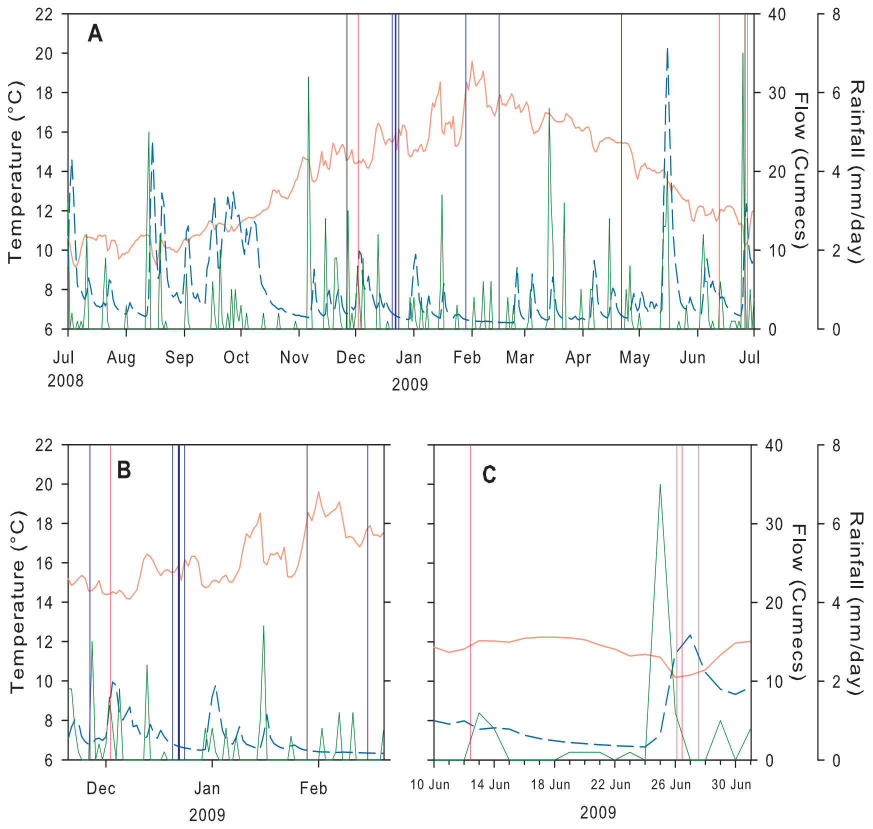


Fig. 25. The timing of the up-river seasonal migration of brown trout. The solid green line indicates the daily rainfall as recorded at the Hobart Bureau of Meteorology weather station. The dashed blue line indicates the river flow through the Tyenna River (which flows into the Derwent estuary). The solid red line indicates the water temperature recorded in situ at receiver 'Der7'. The vertical lines are described in the figure legend. Figure A shows the timing of the migration within a year while figure B-C focus on the temporal periods of interest.

## Acknowlegments

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## Appendix 1

### *Individual movement profiles*

**Sand flathead (*Platycephalus bassensis*) – Derwent estuary**

Individual 113 was released at receiver Der8 on the 27th February 2008. It was regularly detected at this receiver, and occasionally at Der9. It was last detected at Der8 on the 25th of October and was then detected at Der9 for nine days before moving to curtain C (C1) at the Tasman bridge on the 6th November where it was detected for two days. A single detection occurred at curtain B (B1) one day after it left curtain C, before arriving at curtain A at the mouth of the Derwent seven hours later, with the migration from the Tasman bridge to curtain A taking a total of one day and nine hours. The fish remained in the vicinity of curtain A for a total of 41 days, until the 18th December and was detected on receivers A2, A3 and A5 (mid-river) during this period. The return migration began between the 19th December (last detection at curtain A) and the 21st December (first detection at curtain B). A total of three detections were registered on receiver 'B2' over a ten minute period, noting that the fish has again been detected on the western shore of the river at curtain B, similar to its migration down river. The fish was next detected at the Tasman bridge (curtain C) four days later on the 25th December. On the 28th December the fish was detected at 'Der8' where it remained until its last detection on the 13th February 2009, the same receiver where it had displayed strong site attachment prior to migrating to the mouth of the Derwent river (Fig. 7).

Individual 114 was released at receiver Der8 on the 27th February 2008. It was detected at this receiver consistently until the 6th May when it moved to Der9. It was then not detected until the 23rd June when it was detected at Curtain C (C2). It was detected intermittently at this curtain (predominately C2 but occasional detections on C1) until the 10th October. It was next detected back at Der8 on the 22nd October. It was regularly detected at Der8 and occasionally at Der9 until its final detection at Der8 on the 6th January 2009 (Fig. 7).

Individual 115 was released at receiver Der8 on the 27th February 2008. It was detected at this receiver exclusively, with periods of intermittent and consistent detections up until the 15th May. It was then not detected again until the 4th September, again at Der8. It was again detected regularly at this receiver until the 23rd October when it had a single detection at Der9. It was not detected again until the 8th December when it was detected at Curtain C (C2) for a period of approximately 20 minutes before arriving back at Der8 on the 10th December where it was regularly detected until its final detection on the 19th December 2008 (Fig. 7).

Individual 116 was released at receiver Der8 on the 27th February 2008. It was detected at this receiver consistently until the 22nd May where it was detected intermittently between receivers Der9 and Der8 until the 1st September. From this date it was again detected exclusively with a high degree of regularity at receiver Der8 until its final detection on the 9th March 2009 (Fig. 7).

Individual 117 was released at receiver Der8 on the 27th February 2008. It was detected at this receiver regularly until the 14th November. It was not detected again until the 21st

February 2009 again at Der8, where it was detected regularly until its final detection on the 12th March 2009.

Individual 118 was released at receiver Der6 on the 27th February 2008. It was detected at this receiver intermittenlty until the 3rd April. On this date it was detected briefly at Der7. It was not detected again until the 22nd June, briefly at Der8 and then at Der9. It was regularly detected at Der9 until its final detection on the 23rd June 2008 (Fig. 7).

