Inland Waters and Catchment Ecology

SOUTH AUSTRALIAN RESEARCH & DEVELOPMENT INSTITUTE
PIRSA

Lamprey migration in the lower River Murray in association with Commonwealth environmental water delivery in 2019

C M Bice, B P Zampatti, Q Ye and G C Giatas

SARDI Publication No. F2020/000203-01
SARDI Research Report Series No. 1061

SARDI Aquatics Sciences
PO Box 120 Henley Beach SA 5022

June 2020

SOUTH AUSTRALIA

Government of South Australia
Primary Industries and Regions SA

SARDI
SOUTH AUSTRALIAN RESEARCH AND DEVELOPMENT INSTITUTE

Lamprey migration in the lower River Murray in association with Commonwealth environmental water delivery in 2019

C M Bice, B P Zampatti, Q Ye and G C Giatas

SARDI Publication No. F2020/000203-01
SARDI Research Report Series No. 1061

June 2020

This publication may be cited as:
Bice, C M[1], Zampatti, B P[2], Ye, Q[1] and Giatas, G C[1] (2020). Lamprey migration in the lower River Murray in association with Commonwealth environmental water delivery in 2019. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2020/000203-01. SARDI Research Report Series No. 1061, 25 pp.

[1]SARDI Aquatic Sciences, 2 Hamra Ave, West Beach SA 5024
[2]CSIRO Land and Water, Waite Campus, Urrbrae Rd, Urrbrae SA 5064

South Australian Research and Development Institute
SARDI Aquatic Sciences
2 Hamra Avenue
West Beach SA 5024
Telephone: (08) 8207 5400
Facsimile: (08) 8207 5415
http://www.pir.sa.gov.au/research

SARDI Publication No. F2020/000203-01
SARDI Research Report Series No. 1061

Author(s):	C. M. Bice, B. P. Zampatti, Q. Ye and G. C. Giatas
Reviewer(s):	Jason Nicol (SARDI) and Anthony Moore (CEWO)
Approved by:	A/Prof T. Ward, Science Leader, Marine Ecosystems
Signed:	
Date:	19 June 2020
Distribution:	SAASC Library, Parliamentary Library, State Library and National Library
Circulation:	Public Domain

TABLE OF CONTENTS

LIST OF FIGURES

ACKNOWLEDGEMENTS

This project was jointly funded by the Commonwealth Environmental Water Office (CEWO) as part of the Lower Murray Selected Area *Monitoring Evaluation and Research* Project (contingency monitoring), and the South Australian Department of Environment and Water (DEW) under the Murray–Darling Basin Authority's *The Living Murray* program. Thank you to Anthony Moore (CEWO), and Adrienne Rumbelow and Kirsty Wedge (DEW) for facilitating funding and managing this project, and for ongoing support of aquatic ecosystem research in the Lower Murray. Thanks also to several SARDI (Arron Strawbridge, Ian Magraith and David Short) and SA Water staff (Michael Shelton, Ray Maynard, Bryce Buchannan, Greg Bald and Dave Bishop) for assistance with fieldwork. All sampling was conducted under an exemption of section 115 of the *Fisheries Management Act 2007*. Thanks to Jason Nicol and Mike Steer (SARDI), Adrienne Rumbelow and Courtney Glover (DEW), and Anthony Moore, Lucy Carlile and Michelle Campbell (CEWO) for reviewing this report.

EXECUTIVE SUMMARY

Pouched lamprey (*Geotria australis*) and short-headed lamprey (*Mordacia mordax*) are the only anadromous fishes native to the Murray–Darling Basin (MDB). Historically, lamprey were common in the River Murray with spawning migrations potentially extending up to 2,000 km upstream, but they are now rarely encountered, suggesting barriers to migration and flow regulation have impacted these species. In the past decade, however, a focus on restoring connectivity (e.g. fishway construction) and ecologically relevant components of flow regimes, through the delivery of environmental water, have increased opportunities for migration that may aid recovery of lamprey in the MDB. A key objective of the delivery of Commonwealth environmental water in the southern MDB is to improve end-of-system flow and connectivity through the Murray Barrages and Murray Mouth to support fish movement and expanded distributions. The migratory life histories of pouched lamprey and short-headed lamprey make these species well suited to demonstrate the achievement of these outcomes.

The objective of the current project was to assess the abundance of adult lamprey at the Murray Barrages in 2019, and to use passive integrated transponder (PIT) telemetry to investigate subsequent upstream spawning migrations in the MDB. Specifically, the project aimed to:

1. Assess the abundance of migrating lamprey at multiple fishways on the Murray Barrages in winter–spring 2019, and implant individuals with PIT tags;
2. Compare abundance from winter–spring 2019 with previous years of targeted lamprey sampling in 2015–2018;
3. Interrogate PIT telemetry data from fishways along the River Murray to describe the spatio-temporal characteristics of migration, including extent, timing and rate, as well as interaction with fishways; and
4. Evaluate the contribution of Commonwealth environmental water to connectivity, and the abundance and migration of lamprey at the Murray Barrages in 2019.

From May–December 2019, discharge in the lower River Murray at the South Australian border (QSA) was characterised by flows <8,000 $ML.d^{-1}$, punctuated by conspicuous within-channel flow pulses that peaked at ~10,000 and ~15,000 $ML.d^{-1}$ in August and October, respectively. These pulse flows comprised a substantial proportion (66–70%) of Commonwealth environmental water. During sampling (9 July–4 October), discharge from the Murray Barrages ranged from 0–19,166 $ML.d^{-1}$ (mean = 3,236 $ML.d^{-1}$). All water released from the Murray Barrages over this period, including water to operate fishways, was Commonwealth environmental water.

Totals of 45 pouched lamprey (43 PIT tagged) and 16 short-headed lamprey (15 PIT tagged) were captured from fishways during sampling at the Murray Barrages in winter–spring 2019. The abundance of pouched lamprey was moderate to high relative to preceding years with targeted lamprey monitoring, whilst short-headed lamprey was sampled in greatest abundance since 2006. Both species were captured in greatest numbers from fishways on Goolwa and Mundoo barrages. Of PIT tagged individuals, 44% of pouched lamprey were subsequently detected on one or more fishway PIT reader system along the River Murray, with estimated extent of migration ranging from 274–726 km (Lock 1–8). Migration rates varied among individuals and reaches, but were at times rapid (up to 37 $km.d^{-1}$). Just one PIT tagged short-headed lamprey (7%) was detected after release; nonetheless, this individual was detected passing eight main channel fishways, and was last detected exiting the Lock 10 fishway (825 km MTD, middle thread distance). This represents the first known tracking data on the upstream spawning migration of this species.

In winter–spring 2019, releases of Commonwealth environmental water from the Murray Barrages facilitated connectivity between freshwater, estuarine and marine environments, and subsequently resulted in beneficial migration outcomes for lamprey. This included high abundances of both pouched and short-headed lamprey passing the Murray Barrages, and ultimately, migrations that continued for 100's of kilometres upstream.

Data collected in this and allied monitoring projects may be used to inform future environmental water delivery and infrastructure management in the southern MDB. This includes:

- Greatest abundances of migrating pouched lamprey occurred during years of moderate winter–spring barrage discharge (mean daily discharge ≥2,500 $ML.d^{-1}$) with short periods of peak discharge of ~15,000 $ML.d^{-1}$. Thus, the hydrographs delivered in 2015, 2017 and 2019 likely represent appropriate templates for future environmental water planning.
- Importantly, each of these years comprised multi-site watering events and were supported by return flows from delivery of Commonwealth environmental water in the Goulburn River. The delivery of Commonwealth environmental water is critical to maintaining barrage discharge and connectivity during years of low flow; and
- Lamprey primarily pass upstream via fishways on Goolwa, Mundoo and Tauwitchere barrages. Abundances tend to be greater at the Goolwa and Mundoo fishways, likely due to their proximity to the Murray Mouth and greater influence of discharge from these barrages/fishways on downstream salinities. As such, during times of limited water

availability, winter–spring releases that specifically target lamprey migration could be prioritised to Goolwa and Mundoo barrages to maximise attraction.