Individual 119 was released at receiver Der6 on the 27th February 2008. It was detected intermittenlty but exclusively at this receiver until the 3rd July. From this date it was detected intermittenly at receivers Der7 and Der6. On the 6th November it began migrating to curtain A. On the 7th November it was detected at curtain C (C1) for three minutes. It was not detected again until it arrived at curtain A (A3) 33 days later on the 10th December. It was last detected on curtain A (A3) three days later on the 13th December. It was next detected on curtain B (B4) once on the 19th December and was then detected eight days later at curtain C (C1 and C2). It remained in the vicinity of curtain C for two days before passing receiver 'Der8' on the 25th December and returning to Der7 on the 30th December. It was not detected again until its final detection on the 8th February 2009 again at Der7 (Fig. 7).

Individual 120 was released at receiver Der6 on the 27th February 2008. It was detected exclusively and regularly at this receiver until the 20th October when it had a single detection at Der7. On the 23rd October it was detected at Der8 before being detected at curtain C (C1 and C2) for four hours on the 28th October. It was not detected again until arriving at curtain A (A3 and A5) on the 11th November where it stayed for four days before returning to curtain C (C2 and C1) two days later on the 17th November. It was next detected 17 days later again on curtain C (C2) on the 5th December. On the 7th December it was detected at curtain B (B4), where it was again detected on the 10th of December. It was next detected seven hours later at curtain A (A5). Two days later on the 12th December it was detected back at curtain C (C2) for 20 minutes before arriving back at 'Der8' six hours later. Four days later on the 16th December it had returned to 'Der6' where it remained till its final detection on the 6th March 2009.

Individual 121 was released at receiver Der6 on the 27th February 2008. This individual displayed the most movement of all the sand flathead tagged in the Derwent estuary and was the only sand flathead tagged in the Derwent estuary that was detected outside of the estuary. It was detected consistently at 'Der6' during March 2008 before migrating down river to 'Der8' during April/May 2008. In mid-June 2008 it migrated down to the Tasman bridge (curtain C) and by mid-July it was detected at the mouth of the Derwent river at curtain A (A5). It was next detected for a four hour period on the 2nd of August at curtain H (H3) at the entrance of Frederick Henry Bay. It was detected back at 'curtain A' in late August 2008, again at receiver A5, before being detected back at the Derwent bridge four days later. By mid-September it was detected back at 'Der8' until mid-December 2008. This was also the only individual tagged in the Derwent that was detected migrating further up river than where it was released. In mid-December 2008 it was detected at 'Der5' and then 'Der3' in early January 2009, which is where it was last detected (Fig. 7).

Individual 122 was released at receiver Der6 on the 27th February 2008. It was detected consistently at Der6 during March before being detected intermittently at Der7 from April to July and briefly moved down to Der8 before being detected briefly back at Der7 where it recorded its final detection on the 28th July 2009 (Fig. 7).

**Sand flathead (*Platycephalus bassensis*) – Norfolk Bay**

Individual 103 had its last unresolved detection on the 25th March 2008 at the VRAP system. It was first detected at curtain G (G5) on the 3rd April 2008, on the 4th of April the fish had moved to curtain D (D1 and D2) and by the 6th it had moved to D3. From the 6th April to the 4th May it was not detected before again being detected at D3. It was then detected intermittently at D3 until its final detection on the 9th June 2008.

Individual 104 had its last unresolved detection on the 25th March 2008 at the VRAP system. The fish was not detected again until the 12th June 2008 at curtain G (G1). It was detected intermittently on this receiver until the 7th August 2008.

Individual 105 had its last resolved detection on the 2nd March 2008 at the VRAP system. The fish was next detected on the 8th March on curtain G (G1). Five days later it was detected at curtain D (D4). Seven days later on the 20th March it was again detected at curtain G (G5). It was briefly detected as unresolved detections on the VRAP system on the 28th March. It was not detected again until the 2nd July 2008 on curtain F (F2).

Individual 106 had its last unresolved detection on the 2nd April 2008 on the VRAP system. The fish was next detected for two days on the 5th and 6th of April on curtain G (G5 & G6). It was not detected again until the 12th of May where it was detected intermittently for two days on curtain D (D4 and D5).

Individual 107 had its last resolved detection on the 3rd March 2008 on the VRAP system. The fish was next detected on the 6th March at curtain G (G1 and G3) where it was detected for two days. It was next detected on the 2nd April back at G1 where it was detected consistently for four days. It was not detected again until the 3rd May again at G1 where it was detected intermittently until the 8th June 2008.

Individual 108 had its last unresolved detection on the 13th March 2008 on the VRAP system. The fish was next detected on the 16th March on curtain D (D2) where it was detected consistently (and occasionally on D1) until the 27th March. It was next detected again on D2 on the 9th July and again on the 1st August. It was next detected on curtain G (G4) on the 16th August and then 8th September on G2. On the 17th September it was detected back at curtain D (D2 and D3) where it was detected intermittently until the 23rd September. It was next detected on the 12th October back at curtain G (G4) and then on the 14th October it was back at curtain D (D2 and D3) where it was detected intermittently until the 17th October.

Individual 110 had its last unresolved detection on the 22nd April 2008 on the VRAP system. The fish was not detected again until the 10th and 11th of October on curtain G (G1).

Individual 112 had its last unresolved detection on the VRAP system on the 22nd April 2008. The fish was next detected on the 23rd April on curtain G. From this date until the 26th April it had single detections on G1 then G3 before intermittent detections on G4.