The general life histories of pouched lamprey and short-headed lamprey in the MDB remain poorly understood. Specific knowledge gaps for future research to better support management include:

- Assessing migration through the Tauwitchere trapezoidal and Goolwa small vertical-slot fishways. These fishways are yet to be assessed for passage efficiency for the whole migratory fish community, or regarding to lamprey migration;
- Identifying localities (i.e. streams and specific river reaches) that provide spawning and nursery habitats for pouched lamprey and short-headed lamprey in the MDB;
- Investigating the influence of flow magnitude, source and longitudinal integrity of flows on lamprey upstream riverine migrations, including ultimate destination;
- Investigating the downstream migrations of macrophthalmia (sub-adults) with regard to timing, distance, cues and interaction with potential barriers; and
- Investigating the general ecology and threats to the marine life phase of both species.

Keywords: diadromous, *Geotria*, *Mordacia*, fishway, passive integrated transponder

1. INTRODUCTION

1.1. Background

In the Murray–Darling Basin (MDB), Australia's longest and most economically important river system (ABS/ABARES/BRS 2009), pouched lamprey (*Geotria australis*) and short-headed lamprey (*Mordacia mordax*) are the only native anadromous fishes. Both species exhibit a life history characteristic of all anadromous lamprey, including a parasitic marine phase, and upstream adult migrations to freshwater spawning and nursery habitats (Moser et al. 2015). Physico-chemical (e.g. salinity) and olfactory cues of riverine origin (e.g. pheromones from juveniles) are believed important in stimulating and guiding upstream migration (Meckley et al. 2014, Bett and Hinch 2016). Juveniles (ammocoetes) reside in freshwater for several years before metamorphosing into sub-adults (macropthalmia) and migrating downstream to marine habitats. This life history renders lamprey susceptible to human modification of river systems (Jonsson et al. 1999); specifically, flow regulating structures (e.g. dams, weirs, barrages) may delay or obstruct upstream migration, whilst alteration to flow regimes (e.g. reduced magnitude, altered timing) may disrupt migratory cues and degrade freshwater habitat quality (Quinn and Adams 1996). Anecdotally, lamprey in the MDB were once considered common with migrations extending up to 2000 km upstream, but they are now rarely encountered, potentially due to the impacts of flow regulation and barriers to migration (Potter and Strahan 1968, Maitland et al. 2015, Bice et al. 2019a).

Increased focus on restoring connectivity and aspects of natural flow regimes under the *Basin Plan* (2012) have the potential to support rehabilitation of lamprey populations in the MDB. From 2001–2013, an ambitious program was undertaken to reinstate connectivity and opportunities for fish migration along 2000 km of the main-stem of the River Murray from the sea to Hume Dam, through the construction of fishways on the Murray Barrages and 13 main channel weirs (Barrett and Mallen-Cooper 2006). This program has potentially restored access to upstream spawning habitats from which lamprey were largely excluded since the construction of the main channel weirs in the 1920s. In addition, under the *Basin Plan*, a considerable volume of Commonwealth environmental water has now been recovered, with a large proportion reaching the lower River Murray (typically >500 $GL.yr^{-1}$), in conjunction with other environmental water (e.g. water held under *The Living Murray* (TLM) Initiative). Over the last five years, Commonwealth environmental water has contributed to baseflows and freshes in the lower River Murray, particularly as winter and spring–early summer flow pulses, mainly via return flows from upstream watering events (Ye et al. 2020). Direct orders of environmental water to the South Australian border also occurred for specific purposes, often during summer–autumn, primarily to maintain flow from the barrages and connectivity between the Lower Lakes and Coorong.

Environmental water delivery to the South Australian lower River Murray is guided by the objectives of the *South Australian River Murray Long-Term Environmental Watering Plan* (LTWP) (DEWNR 2015), the *Basin-wide environmental watering strategy* (BWS) (MDBA 2014) and Commonwealth Environmental Water Office (CEWO) *expected outcomes*. Explicit objectives and outcomes of these planning documents include improving end-of-system flow and connectivity through the Murray Barrages and Murray Mouth to support fish movement and expand distributions. The migratory life histories of pouched lamprey and short-headed lamprey, and reliance on end-of-system flow and connectivity, make these species well suited to demonstrate the achievement of these outcomes.

Lamprey migration at the Murray Barrages represents an ecological target for the Lower Lakes, Coorong and Murray Mouth Icon Site under TLM and within the South Australian LTWP. Specific monitoring, targeting presumed migration seasons and monitoring subsequent upstream migration, has occurred sporadically since 2013 (Bice et al. 2019a and b). This monitoring has provided important information on the life history of pouched lamprey and the influence of water management, including: demonstrating the importance of discharge from the Murray Barrages and associated fishways to stimulate and facilitate ingress to the MDB; identifying peak periods of freshwater entry; and demonstrating successful use of main channel weir fishways and contemporary upstream migrations of 100s of kilometres. Indeed, Commonwealth environmental water is now commonly delivered and discharged from the Murray Barrages in winter–spring to achieve these outcomes.

1.2. Objectives

The objective of the current project was to assess the abundance of adult lamprey at the Murray Barrages in 2019, and to use passive integrated transponder (PIT) telemetry to investigate subsequent upstream spawning migrations in the MDB. Specifically, the project aimed to:

1. Assess the abundance of migrating lamprey at multiple fishways on the Murray Barrages in winter–spring 2019, and implant individuals with PIT tags;
2. Compare abundance from winter–spring 2019 with previous years of targeted lamprey sampling in 2015–2018;

3. Interrogate PIT telemetry data from fishways along the River Murray to describe the spatio-temporal characteristics of migration, including extent, timing and rate, as well as interaction with fishways; and
4. Evaluate the contribution of Commonwealth environmental water to connectivity, and the abundance and migration of lamprey at the Murray Barrages in 2019.

2. METHOD

2.1. Study area

The MDB covers an area of >1 million km^2. The southern part of the basin, comprising the River Murray and its tributaries, typically contributes the bulk of flow, and is extensively regulated by dams and weirs as well as the Murray Barrages near the river mouth (Walker and Thoms 1993) (Figure 1). The lower River Murray is unique due to a lack of major tributaries downstream of the Darling River junction (a distance of approximately 760 km). The River Murray discharges into Lake Alexandrina (>750 km^2), before reaching the Coorong estuary and Southern Ocean. Several small tributaries (Finniss River, Currency Creek, Bremer River, Angas River) discharge into Lake Alexandrina, which is disconnected from the river estuary (the Coorong) by the Murray Barrages. Overall end-of-system discharge has been greatly reduced due to river regulation and water abstraction with mean discharge (4,723 GL.yr^{-1}) now approximately a third of natural (12,233 GL.yr^{-1}).

All main channel weirs on the River Murray, and the Murray Barrages, have been retrofitted with fishways to facilitate upstream fish movement (Baumgartner et al. 2014). At the Murray Barrages, a total of 11 fishways had been constructed at the time of the study, comprising varying vertical-slot and rock ramp designs (Bice et al. 2017). The main channel River Murray weirs also comprise varying fishway designs: 1) 1:32 slope vertical-slot fishways (Locks 1 and 7–10); 2) 1:23 slope vertical-slot fishways paired with a fishlock (Locks 2–6), 3) a 1:18 slope vertical-slot fishway (Lock 26); or 4) Denil fishways (Lock 11 and 15).

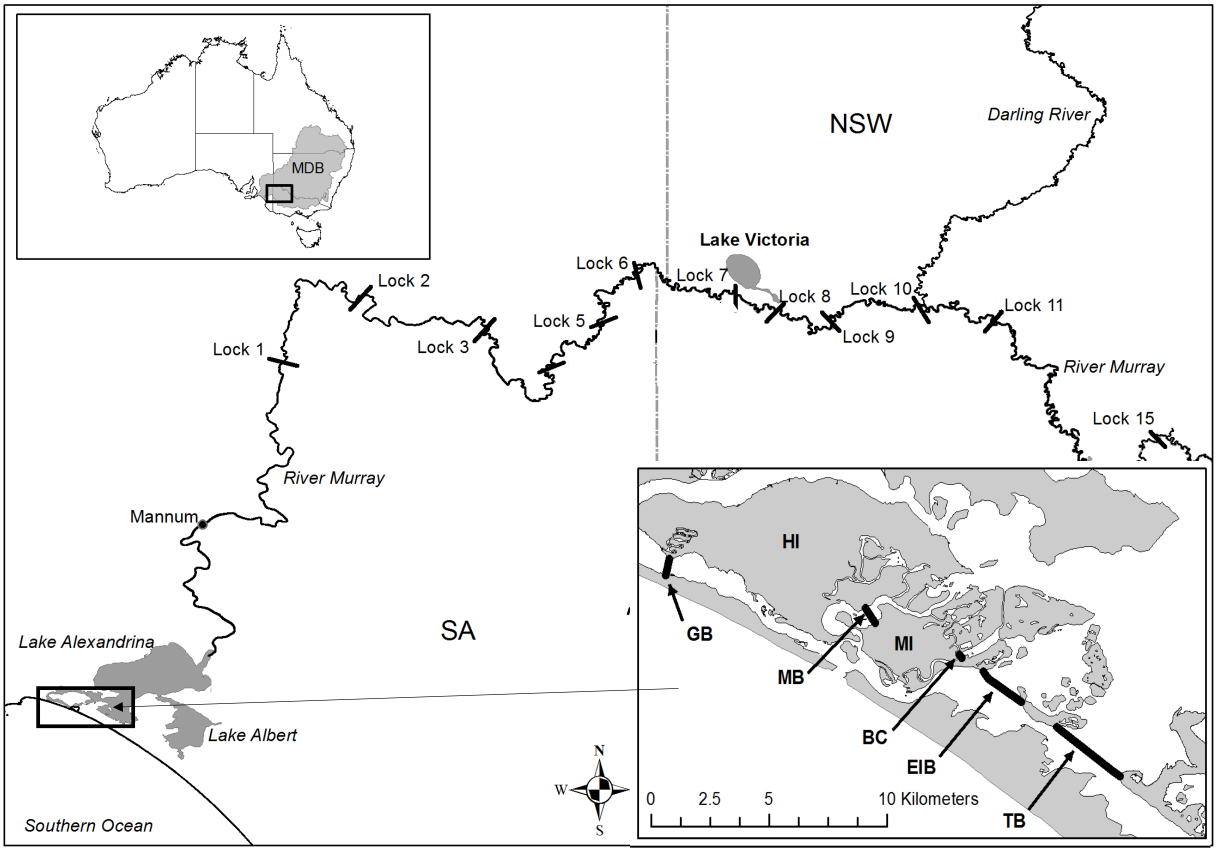

Figure 1. Map of the River Murray from Lock 15 (Euston) downstream to the Murray Mouth showing the positioning of lock and weir structures. Inset map presents the Murray Barrages, namely Goolwa (GB), Mundoo (MB), Boundary Creek (BC), Ewe Island (EIB) and Tauwitchere (TB), as well as Hindmarsh (HI) and Mundoo islands (MI).

2.1. Lamprey sampling and tagging

Pouched lamprey and short-headed lamprey were sampled from fishways on the Murray Barrages using fishway traps (Bice et al. 2017, Bice et al. 2019a). Targeted sampling for lamprey was conducted from 9 July–4 October 2019 (*n* = 11–20 sampling events per fishway) at seven vertical-slot fishways on Goolwa, Mundoo, Boundary Creek, Ewe Island and Tauwitchere barrages (Figure 1 and Table 1). Additional sampling occurred on 21–25 October and 18–22 November at five fishways on Goolwa and Tauwitchere barrages, and the Hunters creek causeway, as part of TLM condition/intervention monitoring, and data on lamprey captures from these events are also reported. During each sampling event, traps were set overnight, and deployed and retrieved using a crane truck. Upon retrieval, all trapped fish were removed and placed into aerated holding tanks. Lamprey were sorted from the catch for processing and all remaining fish released upstream.

Table 1. Details of fishway sampling sites at the Murray Barrages, including number of sampling events during targeted lamprey sampling and TLM condition monitoring.

Name	Abbrev.	Barrage	Latitude	Longitude	Targeted lamprey sampling nights	TLM sampling events
Tauwitchere large vertical-slot	TVS	Tauwitchere	35°35’09.35’’S	139°00’30.58’’E	20	4
Tauwitchere small vertical-slot	TSVS	Tauwitchere	35°35’23.44’’S	139°00’56.23’’E	14	6
Tauwitchere rock ramp	TRR	Tauwitchere	35°35’23.60’’S	139°00’56.30’’E	-	2
Tauwitchere trapezoidal	TT	Tauwitchere	35°35’08.74’’S	139°00’29.34’’E	-	-
Goolwa vertical-slot	GVS1	Goolwa	35°31’34.44’’S	138°48’31.12’’E	20	6
Goolwa vertical-slot 2	GVS2	Goolwa	35°31’26.48’’S	138°48’32.89’’E	20	-
Goolwa small vertical-slot	GSVS	Goolwa	35°31’37.65’’S	138°48’30.57’’E	-	-
Hunters Creek vertical-slot	Hunters	Hunters Creek causeway	35°32’07.08’’S	138°53’07.48’’E	-	6
Mundoo dual vertical-slot	MDVS	Mundoo	35°32’27.59’’S	138°54’16.97’’E	19	-
Ewe Island dual vertical-slot	EIDVS	Ewe Island	35°33’48.25’’S	138°57’51.63’’E	11	-
Boundary Creek small vertical-slot	BCVS	Boundary Creek	35°33’13.05’’S	138°56’48.42’’E	20	-

Following capture, lamprey were anaesthetised individually using a 0.05 ml.L^{-1} solution of AQUI-S (AQUI-S, Lower Hutt, New Zealand) in a 20L dosing tank. Anaesthesia times were typically <10 min. Individuals were then measured for total length (TL, mm) and weight (g), and placed in an elongated v-shaped support. A short (~5 mm) incision was made on the ventral surface, anterior to the first dorsal fin, and a PIT tag inserted into the peritoneal cavity. Surgical openings were closed with Vetbond surgical glue (3M, Sydney, NSW, Australia) and procedures typically completed within one minute. All tagged lamprey were observed until they exhibited natural behaviors (e.g. ability to maintain balance and swim freely), which typically occurred within five minutes of procedures, and were subsequently released upstream of the barrages.

2.2. Tracking upstream movements

All fishways on main channel weirs of the River Murray from Lock 1 to Lock 26 are fitted with KarlTek KLK5000 PIT reader systems (KarlTek Pty Ltd, Melbourne, Australia). These systems are half- and full-duplex compatible and comprise multiple digital-signal-processing (DSP) decoders ('readers') and waterproof antennas. The antennas are mounted around the vertical-slots of each fishway to detect tagged fish passing through. The number of antennas at each fishway ranges from two to five; at a minimum, each fishway has an antenna at the fishway entrance and exit slots, while some fishways have additional antennas between the entrances and exits. The systems are auto-tuning, providing optimal tag read-range year-round, and data are transmitted to a central database. At sites where vertical-slot fishways are paired with fishlocks (Locks 2–6), PIT readers are not installed on fishlocks. The MDB fishway PIT telemetry database was interrogated for detections of lamprey tagged in the current study.