Individual 123 was first detected on the 12th March 2008 at curtain D (D1) for two days. The fish was next detected on the 2nd April at curtain G (G1) where it was detected intermittently until the 30th July. From the 30th July the fish moved from G1 to G2 on the 1st August it had moved to G3 where it was detected intermittently until the 5th August. It was next detected on the 10th August back at curtain D (D2) where it was detected intermittently until the 13th August. It was next detected back at curtain G (G3) on the 5th September. On the 7th September it was again detected back at curtain D (D2) where it was detected intermittently until the 19th September. It was then briefly detected at curtain G (G3) on the 27th of September. It again moved back to curtain D (D2) on the 5th October where it was detected intermittently until the 13th October. On the 17th October it was again back at curtain G (G3 and G4) where it remained until the 19th before again moving to curtain D (D2) where it was detected intermittently until the 24th October. It was next detected on the 25th October at Eaglehawk Neck (L2 and L1) where it was detected intermittently until the 30th October. It was finally detected back at curtain D (D2 and D4) on the 28th and 29th of November.

Individual 126 was detected on the 12th and 13th of March 2008. During this two day period it was detected intermittently on curtain G (G5 and G6) and curtain D (D1 and D2).

Individual 127 was first detected on the 12th March 2008 on curtain G (G5 and G6) and curtain D (D1 and D2). On the 13th it was detected on curtain G (G3 and G4). The fish was next detected on the 17th March on curtain F (F2 and F3).

Individual 129 was first detected on the 12th March on curtain D (D1 and D2) and curtain G (G5). The fish was next detected on the 9th April at curtain D (D1 and D2) on the 10th of April it was again detected on curtain D (D1) and curtain G (G5). It was next detected on the 12th April at curtain G (G6). On the 13th April it moved to G7 where it was detected consistently until the 13th of May when it moved back to G6 where it stayed until the 14th of May. Ninety minutes after its last detection at G6 it had a single detection on curtain F (F3), then 12 hours later it was detected on curtain E (E3). Ten days later on the 25th June it was detected at the entrance to Frederick Henry Bay at curtain H (H3) on the 26th June it was still detected at curtain H (H3 and H5). On the 4th of July it was again detected at curtain H (H3) and again on the 22nd July it was again detected at curtain H (H3). It was next detected again at curtain H (H5) on the 26th August. On the 30th August it had moved back to curtain E (E4). On the 6th September 2008 it had its final detections back at curtain F (F3).

Individuals 124, 125, 128, 130 and 131 all had the same detection profile. They were first detected on the 12th March 2008 on curtain D (D1) where they were detected consistently until the 27th May 2008. On this date the receiver battery was replaced and unfortunately the replacement receiver failed. Based on the inactivity of these five individuals it is possible that these fish did not survive the surgical tagging. However sand flathead tagged in the Derwent estuary displayed very limited movement with small home ranges.

**Black bream (*Acanthopagrus butcheri*)**

After release in the vicinity of receiver Der6 on the 1st March 2008 individual 1 moved quickly up river (within one day) to receiver Der3 where it was detected until late March. It was next detected intermittently on receivers Der4 and Der5 from mid-May to late June. It was last detected on the 21st June 2008 at receiver Der7 (Fig. 20).

After being released in the vicinity of Der6 on the 1st March 2008, individual 2 remained around Cadbury point, and was regularly detected on receiver Der7. On the 14th March this fish made a brief but rapid migration upriver to receiver Der3 before returning to Der7 on the 15th March where it remained resident with regular detections through to mid-September and then intermittent detections through to mid-December 2008. Its final detection was on receiver Der7 on the 17th December 2008 (Fig. 20).

After release at Der6 on the 1st March 2008, individual 3 moved quickly up to Der3 (within one day) where it was detected intermittently to early April. On the 25th April it was next detected at receiver Der4 and Der5 where it was intermittently detected through to late September. During October it migrated back up river, where it was first detected on Der2 on the 4th November and then at Der1 on the 15th November. It was detected at Der1 for a period of approximately two weeks. In mid-December it was detected briefly back down at Der4, before again being detected back at Der1 on the 13th and 14th of January 2009. By February 2009 it was again residing in the vicinity of Der4 and Der5, where it recorded its last detection on the 8th March 2009 (Fig. 20).

Individual 4 was released in the vicinity of Der6 on the 1st March 2008 from here it moved upriver as far as Der2 (arriving on the 6th March). On the 10th March it briefly migrated back down river as far as receiver Der7. However by the 12th March it had again returned upriver to receiver Der3 but then on the same day was detected back at receiver Der5. In early May it was detected at Der6 for four consecutive days. From June to August it was detected intermittently on Der5, Der6 and Der7. From August to early December it was not detected. It was next detected at Browns River on the 8th December 2008 where it quickly moved up river to BR3 where it remained for five days. On the 12th December it moved quickly to the mouth of Browns River. It was next detected on a single day back up at Der2 in late December before again returning to Browns River and promptly migrating up to BR3 on the 16th January 2009, where it remained for a further nine days until again quickly moving back down Browns River. By the 30th January 2009 it was detected back in the Derwent estuary at Der3, where it was only detected on the one day before not being heard from again (Fig. 20).

After being released in the vicinity of receiver Der6 on the 1st March 2008, individual 5 quickly migrated up to receiver Der3 where it remained for approximately 5 days before a day of significant activity where it migrated between receivers Der3, Der4, Der5 and Der6. It was not detected for a period of approximately two and a half months from mid-March to mid-May, when it was briefly detected at receiver Der8. It was next detected on the 15th June with a single detection at curtain C (C1) at the Tasman bridge, before its next detection in Browns River on the 17th June. During June and into early July the individual moved repeatedly up and down Browns River, but focused more time in the mid and lower reaches of the river. From early July to late August it was detected intermittently and BR3 and BR2. From September through to mid-November it was detected almost exclusively at BR3 with the exception of two migrations down to BR1 in mid-October and early November. Then on the 17th November it was detected back in the Derwent estuary at Der2 where it was detected intermittently for approximately two weeks. In mid-January it was detected briefly at Der3, before its final detection on the 4th February 2009 at receiver Der4 (Fig. 20).

Individual 6 was released at receiver Der3 on the 1st March 2008. After release it briefly moved to receiver Der4 in the Jordan River before returning to receiver Der3. In mid-March it moved to the vicinity of Der2 where it remained for approximately two weeks before again returning to receiver Der3 where it remained to mid-May. From this point until July it was detected between both receivers Der3 and Der4. From July it was detected exclusively at receiver Der4 in the Jordan River until October. On the 1st of November it was detected at receiver Der2 migrating up to Der1 where it was detected on the 13th of November. From this point until early January 2009 it moved down river - generally to the vicinity of Der4 or Der5 but as far as Der8 on one occasion, before returning to Der1 on two occasions. From this point it was detected intermittently on receivers Der2 down to Der5, where it had its final detection on the 27th January 2009 (Fig. 20).

Individual 7 was released at Der3 on the 1st March 2008, but was not detected until the 16th March (at receiver Der3). The fish was intermittently detected here until mid-April. It then moved down to Der5 where it was detected until early May. On the 2nd May the individual began moving down river over a period of two days to receiver Der9. It was not detected again until the 28th May when it was again detected at receiver Der9 before migrating up river over a period of five days, returning to receiver Der5. From early June to late July it was detected regularly on receiver Der5. From August to October it was detected intermittently on receivers Der4 and Der5 before brief detections as far down river as receiver Der8. On the 13th November it was detected for the first time on receiver Der2 whilst migrating to Der1, where it arrived on the 17th November and remained for seven days. From here it moved back down to receiver Der3 before returning briefly to Der1 on the 5th December. From mid-December to mid-February 2009 the individual was detected intermittently between receivers Der3 and Der8 with the greatest number of detections at Der5. It had its final detection on the 9th February 2009 at receiver Der7 (Fig. 20).

Individual 8 was released at receiver Der3 on the 1st March 2008 where it was detected with reasonable consistency between March and late May. From this period to early July it was detected consistently at receiver Der5 with the exception of two days where it was detected at receiver Der4. From July to early September it was detected intermittently at receiver Der4. During October it was detected regularly in the vicinity of receivers Der3 and Der4 and on the 3rd November it was first detected at receiver Der2 whilst migrating to Der1, where it arrived on the 27th November and remained for four days. From this point in time the individual made a further four migrations back down to receiver Der3, and on some occasions Der4, before returning to Der1 for short periods. By early February it returned to receiver Der3 where it was detected intermittently until its final detection on the 6th March 2009 (Fig. 20).

Individual 9 was released at receiver Der3 on the 1st March 2008. It was detected intermittently from March to early October in the vicinity of receiver Der3 and Der4, with a short visit to receiver Der2 on the 20th March. On the 25th October it was next detected at curtain B (B1) before being detected later that day at curtain C (C1). It was next detected on the 28th October at receiver Der4 and then the 30th October at receiver Der3. It was next detected on the 3rd November at Browns River (BR1) where it proceeded quickly up river to BR3 where it was detected until the 19th November before it moved back down river. Five days later on the 24th November it was detected back up the Derwent estuary at receiver Der3. It remained in the vicinity of Der3 until early January. On the 9th of January the individual was detected back in Browns river where again it moved up to BR3 within a day where it stayed for nine days until the 18th January 2009. From this point it was detected back at receiver Der3 on the 31st January on the 5th February it moved briefly down to curtain C (C1) before returning to receiver Der5 on the 10th February and then finally detected at receiver Der5 on the 19th February 2009 (Fig. 20).

Individual 10 was released at receiver Der3 on the 1st March. It was detected at this receiver intermittently throughout March and briefly detected at receiver Der2 on two consecutive days from the 20th March. In early April it was detected at receiver Der5 on one day but was then not detected again until late July. From here it was intermittently detected between receiver Der4 and Der7 until mid-October. On the 30th October it was detected at Der2 where it remained until moving for a single day to Der1 on the 7th November. It then moved back to Der2 where it remained until late December from where it briefly migrated down river to Der6 before returning to Der1 on the 6th December for a period of six days. It was detected shortly after around receivers Der5 and Der6 until early January where it spent a month in the vicinity of receivers Der2 and Der3 before being finally detected back at Der6 on the 10th February 2009 (Fig. 20).

Individual 11 was released at Der7 on the 2nd March 2008. From here it migrated up to receiver Der3 over a period of several days. It was intermittently detected on Der2 and Der3 from mid to late March. It was next detected at curtain C (C1) on the 4th April, before arriving at Browns River (BR1) on the 10th April. From here it moved up to BR3 over two days. It was detected intermittently but exclusively on BR3 for the next two and a half months before a brief migration to BR1. From this point to mid-October it was only detected occasionally although these detections were again exclusively at BR3. During late-October and early November the individual made two migrations the length of the receiver span in Browns River last detected at BR1 on the 13th November. It was next detected three days later on the 16th November back in the Derwent estuary at receiver Der5. On the 28th November it was detected at receiver Der2, where it was detected intermittently through December. During January the individual was only detected intermittently but was detected migrating down to receiver Der8 and back up to Der2. During February it was again detected intermittently but moved from receiver Der5 down to Der3 and back to Der5 where it was finally detected on the 3rd March 2009 (Fig. 20).

Individual 12 was released at receiver Der7 on the 2nd March 2008. From here it quickly moved up to receiver Der3 where it remained for approximately two weeks before a migration lasting approximately one week back down to Der7 before returning quickly to Der3 on the 16th March. From April to early November there were very few detections of this individual although they were on Der4 and Der5. In early November this individual moved to receiver Der3 and then on to Der2 before arriving at Der1 on the 8th December where it remained until the 12th December. After this date the individual was again only detected intermittently on receivers Der5 and then on Der3 and Der2 during late January and early February. It was finally detected (single detection) on the 5th March 2009 at receiver Der7 (Fig. 20).