2.3. Data interpretation and analysis

Abundance of pouched lamprey was compared among fishways and years in which targeted lamprey sampling has occurred (2015–2019). Differences in relative abundance (fish.hour^{-1}.trap event^{-1}) among fishways and years were analysed using uni-variate two-factor PERMANOVA (permutational ANOVA and MANOVA), in the software package PRIMER v. 7.0.13 and PERMANOVA+1 (Anderson et al. 2008). Differences are interpreted in the context of discharge, including Commonwealth environmental water, from the associated barrages. Migration was characterised by calculating the extent, timing and rate of movement. Extent of migration (distance) was defined as the reach (i.e. weir pool) in which migration appeared to cease based upon detections on PIT reader systems. Migration timing was estimated for the point of capture (Murray barrages ~7 km MTD, middle thread distance), and PIT system locations (Lock 1–10), and presented as median dates, as well as date of first and last detections at each site. Migration rates (km.d^{-1}) were calculated from date–time stamps from PIT reader systems and known distances between systems. Estimated daily barrage discharge and salinity data were obtained from the Department for Environment and Water (DEW), while data on flow at the South Australian border (QSA) and contributions of environmental water and entitlement were obtained from the Murray–Darling Basin Authority.

3. RESULTS

3.1. Hydrology

From May–December 2019, discharge at the South Australian border (QSA) was characterised by flow <8,000 ML.d^{-1}, punctuated by conspicuous within-channel flow pulses that peaked at ~10,000 and ~15,000 ML.d^{-1} in August and October, respectively (Figure 2a). Delivery of South Australian entitlement flow comprised the majority of QSA except for the winter and spring flow pulses, when Commonwealth environmental water comprised a major proportion (up to 70%) (Figure 2a).

Over the same period, discharge from the Murray Barrages was more variable, ranging 0–24,908 ML.d^{-1} (Figure 2b). During sampling from 9 July–4 October, discharge ranged 0–19,166 ML.d^{-1}, with a mean discharge (± SE) of 3,236 ± 327 ML.d^{-1}. Throughout this period, most water was discharged through Tauwitchere (mean daily proportion of barrage discharge = 50%), followed by Goolwa (~29%) and Mundoo barrages (~19%), with minor proportions discharged through Ewe Island (~2%) and Boundary Creek (~0.3 %). Correspondingly, salinity (measured as electrical conductivity) was also variable across the sampling period, and of the major barrages, was generally lowest downstream of Goolwa (range = 9,090–49,096 µS.cm^{-1}, mean ± SE = 30,587 ± 1,367 µS.cm^{-1}), followed by Mundoo (range = 18,404–46,096 µS.cm^{-1}, mean ± SE = 38,707 ± 619 µS.cm^{-1}) and Tauwitchere (range = 21,897–55,766 µS.cm^{-1}, mean ± SE = 41,294 ± 1,094 µS.cm^{-1}) barrages (Figure 2c). Over the sampling period there were three events of complete closure (zero barrage discharge) due to storm surges and high water levels in the Coorong in July, August and September. All water discharged from the barrages in 2019 was Commonwealth environmental water.

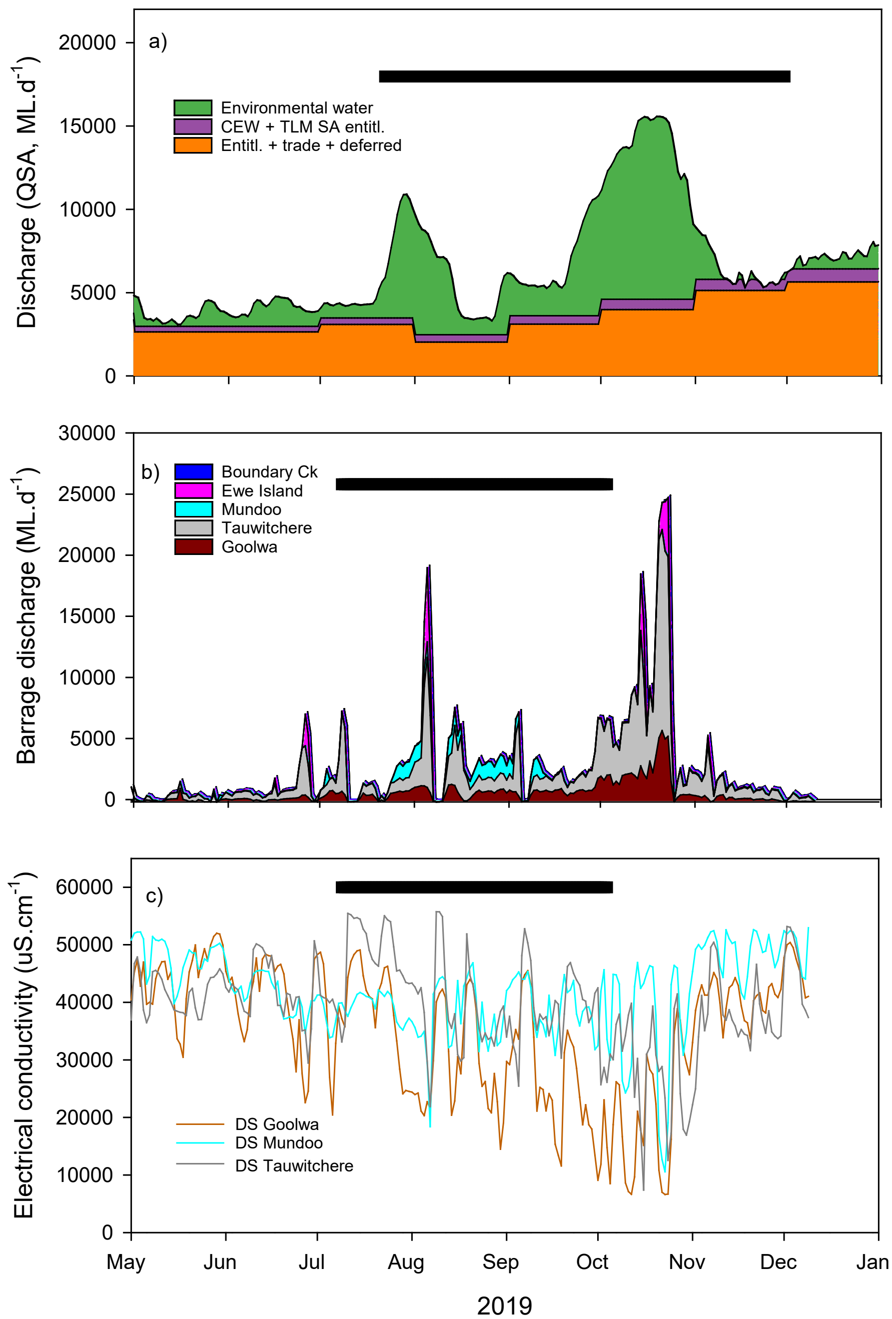

Figure 2. a) Discharge (ML.d^{-1}) at the South Australian border from May–December 2019, including contributions of entitlement flow and environmental water; b) discharge at the Murray Barrages from May–December 2019, including releases from different barrages; and c) electrical conductivity downstream of Goolwa (Reedy Island station), Mundoo (Barkers Knoll station) and Tauwitchere barrages (Pelican Point station). Horizontal black bar in plot 'a' represents the period of fishway PIT reader detections for tagged lamprey, and in plots b–c, represents the sampling period at the barrages. Note all discharge from the barrages in 2019 was Commonwealth environmental water (CEW). TLM = The Living Murray.