Individual 13 was released at receiver Der7 on the 2nd March 2008. From here it moved up to Der5 within a 24 hour period. It was detected here until mid-March before a rapid migration down river to Der9. It was then not detected for approximately two weeks until being re-detected on Der9 on the 30th March before again migrating rapidly this time upriver back to Der5. It remained in the vicinity of Der5 from April through to July. From this point it was intermittently detected on Der4 and Der5 until a single of detection on curtain C (C1) on the 27th October. It was next detected on the 8th November back at receiver Der5 before migrating up to Der2 on the 10th November before being detected at Der1 on the 16th of November where it was detected for two days before returning to Der4. On the 17th December the individual rapidly migrated down to the curtain C (C2). It was next detected on the 17th February at receiver Der5. It was finally detected on the 27th February 2009 back down at curtain C (C2) (Fig. 20).

Individual 14 was released at receiver Der7 on the 2nd March 2008. From here it moved to receiver Der6 for a period of approximately one week before rapidly migrating down to curtain C (C2) on the 9th March. It was not detected again until the 29th April where it was again detected on curtain C (C2). It next rapidly migrated back to receiver Der7 where it remained for the next two months. From early July it was again not detected for a period of approximately two months before being detected consistently around Der6 and Der7. On the 8th November it began migrating up to Der1 where it arrived on the 15th November and remained for 10 days. From here it migrated back to the vicinity of Der5 to Der7 where it spent time in late November and early December before again briefly returning to Der1 on the 10th December for two days. After this it migrated back to the vicinity of Der5 to Der8. On the 11th February the fish was next detected at curtain C (C2). Approximately 15 hours later it was detected at Der5 where it was intermittently detected until the 22nd February 2009 when its last detection was recorded (Fig. 20).

Individual 15 was released at receiver Der7 on the 2nd March 2008. This individual had the lowest number of detections of any Bream tagged and was only detected intermittently between March and late July 2008 but exclusively at Der7. Based on the relative activity of other Bream we propose there is a high probability that this individual did not survive post-release (Fig. 20).

Individual 16 was released at receiver Der8 on the 2nd March 2008. Within two days it had moved up river to Der5. It was then detected intermittently from early March to mid-April on Der3 to Der5. From this point to late May it was not detected. From late May to late

September it was regularly detected on either Der4 or Der5. For a month from late September to late October it was not detected before again being detected at Der4. It migrated up river arriving at Der2 on the 14th November. It stayed in the region of Der2 and Der3 until mid-December. From this point it was detected intermittently between Der3 and Der5, until its final detection on the 10th February 2009 at receiver Der3 (Fig. 20).

Individual 17 was released at receiver Der8 on the 2nd March 2008. Within a week it had migrated up to Der3 where it remained for approximately three weeks before migrating back down to Der7. It was detected at Der7 with periods of regular and intermittent detections until its final detection on the 25th June 2008 (Fig. 20).

Individual 18 was released at receiver Der8 on the 2nd March 2008. From here it quickly moved up river (< two days) to Der3 where it remained for the rest of the month of March. From this point it was not detected again until 26th May when it was regularly detected on Der5. In late June it moved down river to Der6 where again it was detected regularly, with three brief periods of detection at Der7, until early August. From early August to late October it was intermittently detected on Der4 before migrating up river arriving at Der2 on the 1st November before moving briefly to Der1 on the 6th November. It was again detected at Der1 on the 13th November before moving down to Der4 and then back up to Der1 arriving on the 6th December where it was detected for the next three days. From this point it spent time between receivers Der2 and Der4 until again returning for a single day to Der1 on the 27th January. After leaving Der1 it was detected at Der4 in late January and was then regularly detected on Der5 from mid-February to mid-March. Its final detection was at receiver Der5 on the 15th March 2009 (Fig. 20).

Individual 19 was released at receiver Der8 on the 2nd March 2008. Within one week it had moved up to Der3 before quickly moving back down to Der7. It was then detected intermittently at Der7 until early July before two days of detection at Der6. From this point it was not detected again until mid-October when it was again detected on receivers Der6 and Der7. In early November it migrated up river, detected at Der2 for a single day on the 16th November before spending time moving regularly between Der4 and Der6. Through the middle of December it was detected twice briefly at Der8 before again moving up river and spending a period of approximately one month moving regularly between Der2 and Der5 until its final detection on the 12th January 2009 at receiver Der3 (Fig. 20).

Individual 20 was released at receiver Der8 on the 2nd March 2008. From here it moved up to Der3 within three days. It was then detected intermittently on Der3 until mid-April. It was next detected on Der5 and Der6 for a period of a week from the 9th April. From this point it moved back to Der3 and was detected intermittently through till late April. After this it was not detected again until July where it was detected at Der7 on a couple of brief occasions and more regularly at Der6 until late August. It was then again not detected until mid-October where it was detected moving up river arriving at Der2 on the 31st October before moving on to Der1 arriving on the 6th November. It was then not heard from until the 14th November when again it was detected on Der1 and this is where it stayed for the next two days. From this point the individual spent time moving between receivers Der2 and Der5 until moving down to Der8 where it was briefly detected twice, once in late February and its final detection on the 16th March 2009 (Fig. 20).

**Brown trout (*Salmo trutta*)**

Individual 201 was released at Der6 on the 17th June 2008. It was detected moving regularly between Der6 and Der7 from mid-June to mid-July, with a brief (<1 day) period of detection at Der5 on the 27th June. On the 11th July it was briefly detected at Der8. It was not detected again until the 16th August when it was detected back at Der6 and Der7. It remained in this area for approximately one day, it also ventured briefly to Der8 during this period. From the 22nd August it was not detected again until the 22nd of December when it was detected moving from Der3 to Der1 over a 24hr period. It was last detected at Der1 on this date (Fig. 24).