3.2. Lamprey abundance and timing of freshwater entry

In winter–spring 2019, a total of 45 pouched lamprey and 13 short-headed lamprey were captured from fishways during targeted lamprey sampling at the Murray Barrages. In late October and early November 2019, a further three short-headed lamprey were sampled during TLM monitoring of fishways. Overall, the greatest numbers of pouched lamprey (PL, n = 34) and short-headed lamprey (SHL, n = 14) were sampled from fishways on Goolwa Barrage, with lower numbers from Mundoo (PL n = 9 and SHL n = 1), Tauwitchere (PL n = 1 and SHL n = 1) and Boundary Creek (PL n = 1 and SHL n = 0), whilst neither species was detected at Ewe Island. Pouched lamprey were captured from fishways from 9 July to 2 October, but the greatest number (n = 21) were sampled in August (Figure 3a). Short-headed lamprey were detected from 10 July to 21 November, but the greatest number were sampled in September (n = 5) and October (n = 6) (Figure 3a). Of the lamprey sampled, 43 pouched lamprey (mean TL ± SE = 554 ± 5 mm) and 15 short-headed lamprey (mean TL ± SE = 429 ± 6 mm) were implanted with PIT tags.

Across years, overall numbers and abundances of pouched lamprey varied substantially, with greatest relative abundance in 2015, followed by 2017 and 2019, and lowest abundance in 2016 and 2018. PERMANOVA indicated a significant interaction between year and fishway ($Pseudo\text{-}F_{9,\ 242}$ = 2.11, p = 0.036), suggesting that the pattern of variability among fishways was not consistent across years. This is best illustrated by peak abundance at the barrages occurring at different fishways in given years, namely the GVS1 (2015, 2016 and 2018), TVS and Mundoo (2017) and GVS2 (2019) (Figure 3).

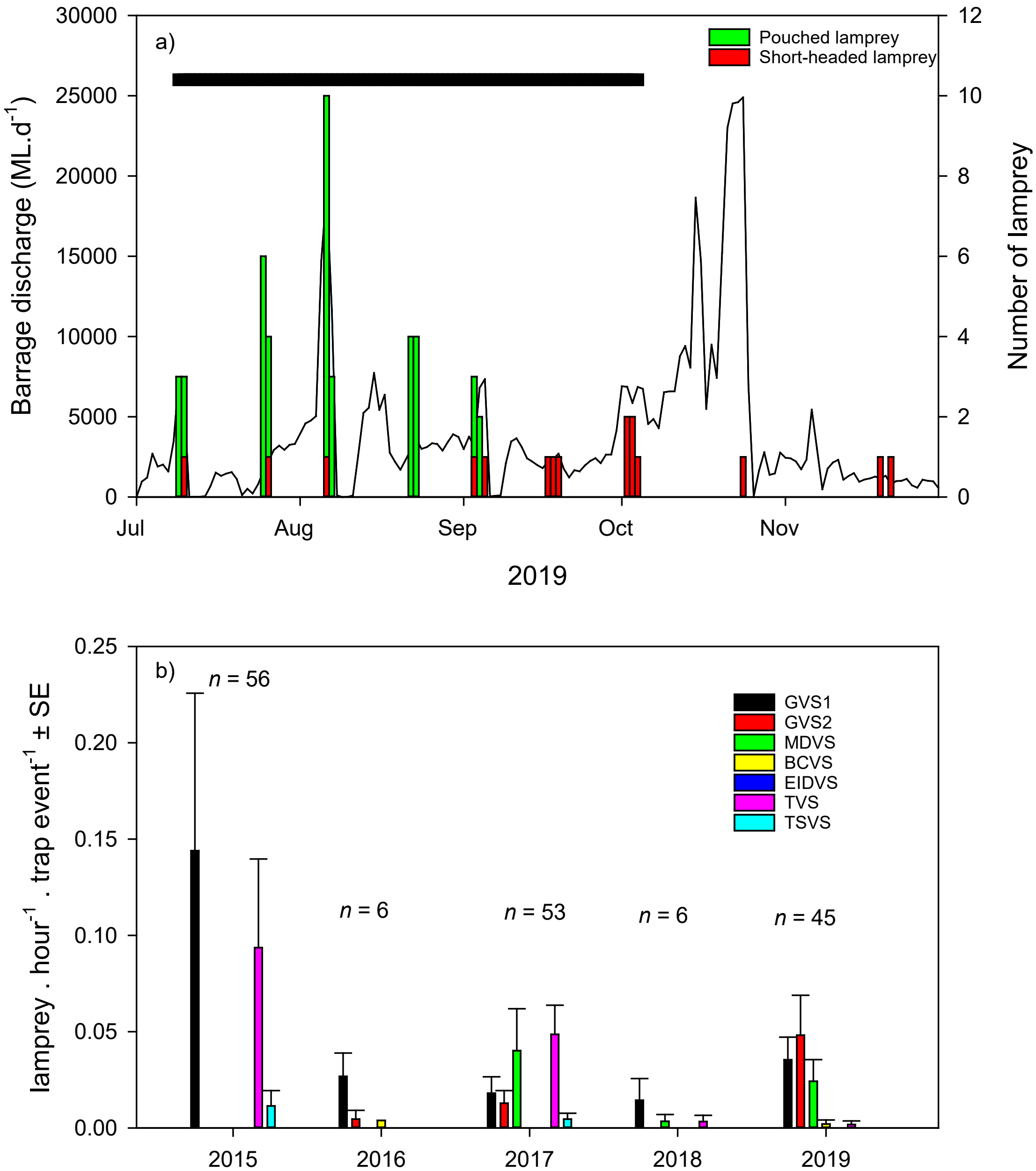

Figure 3. a) Numbers and date of capture for pouched and short-headed lamprey in 2019, presented with total daily barrage discharge (ML.d^{-1}). Horizontal back bar represents period of targeted lamprey sampling; and b) relative abundance (lamprey per hour per trap event) of pouched lamprey sampled from various fishways from 2015–2019 (total numbers sampled in each year are also presented). See Table 1 for fishway acronyms. Note MDVS was not sampled in 2015 or 2016, while GVS2, EIDVS and BCVS were not sampled in 2015.

3.3. Fishway PIT reader detections and riverine migration

Of the 43 pouched lamprey implanted with PIT tags, 19 (44%) were subsequently detected on main channel weir fishway PIT reader systems from Lock 1 to Lock 8. This included 19 (44%) at Lock 1 (274 km MTD), 12 (28%) at locks 2 and 3 (362 and 431 km MTD), three at locks 4 and 5 (516 and 562 km MTD), two at Lock 7 (697 km MTD), and one at Lock 8 (726 km MTD). No individuals were detected at the Lock 6 fishway, suggesting some individuals passed this weir via the fish lock, navigation lock or Chowilla Anabranch. Similar cases of missed detections at given fishways followed by detection at an upstream fishway also occurred at Locks 2, 4 and 5. Timing of first detections at fishways ranged from 22 July to 2 November, and the median date of first detections generally increased with distance upstream (Figure 4). Of the 14 short-headed lamprey implanted with PIT tags, just one was detected on the fishway PIT reader systems. Nonetheless, this individual was detected passing eight of the fishways, and was last detected exiting the Lock 10 fishway (825 km MTD) on 3 November (Figure 4).