Individual 202 was released at Der7 on the 17th June 2008. It was regularly detected over the next month at this receiver, there were also two brief detections on Der6. In late July the detections at Der6 became more regular. From early August to late September the individual was predominately detected in the vicinity of Der6 and Der7 although it was also detected on three separate occasions further up river at Der5. It was last detected on 26th September 2008 at Der7 (Fig. 24).

Individual 203 was released at Der7 on the 17th June 2008. Apart from a brief detection on Der6 five days after tagging the individual was detected exclusively and with high regularity on Der7 for over a year until the 2nd of July 2009. Based on the comparative behaviour of the other tagged brown trout we propose that this individual did not survive post-release (Fig. 24).

Individual 204 was released at Der7 on the 17th June 2008. For four days post release the individual was detected regularly in the vicinity of Der6 and Der7. It then moved to the vicinity of Der4 and Der5 for two days. From the 20th June it was intermittently detected on Der5 to mid-October. From the 9th October the individual appeared more active moving regularly between Der5 and Der7. On the 16th October it moved to Der8 from where it was intermittently detected moving between Der8 and Der9 until it was finally detected on the 26th of October 2008 at Der9 (Fig. 24).

Individual 205 was released at Der7 on the 17th June 2008 where it was detected for less than a 24 hour period. It was not detected again until the 5th July where it was detected intermittently but exclusive at Der8 until the 19th October. It was then not detected for a period of approximately three months before it was detected on the 7th December moving up river from Der8 to Der1 over the period of eight days. Through this migration it was detected on all receivers from Der8 to Der1 with the exception of Der4 in the Jordan River. After being detected at Der1 on the 15th of February for a period of less than 24 hours it was not detected again (Fig. 24).

Individual 206 was released at Der5 on the 17th June 2008. It was subsequently detected exclusively at this receiver with periods of regular and intermittent detections. Its final detection was at Der5 on the 29th July 2008 (Fig. 24).

Individual 207 was released at Der6 on the 24th July 2008. From its release date to early November it was detected regularly moving between Der5 and Der7. In mid-September it was briefly detected on Der3. From 14th November untill mid-January it was not detected. It was next detected on the 13th January briefly at Der8. Then from the 18th January it resumed moving regularly between Der5 and Der7 until its final detection on the 15th February at Der5 (Fig. 24).

Individual 208 was released at Der6 on the 24th July 2008. Within 24 hours of being released it was detected on Der6 before briefly being detected on Der7 and then moving up to Der5. It was detected on Der5 intermittently between late July and mid-August before a two week period of regular detections on Der6 and Der7. On the 28th August it was briefly detected on Der8 and was then not detected again until mid-December. On the 21st December it moved from Der7 to Der1 over a period of two days being detected on all receivers except Der6 and Der4 which is in the Jordan River. After being detected at Der1 on the 22nd of December it was not detected again until the 26th of June 2009 where it was detected moving down through Der1, Der2 and Der3. It was next detected on the 22nd July 2009 at Der5 where it was regularly detected until its final detection on the 7th August 2009 (Fig. 24).

Individual 209 was released at Der5 on the 24th July 2008. It was detected at this receiver for two days and was then not detected again until 17th August where it was detected moving from Der6 to Der3 over a period of less than 24 hours. It was then finally detected on 3rd September at Der5 (Fig. 24).

Individual 210 was released at Der5 on the 24th July 2008. It was detected intermittently on this receiver through to 1th October. It was then not heard from until 18th December where it was detected at Der5. On the 24th December it migrated up river from Der5 to Der1 within a 24 hour period. While migrating up river it was detected on all receivers with the exception of Der3 and Der4 in the Jordan River. It had its final detection at Der1 on the 25th of December 2008 (Fig. 24).This fish was subsequently recaptured by a recreational angler four days later in the Styx River, indicating that I moved significantly further up river than the acoustic array.

Individual 211 was released at Der5 on the 24th July 2008. It was detected here intermittently until 23rd August when it moved down to Der7 and back up to Der5 in a 24 hour period. It was detected intermittently on the 2nd and 3rd of September at Der5. It was then not detected until the 16th October when it was detected at Der6. It was then not detected again until the 28th of January 2009 when it was detected migrating up river through Der3 to Der1 within a 24 hour period. On the 27th June 2009 it was detected migrating back down river through receivers Der1 to Der3 over a three day period. It was then not detected until its final detections on the 22nd July 2009 at Der5 (Fig. 24).

Individual 212 was released at Der6 on the 24th July 2008. For a period of approximately two weeks it moved regularly through the region between Der5 and Der7. From the 7th August it was not detected until the 3rd September when it was detected at Der2. It was intermittently detected at Der2 until the 8th September when it moved down river being detected at Der3 and Der5. It remained in the region of Der5 until the 11th September. On the 15th and 16th of

September it was detected at Der6 and Der7. On the 20th September it had a single detection at Der9. Then on the 24th September it was detected at Curtain B (B5) for a period of 20 minutes (Fig. 24). It was then finally detected at Curtain H (H11) on the eastern side of Wedge Island in Frederick Henry bay on the 28th of September for a period of five and a half hours.

Individual 213 was released at Der6 on the 24th July 2008. Two days after release it moved up to Der2, detected on Der5 and Der3. On the 30th July it had moved back down to Der4 where it was detected with reasonable regularity until the 25th November when it migrated up to Der2 and then onto Der1 where it was detected on the 26th of November. It was not detected again until the 2nd December when again it was detected on Der1 before moving on the same day to Der2 where it had its final detection (Fig. 24).

Individual 214 was released at Der6 on the 24th July 2009. For five days after release it was detected regularly on both Der6 and Der7. Then from this point it was detected intermittently but exclusively on Der6 until the 6th of February 2009. It was next detected on the 17th April at Der5 from where it moved to Der2 and then Der1 on the 21st April. It was then not detected again until the 26th June as it moved down past Der1 to Der3 over a 24 hour period. It was then not detected until the 28th July at Der5, where it was finally detected on the 7th August 2009 (Fig. 24).

Individual 215 was released at Der2 on the 3rd September 2008. It remained here for the majority of time for which it was detected, initially with regularity and then from mid-October the detections became more intermittent. In mid-September the individual was detected for two days at Der3. Given the distance between Der2 and Der3 we interpret this as evidence that the fish did not suffer post-release mortality at least in the first two weeks post-release (Fig. 24).

Individual 216 was released at Der2 on the 3rd September 2008. Within two days of release it was detected at Der1 where it was detected regularly for approximately six weeks before a final detection on the 10th October 2008 (Fig. 24).

The tag implanted in individual 217 failed to report.

Individual 218 was released at Der2 on the 3rd September 2008. It was detected regularly on this receiver until the 25th of September when it migrated down river to Der7 and back up to Der2 over a two day period. It was then again intermittently detected at Der2 until the 20th of December when it recorded its final detections on Der1 (Fig. 24).

Individual 219 was released at Der2 on the 3rd September 2008. It was detected regularly on this receiver up until early November when the detections became irregular. On the 22nd December it was detected at Der1. It was not detected again until the 12th June 2009 at Der1. Several days later it was again located at Der2 where it was detected regularly until its last detection on the 5th August 2009 at this receiver (Fig. 24).

Individual 220 was released at Der2 on the 3rd September 2008. It was detected at this receiver for a 24 hour period and then for a period of approximately one week at Der3where it had its final detection on the 11th September 2008 (Fig. 24).

## Appendix 2

# 1 Appendix: Acoustic model

There are two common approaches in the design and deployment of acoustic receivers to passively track animal movement depending on the study objectives. One option is to deploy the receivers as a series of gates or curtains to monitor movement across a particular path (Hobday, 2003; Welch et al., 2002; Pecl et al., 2006). The second commonly applied option is to deploy an array of receivers in either a systematic or non-systematic pattern to examine movement within a particular domain (Heupel et al., 2004; Yeiser et al., 2008; Sakabe and Lyle, 2010). The data used here was collected by a 'gate' system, in this context the problem becomes one dimensional, which simplifies the description of our model, however this methodology can be applied to all forms of deployment design.

## 1.1 Base Model

Space is treated as one-dimensional to simplify the presented equations. This simplification is particularly appropriate for our data set which considers a narrow estuary, however extending the approach to two-dimensions is straightforward.

The model divides space into $n_r$ discrete regions and time into discrete steps of length $\delta$. In this discrete setting, movement can be modelled by a transition matrix, $M$, of size $n_r \times n_r$. The value in the $i$th row and $j$th column gives the probability of an individual located in area $i$ moving to area $j$ in a single time step. If the matrix is raised to the $t$th power, the $i$th row and $j$th column of the resulting matrix, $M^t$, give the probability of an individual located in area $i$ moving to area $j$ in $t$ time steps along any possible path. A sufficiently small time step, $\delta$, is required to ensure that an individual will have a negligible probability of moving multiple spatial steps in a single time step.

We begin with a simple base model where movement is completely random in direction and magnitude – both spatially and temporally. Defining $\alpha$ as the probability of moving to each adjacent area in one time step we obtain the following transition matrix:

$$M_{i,j} = \begin{cases} 1-\alpha & \text{if } i = j \text{ and } i > 1 \text{ and } i < n_r \\ 1-2\alpha & \text{if } i = j \text{ and } (i = 1 \text{ or } i = n_r) \\ \alpha & \text{if } |i-j| = 1 \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

The first two lines specify the probability of remaining in the same area, this is higher at the boundary of the model as there is only one direction in which an individual can move. The third line gives the probability of moving to an adjacent region and the last line simply states that all other movements are not possible. In the two-dimensional case there will be more non-zero entries which describe the movement between an area and all its neighbours.

$M$ defines a simple movement model that is independent of the acoustic tracking system. In an ideal situation the acoustic tracking system would detect an individual each time it enters an area containing a receiver. This is clearly not the case and the probability of detecting an individual is poorly understood, consequently it is necessary to use a simple model of the acoustic tracking system. The acoustic model can be represented by a vector, $\vec{d}$, of length $n_r$ in which the $i$th value gives the probability of an individual in area $i$ being detected by the acoustic array in a single time step. For ease of notation we also introduce $\hat{\vec{d}}$ as the probability of not being detected ($\hat{d}_i = 1 - d_i$). An appropriate choice of discrete regions will ensure that a receiver can only detect an individual if it is located in the same area as the receiver. Formally we have:

$$\vec{d}_i = \begin{cases} \gamma_k & \text{if receiver } k \text{ is in area } i \\ 0 & \text{if no receiver is in area } i, \end{cases} \tag{2}$$

where $\gamma_k$ are the detection probabilities of the individual transmitters.

Using $\hat{\vec{d}}$ and $M$, we introduce a matrix, $N$, where $N_{i,j}$ gives the probability of moving from $i$ to $j$ and not being detected at either position:

$$N_{i,j} = M_{i,j}\sqrt{\hat{d}_i \hat{d}_j}. \tag{3}$$

Taking the $t$th power of this matrix (i.e. $N^t$) results in a matrix where $[N^t]_{i,j}$ (the element in the $i$th row and $j$th column) gives the probability of a individual moving from position $i$ to position $j$ over $t$ time steps without being detected.

We assume that movement is not auto-correlated – each set of sequential detections is independent. With this assumption each detection-re-detection event can be considered a single observation, $o$, consisting of an initial location $a_o$, a final location, $b_o$ and a time between these, $t_o$. Using our notation the probability of a single observation under specific model parameters ($p(o|\text{model})$) becomes:

$$p(o|\text{model}) = d_{a_o}[N^t]_{a_o,b_o} d_{b_o}/\hat{d}_{b_o},$$

here, $d_{a_o}$ accounts for the initial detection and $d_{b_o}/\hat{d}_{b_o}$ for the final detection ($N$ assumes that no detection occurred at all time steps, including the last one, dividing by $\hat{d}_{b_o}$ accounts for this). Note that $N^t$ contains the probability of moving from any area to any other without being detected via any path over $t$ time steps. Hence once this has been calculated for a given duration, $t$, and a given model, it can be used to find the probability of all observed movements that took $t$ time steps. The computational importance of this is considered later in this paper.