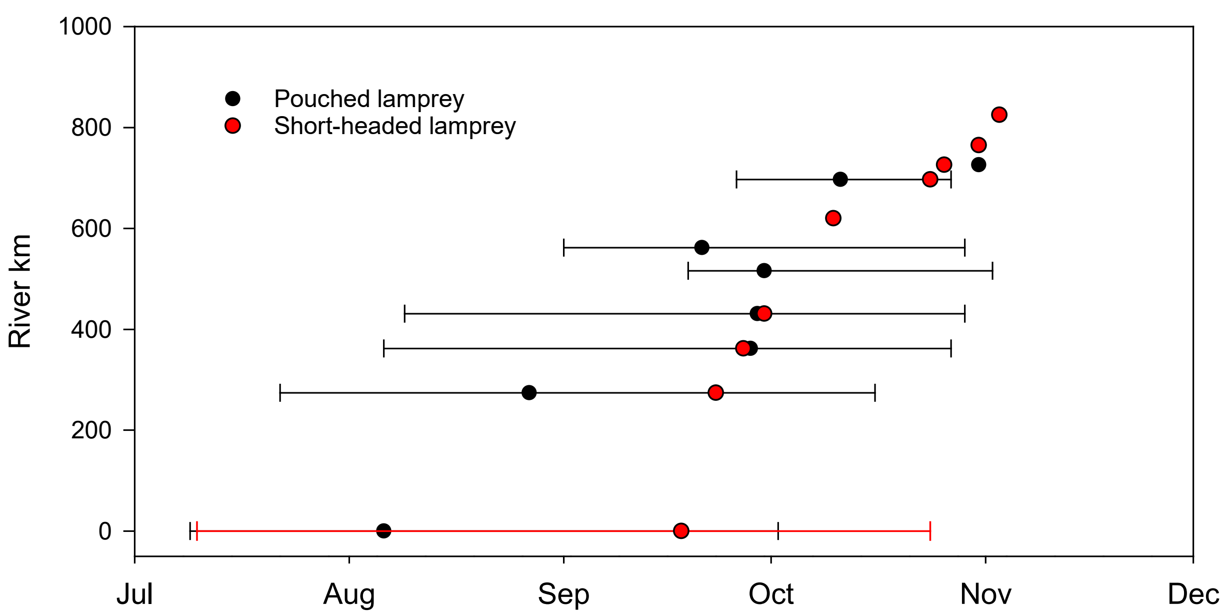

Figure 4. Migration timing distributions for upstream migrating pouched lamprey (*black circle*) and short-headed lamprey (*red circle*), presenting the median, and earliest and latest dates (error bars), of first detection on fishway PIT readers in 2019.

Migration rates were calculated for pouched lamprey through the following reaches: barrages to Lock 1 (274 km; *n* = 19); Lock 1 to Lock 2 (88 km; *n* = 12); Lock 2 to Lock 3 (69 km; *n* = 11); and Lock 3 to Lock 4 (85 km; *n* = 3). Migration rates for the remaining reaches could not be calculated due to absence of PIT reader data at either the upstream or downstream boundary of the reach, which signifies passage past a weir via a route other than the vertical-slot fishway (e.g. via fish lock or navigation lock). Within reaches, rates of migration among individuals varied over similar ranges, but the median rate was lowest from the barrages to Lock 1 (median = 10 $km.d^{-1}$, range = 4–32 $km.d^{-1}$), followed by Lock 1 to Lock 2 (median = 22 $km.d^{-1}$, range = 2–31 $km.d^{-1}$), and was greatest for Lock 2 to Lock 3 (median = 34 $km.d^{-1}$, range = 3–37 $km.d^{-1}$) and Lock 3 to Lock 4 (median = 30 $km.d^{-1}$, range = 29–31 $km.d^{-1}$).

At all weirs where pouched lamprey were detected on PIT reader systems, with the exception of Lock 3 (83%), vertical-slot fishway passage efficiency (i.e. proportion of fish detected in the fishway that successfully ascended the fishway) was 100%. Most lamprey-fishway interactions involved single successful ascents of the fishways. There were, however, instances of multiple successful ascents by individual pouched lamprey at Lock 1, 2 and 3 suggesting that some ascents were followed by fallback over the weirs.

4. DISCUSSION

The current study aimed to assess the abundance of lamprey migrating upstream at the Murray Barrages in winter–spring 2019 and monitor subsequent upstream migration. Pouched lamprey were sampled in similar or greater numbers relative to previous years when similar sampling effort was undertaken (2015–2018), while short-headed lamprey were sampled in the greatest numbers since 2006/07 (Bice et al. 2019a). In 2019, all water discharged from the Murray Barrages and associated fishways over the migration period was Commonwealth environmental water, and as such, directly resulted in maintenance of connectivity between freshwater, estuarine and marine environments, and migration outcomes for lamprey.

4.1. Timing of freshwater entry and abundance at the barrages

Pouched lamprey were sampled at the Murray Barrages from 9 July to 2 October 2019, with peak migration occurring in early August. Migration may have commenced in June, prior to commencement of sampling, but this general migration season with a peak in August is consistent with previous years monitoring (Bice et al. 2019a and b). Short-headed lamprey were sampled from 10 July to 21 November, but greatest numbers were captured in September and October. This project represented the first year in which fishways at the Murray Barrages were sampled continuously through late winter and spring, and confirmed the expectation that this period is the peak upstream migration period for short-headed lamprey at the barrages (Bice et al. 2019a).

Abundance of pouched lamprey in winter–spring 2019 was similar to that in 2017, greater than that recorded in 2016 and 2018, but less than that in 2015. Inter-annual differences in the abundance of pouched lamprey appears associated with varying hydrology during winter and associated influences on migration and detectability. Lowest abundance was recorded in 2018, when daily barrage discharge during winter averaged ~1,370 $ML.d^{-1}$ (max = 10,743 $ML.d^{-1}$), while higher abundances were associated with intermediate mean daily discharge, but more conspicuous peaks, in the winters of 2015 (mean = 2,819 $ML.d^{-1}$, max = 18,437 $ML.d^{-1}$), 2017 (mean = 4,557 $ML.d^{-1}$, max = 15,910 $ML.d^{-1}$) and 2019 (mean = 2,557 $ML.d^{-1}$, max = 19,166 $ML.d^{-1}$). An exception to this pattern was 2016. Discharge in June and early July 2016 was limited to fishways (typically <170 $ML.d^{-1}$), but increased drastically in mid-July and averaged ~18,000 $ML.d^{-1}$ for the remainder of winter with a peak discharge of ~48,000 $ML.d^{-1}$. Under such conditions, numerous gates are opened on all barrages, and fishway discharge represents a minor proportion of overall discharge (Bice et al. 2017). These conditions may result in low attraction of individuals to fishways, and increased potential for individuals to pass upstream via gate openings, and thus, overall abundances of migrating lamprey are likely to be underestimated.

Spatial variability in the abundance of upstream migrating lamprey among barrages is likely a result of a combination of variability in discharge from individual barrages and sampling bias. In winter–spring 2019, pouched lamprey were sampled in greatest numbers from fishways on Goolwa and Mundoo barrages, with lower numbers from fishways on Tauwitchere and Boundary Creek barrages. Historically, the species has commonly been sampled in greatest abundance from Goolwa Barrage (Bice et al. 2019a and b), but in some years, notably 2015 and 2017, were sampled in high numbers from Tauwitchere Barrage. In these years, particularly 2017, greater volumes of water were discharged from Tauwitchere than in 2018 and 2019, and the Tauwitchere trapezoidal fishway had yet to be completed, meaning all upstream migration at this barrage was limited to the original large and small vertical-slot fishways. By winter 2018, however, the trapezoidal fishway had been completed, but was not sampled in either 2018 or 2019 as traps for this fishway had yet to be constructed. This fishway discharges considerable volumes of water and is likely to provide favourable attraction flow to upstream migrating lamprey. Therefore, low abundances recorded from vertical-slot fishways on Tauwitchere Barrage in 2018 and 2019 may be in part due to individuals migrating upstream through the trapezoidal fishway and thus not accounted for in existing monitoring. Consequently, trapping of the Tauwitchere trapezoidal fishway, in conjunction with the fishways already sampled, is a priority for monitoring in coming winter–spring seasons to better elucidate the influence of individual barrage discharge on lamprey migration.

Other factors may also promote discrepancies in catch among barrages. Freshwater discharge into the narrower channels downstream of both Goolwa and Mundoo barrages, relative to Tauwitchere, is associated with greater reductions in salinity downstream of these barrages. Despite Goolwa and Mundoo barrages discharging lower absolute and proportional volumes of water, compared to Tauwitchere, the closer proximity of these barrages to the Murray Mouth, may attract greater abundances lamprey. As such, during times of limited water availability, releases from Goolwa and Mundoo barrages may elicit greater outcomes with regard to lamprey migration. Nonetheless, trapping of the Tauwitchere trapezoidal fishway, in conjunction with the fishways already sampled, is a priority for monitoring in coming winter–spring seasons to better elucidate the influence of individual barrage discharge on lamprey migration.

4.2. Extent, timing and rate of riverine migration

For tagged pouched lamprey subsequently detected on PIT reader systems in 2019, the estimated extent of migration ranged 274–726 km MTD. The proportion of PIT tagged pouched lamprey that ceased migration in given reaches was highest for the barrages to Lock 1 (56%, *n* = 22), followed by Lock 3–4 (17%, *n* = 7) and Lock 1–2 (15%, *n* = 6), with lower proportions from Lock 4–5, Lock 5–6, Lock 7–8 and Lock 8–9 (2.5–5%, *n* = 1–2). Upstream migration of pouched and short-headed lamprey is an obligate reproductive movement and locating favorable spawning habitat promotes cessation of lamprey migration (Moser *et al.* 2015). In previous years, individual pouched lamprey caught at the Murray Barrages and tagged with acoustic tags have been detected migrating upstream into the Finniss River and Currency Creek (Bice et al. 2019b), while ammocoetes have in the past been sampled downstream of Lock 1 (SARDI unpublished data). This suggests that individuals locating favourable spawning sites downstream of Lock 1 may have contributed to the high proportion of cessation of migration in this reach, and may explain cessation of migration in other reaches. Predation may also interrupt migration, and whilst rates of predation on upstream migrating lamprey in the River Murray are unknown, this mechanism also likely contributes to perceived cessation of migration throughout the river.

Similarly for short-headed lamprey in 2019, >90% of tagged individuals (*n* = 13) were not detected after capture suggesting migration ceased downstream of Lock 1. The upstream migration of this species is less understood than pouched lamprey, but mechanisms for cessation of migration are likely the same. The one individual that was subsequently detected, however, undertook a substantial upstream migration of at least 825 km. Pre-regulation, this species undertook upstream migrations of up to 2,000 km (Potter and Strahan 1968). The results from this study represent the first contemporary data on the upstream migration of this species, and suggest long-distance upstream migration still occurs in the MDB. This individual passed through eight main channel weir vertical-slot fishways; whilst data on fish passage are obviously limited, this provides a preliminary indication that the vertical-slot fishways installed on the lower River Murray successfully facilitate the upstream passage of this species.

Overall, migration timing for pouched and short-headed lamprey, based on fishway detections, extended from July to early-November. This result is consistent with migration timing of pouched lamprey in the River Murray from previous studies (Bice and Zampatti 2015, Bice et al. 2019b). Nevertheless, the temporal extent of upstream migration likely extends over a broader period than indicated by data from 2019. Indeed, in early December in 2015, a PIT tagged lamprey was detected at Lock 10 (Wentworth, 825 km MTD), whilst newspaper articles from 1949/50 note the presence of 'lamprey' at Mildura (Lock 11) and Euston (Lock 15) in January (The Riverine Herald 1950). Consequently, in the southern MDB, migration of pouched lamprey, and potentially short-headed lamprey, likely extends from at least June to January.

Migration rates of individual pouched lamprey ranged 2–37 $km.d^{-1}$, consistent with rates previously reported from the River Murray (Bice et al. 2019b). In addition, migration rates were lowest between the barrages and Lock 1, incorporating the lacustrine habitats of Lake Alexandrina, and greatest in riverine reaches (e.g. Lock 2 to Lock 3). This aspect of migration is comparable to the similar-sized Pacific lamprey (*Entosphenus tridentatus*) in the Snake River Basin, USA, which also exhibits lowest rates between release and location of first detection, and similar migration rates to pouched lamprey post first detection (McIlraith et al. 2015). These slower initial rates may reflect recovery from tagging, physiological adaptation following transition from marine to fresh waters or in the case of pouched lamprey in the River Murray, greater difficulty in navigating upstream through Lake Alexandrina in comparison to linear river reaches.

4.3. Contribution of Commonwealth environmental water

In 2019, all water discharged through the Murray Barrages was Commonwealth environmental water. This included a substantial volume of water delivered in winter, largely supported by return flows from watering events in the Goulburn River. In winter–spring 2019, Commonwealth environmental water provided connectivity between freshwater, estuarine and marine environments and migration outcomes for lamprey, including: high abundances of both pouched and short-headed lamprey passing the Murray Barrages, and ultimately, migrations that continued for at least 726 and 835 km upstream, respectively.

4.4. Future research and management

Understanding of contemporary ecology of lamprey in the MDB has improved in recent years, particularly with regard to upstream migration. Yet many knowledge gaps remain and represent priorities for future research to better support management, and are related to: 1) spawning and the ecology of early life stages; 2) downstream migration of sub-adults (i.e. macrophthalmia); 3) the ecology of the parasitic marine life phase; and 4) upstream spawning migrations.

Identifying locations (i.e. streams and specific river reaches) that provide spawning and nursery habitats for pouched and short-headed lamprey should be a focus of future investigations to support the protection and enhancement of these habitats. Previous detection of individuals entering Eastern Mount Lofty Ranges tributaries (e.g. Currency Creek and the Finniss River) (Bice *et al.* 2019b) and cessation of migration across multiple reaches of the River Murray suggests spawning/nursery sites may be widespread. Nonetheless, confidently identifying such sites relies on detecting ammocoetes, which often requires specialised sampling approaches due to their cryptic benthic habit (Moser et al. 2007). We suggest that a combined methodology of active (e.g. electrofishing) and passive (e.g. environmental DNA) sampling would be appropriate to assess nursery habitat distribution in the southern MDB, particularly targeting tributary streams and tailwaters of weirs in reaches of the lower and mid River Murray.

For pouched lamprey and short-headed lamprey, knowledge of downstream migration of recently metamorphosed macrophthalmia, as well as the general ecology of the parasitic marine phase, is limited. In New Zealand and southwestern Australia, downstream migration of pouched lamprey macrophthalmia is suggested to occur in winter and spring, respectively (Empson and Meredith 1987; Potter 1980), but there is no data from southeastern Australia for this species, or short-headed lamprey. Importantly, these migrations may be threatened by physical (e.g. closed barrages) and hydraulic barriers (e.g. altered hydraulics in weir pools) (Maitland *et al.* 2015), which are prevalent in the lower River Murray. Very little is known regarding the ecology of the marine parasitic life phases of pouched lamprey or short-headed lamprey across their potential ranges, including general distribution, movements, feeding ecology and threats (James *et al.* 2008).

Data collected in this and allied monitoring projects (e.g. Bice et al. 2016, Bice and Zampatti 2019, Bice et al. 2019b) have improved understanding of upstream migration of pouched lamprey, and generated the first ever tracking data on the upstream migration of short-headed lamprey. This understanding may inform environmental water delivery and structure management in the southern MDB, with the objective of promoting spawning migration outcomes for lamprey, and the migrations of other diadromous species (e.g. congolli, *Pseudaphritis urvillii*). Of importance is attraction of lamprey to the Murray Mouth and subsequent river ingress. The reliance of lamprey on physico-chemical and olfactory cues to stimulate marine–freshwater transition, and connectivity between estuarine and freshwater environments to facilitate migrations, highlights the importance of maintaining discharge from the Murray Barrages during winter–spring. Conspicuous barrage flows, supported by Commonwealth environmental water, have been delivered during winter in the past five years, and pouched lamprey have been sampled in association with each of these events, albeit in variable abundance. Greatest abundances have been detected during years of moderate discharge (mean daily discharge ≥2,500 $ML.d^{-1}$) with short periods of peak discharge of ~15,000 $ML.d^{-1}$. Abundances during years of high flow remain unquantified due to difficulty of sampling. Nonetheless, the hydrographs delivered in 2015, 2017 and 2019 likely represent appropriate templates for future environmental water planning. Pouched lamprey were detected during lower discharge in 2018; as such lamprey migration remains an objective of the delivery of similar low volumes, but expected outcomes are likely to be reduced in magnitude.