The product of $p(o|\text{model})$ over all observations provides the probability of obtaining the observed data from our model:

$$p(\text{data}|\text{model}) = \sum_o p(o|\text{model}) \tag{4}$$

$$= \sum_o \left[ d_{a_o}[N^t]_{a_o,b_o} d_{b_o}/\hat{d}_{b_o} \right]. \tag{5}$$

### 1.2 Habitat model

In most studies species and/or individual animals will have preferred habitat and locations within the acoustic network, in this section we present a simple variation of the movement matrix that takes this into account. We denote the central location of the habitat by $\omega$ and the distance from area $i$ to this point by $s(i,\omega)$. Note that $\omega$ could be specific to a species or an individual. To model preferred movement towards $\omega$ a movement bias is introduced such that an animal in area $i$ has a probability of $\alpha_{i,near}$ of moving towards $\omega$ and a probability of $\alpha_{i,far}$ of moving further away from $\omega$. A possible implementation of this bias is given by:

$$\alpha_{i,near} = 2\frac{\alpha}{1+\exp^{-\kappa s(i,\omega)}} \tag{6}$$

$$\alpha_{i,far} = 2\alpha - \alpha_{near}, \tag{7}$$

where $\kappa$ determines the strength of the movement bias. This functional form ensures that the movement probabilities are equal when the individual is at $\omega$ and that this rapidly shifts towards biased movement back towards $\omega$. Other functional forms of greater appropriateness to the target species can readily be used.

Using the biased movement parameters the one dimensional movement matrix becomes:

$$M_{i,j} = \begin{cases} 1-2\alpha & \text{if } i=j \\ \alpha_{i,near} & \text{if } |i-j|=1 \text{ and j is closer to } \omega \\ \alpha_{i,far} & \text{if } |i-j|=1 \text{ and j is further from } \omega \\ 0 & \text{otherwise.} \end{cases} \tag{8}$$

### 1.3 Model Fitting

Equation 5 gives the probability of obtaining the observed data from a given model with a specific set of parameters. Two widely used approaches for obtaining parameter values are maximum likelihood and Bayesian MCMC simulation. Maximum likelihood methods aim to identify the parameter values that maximise equation 5. Maximum likelihood approaches are a specific instance of a Bayesian approaches are a generalisation of maximum Here we utilise a Bayesian approach (for an introduction to Bayesian methodology see **?**). The key benefits of a Bayesian approach in this context are threefold: (i) existing information about the model parameters (eg. movement rates) can be incorporated in the form of priors, (ii) the posterior (fitted) probability distributions for each model parameter that can have an arbitrary form (eg. bimodal) and (iii) even relatively complex models can be fitted relatively easily using a Markov Chain Monte Carlo approach (for an introduction to MCMC see **?**).

Core to this approach is Bayes' Law which states that the probability of a model given some data or observations is proportional to the probability of obtaining that data from the model times the prior probability that was placed on the model:

$$p(\text{model}|\text{data}) \propto p(\text{data}|\text{model})p(\text{model}).$$

Equation 5 gives $p(\text{data}|\text{model})$ for our developed models which can be readily calculated for a given set of parameters. The prior probability of the model, $p(\text{model})$, encapsulates pre-existing knowledge about the phenomenon being observed; for example, in our context a low probability may be placed on a model with biologically unrealistic movement rates. The models considered here contain unknown continuous parameters, it is important to recall that the model referred to in equation 1.3 encapsulates both the model structure and a particular set of parameter values. The utility of Bayes' Law is that if the quantities on the right hand side can be calculated, models (and their parameter values) can be sampled from the multidimensional distribution of $p(\text{model}|\text{data})$, using well established Markov Chain Monte Carlo (MCMC) approaches. In practice, this is most readily achieved by implementing the specified model in a software package designed for sampling such as PyMC for Python (Patil et al., 2010), or OpenBUGS (**?**).

When fitting a model using MCMC, the initial samples will not be true samples of the posterior distribution. Care must be taken to discard a sufficient number of initial samples. Most MCMC software packages provide some functionality that provides an indication of convergence on the posterior distribution. Here we used two approaches, firstly for each parameter there should be no discernible trend if the sampled values are plotted against the iteration number. More formally, there are statistical tests available to test for convergence. One such test is Geweke's convergence diagnostic (Geweke, 1992) which compares the mean of the first part of the chain with the last part. If the means differ significantly the chain has not converged and more of the initial samples must be discarded (and possibly the MCMC sampling process may need to be run longer to obtain more samples).

### 1.3.1 Computational efficiency

For many acoustic datasets, a naïve implementation of the framework presented here may result in a problem of such computational complexity that it is either problematic or even insoluble by any computer. Careful consideration is required to keep the computational complexity under control. Here we present some suggestions, their individual importance will depend on the problem to which the methodology is being applied.

*Reducing the number of parameters* The number of parameters defines the dimensionality of the parameter space which must be explored by the sampler. Reducing this will decrease the required burn-in period and the number of iterations required to sample the parameter space adequately.

*Coarser discretisation* Reducing the number of areas will decrease the size of the transition matrix, thereby reducing the time taken to calculate the matrix powers. Increasing the temporal step will decrease the number and magnitude of the matrix powers required, thereby also reducing the time required to calculate these.

*Optimising the code* The optimised code for this case study uses 2% of the processing time of an initial naïve implementation. In the final optimised code, two lines of code use 75% of the processing power: 40% is spent calculating powers of the transition matrix and 35% calculating the logs of the required probabilities and summing these. There is no clear way to decrease the time taken by these two processes further without applying changes to the model such as have been suggested here.

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