Regarding discharge from individual barrages, lamprey appear to primarily enter freshwater via Goolwa, Mundoo and Tauwitchere barrages. Releases from these three barrages typically comprise most of the overall barrage discharge. In 2019, abundance of upstream migrating lamprey was greatest at Goolwa and Mundoo barrages, despite greater volumes of water being discharged from Tauwitchere Barrage. This may be a result of sampling bias (passage through the Tauwitchere trapezoidal fishway was not monitored), but also the closer proximity to the Murray Mouth and greater relative influence of discharge on salinity downstream of Goolwa and Mundoo than Tauwitchere barrage. To support this assertion, however, assessment of migration through the Tauwitchere trapezoidal fishway, and the Goolwa small vertical-slot fishway are key priorities for monitoring in coming winter–spring seasons.

For both pouched and short-headed lamprey, the use of olfaction to detect cues from conspecifics (e.g. larval pheromones) and guide migration (see Bett and Hinch 2016) warrants further investigation, particularly in regard to the source and longitudinal integrity of riverine flows. Riverine ingress is likely influenced by conspecific pheromones in outflowing water together with salinity (Meckley et al. 2014), but the ultimate extent of riverine migration may also be influenced by discharge and pheromones (Moser et al. 2015). As such, overall river discharge and tributary contributions, as well as densities of ammocoetes in different localities may influence lamprey migratory behaviour. In the context of the River Murray, discharge from Eastern Mount Lofty Ranges tributaries due to local rainfall, or from upstream tributaries due to dam releases (e.g. the Goulburn River), and re-regulation of flow through Lake Victoria, may all influence behaviour, migratory extent, and ultimately population dynamics. However, improved knowledge of the influence of flow on migration and population dynamics is first reliant on identifying spawning and nursery locations.

5. CONCLUSION

This project has collected essential data to evaluate the contribution of Commonwealth environmental water to lamprey migration at the Murray Barrages. It has also contributed to general understanding of upstream spawning migrations of pouched and short-headed lamprey in the River Murray. Migrations of both species occur over a defined period, may be long-distance (100s of km) and rapid, and are aided by barrage and fishway discharge. Importantly, all water discharged from the barrages in 2019 was Commonwealth environmental water, and this directly contributed to positive outcomes for both species. Many aspects of pouched and short-headed lamprey ecology remain unknown, but the current project serves to provide direction for future research and management.

6. REFERENCES

Anderson, M. J., R. N. Gorley and K. R. Clarke (2008). PERMANOVA+ for PRIMER: Guide to Software and Statistical Methods, PRIMER-E: Plymouth, UK.

Barrett, J. and M. Mallen-Cooper (2006). The Murray River's 'Sea to Hume Dam' fish passage program: Progress to date and lessons learned. *Ecological Management and Restoration* **7**: 173-183.

Baumgartner, L., B. Zampatti, M. Jones, I. Stuart and M. Mallen-Cooper (2014). Fish passage in the Murray-Darling Basin, Australia: Not just an upstream battle. *Ecological Management & Restoration* **15**: 28-39.

Bett, N. N. and S. G. Hinch (2016). Olfactory navigation during spawning migrations: a review and introduction of the Hierarchical Navigation Hypothesis. *Biological Reviews* **91**: 728-759.

Bice, C. M. and B. P. Zampatti (2015). Fish assemblage structure, movement and recruitment in the Coorong and Lower Lakes in 2014/15, South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI publication No. F2011/000186-5. SARDI Research Report Series No. 862. 64 pp.

Bice, C. M. and B. P. Zampatti (2019). Fish assemblage structure, movement and recruitment in the Coorong and Lower Lakes in 2017/18, South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2011/000186-6. SARDI Research Report Series No. 1007. 81 pp.

Bice, C. M., B. P. Zampatti and J. Fredberg (2017). Assessment of biological effectiveness of newly constructed fishways on the Murray Barrages, South Australia, 2015-2017, South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2016/000452-2. SARDI Research Report Series No. 952. 65pp.

Bice, C. M., B. P. Zampatti and J. Fredberg (2019a). Fish assemblage structure, movement and recruitment in the Coorong and Lower Lakes in 2018/19. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2011/000186-9. SARDI Research Report Series No. 1043. 67 pp.

Bice, C. M., B. P. Zampatti and J. F. Fredberg (2016). Fish assemblage structure, movement and recruitment in the Coorong and Lower Lakes in 2015/16 South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2011/000186-6. SARDI Research Report Series No. 921. 77 pp.

Bice, C. M., B. P. Zampatti and W. Koster (2019b). Tracking lamprey spawning migrations in the River Murray, South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2019/000190-1. SARDI Research Report Series No. 1027. 36 pp.

Bice, C. M., B. P. Zampatti and M. Mallen-Cooper (2017). Paired hydraulically distinct vertical-slot fishways provide complementary fish passage at an estuarine barrier. *Ecological Engineering* **98**: 246-256.

Department of Environment, Water and Natural Resources (2015). South Australian River Murray Long-Term Environmental Watering Plan. November 2015. https://www.mdba.gov.au/sites/default/files/pubs/long-term-e-water-plan-sa-river-murray-nov-15.PDF.

Empson, P. W. and A. S. Meredith (1987). Downstream migration of *Geotria australis* juveniles in the lower Waikato River (note). *New Zealand Journal of Marine and Freshwater Research* **21**: 643-644.

Jonsson, B., R. S. Waples and K. D. Friedland (1999). Extinction considerations for diadromous fishes. *ICES Journal of Marine Science* **56**: 405-409.

Maitland, P. S., C. B. Renaud, B. R. Quintella, D. A. Close and M. F. Docker (2015). Conservation of native lampreys. Lampreys: biology, conservation and control. M. F. Docker, Springer. **Vol 1.:** 375-428.

MDBA (2014). Basin-wide environmental watering strategy, Murray-Darling Basin Authority, Canberra. MDBA Publication No. 20/14.

Meckley, T. D., C. M. Wagner and E. Gurarie (2014). Coastal movements of migrating sea lamprey (*Petromyzon marinus*) in response to partial pheromone added to river water: implications for management of invasive populations. *Canadian Journal of Fisheries and Aquatic Sciences* **71**: 533-544.

Moser, M. L., P. R. Almeida, P. S. Kemp and P. W. Sorenson (2015). Lamprey spawning migration. Lampreys: biology, conservation and control. M. F. Docker, Springer. **Vol. 1:** 215-263

Potter, I. C. (1980). Ecology of larval and metamorphosing lampreys. *Canadian Journal of Fisheries and Aquatic Sciences* **37**: 1641-1657.

Potter, I. C. and F. L. S. Strahan (1968). The taxonomy of the lampreys *Geotria* and *Mordacia* and their distribution in Australia. *Proceedings of the Linnean Society of London* **179**: 229-240.

Quinn, T. P. and D. J. Adams (1996). Envoironmental changes affecting the migratory timing of American shad and sockeye salmon. *Ecology* **77**: 1151+.

Walker, K. F. and M. C. Thoms (1993). Environmental effects of flow regulation on the lower River Murray, Australia. *Regulated Rivers: Research & Management* **8**: 103-119.

Ye, Q., G. Giatas, J. Brookes, D. Furst, M. Gibbs, R. Oliver, R. Shiel, B. Zampatti, K. Aldridge, L. Bucater, B. Busch, M. Hipsey, Z. Lorenz, R. Maas and J. Woodhead (2020). Commonwealth Environmental Water Office Long-Term Intervention Monitoring Project 2014–2019: Lower Murray River Technical Report. A report prepared for the Commonwealth Environmental Water Office by the South Australian Research and Development Institute, Aquatic Sciences.