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# Reconnecting the Waters: exploring barrage transparency to improve estuarine ecosystem health in the CLLMM region

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Brenton Zampatti, Matt Gibbs, Luke Mosley, Chris Bice, Ruan Gannon and Arron Strawbridge

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Enquires should be addressed to: CLLMM Research Centre
Level 1, 92 Barrage Road
Goolwa, SA 5214
e-mail: info@cllmmresearchcentre.org

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## Disclaimer

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# Executive Summary

The Coorong, Lower Lakes and Murray Mouth (CLLMM) region, at the terminus of the Murray–Darling Basin, has immense socio-cultural, economic and environmental importance. In the late 1930s, in response to expanding upstream irrigation and declining freshwater flow, the Murray Barrages were constructed to mitigate impacts of increasing saltwater ingress to the freshwater Lower Lakes. Whilst securing the upstream freshwater environment, the barrages, in conjunction with reduced freshwater flow, restrict the physical extent of the remnant downstream estuary and under low–average flows, form an abrupt interface, fragmenting freshwater, estuarine and marine habitats. Climate change is likely to exacerbate these impacts.

This study investigated how a more hydrologically transparent operating regime at the Murray Barrages—allowing periods of bidirectional flow during "reverse flows" (when Coorong water levels exceed lake levels)—can improve connectivity and estuarine ecosystem function while managing risks to lake salinity and freshwater-dependent habitats. From June 2025 to March 2026, we undertook operational trials (in collaboration with SA Water and DEW) at Boundary Creek and Ewe Island barrages, intermittently keeping one barrage bay open to enable reverse flows. We collected water quality and hydrodynamic data (salinity, temperature, water level and velocity) upstream of the barrages. In concert, we assessed fish movement through the barrages using larval drift/tow nets, and open-bay and fishway trapping, and initiated ongoing investigations using high-frequency sonar and acoustic telemetry. We also refined and applied an integrated hydrodynamic model to evaluate salinity risks and explore alternative barrage operating scenarios.

## Key findings

- **Controlled reverse flows produced short-lived, spatially constrained salinity increases upstream of the barrages.** Salinity increased upstream of the barrages when gates were open during reverse flows (notably July–August 2025) but effects attenuated with distance from the barrages and receded once downstream discharge resumed.
- **Reverse flows can facilitate the movement of larval and juvenile/adult fish across the barrage interface.** Larval sampling captured 11 species of fish with catches dominated by the catadromous common galaxias (*Galaxias maculatus*) and marine-estuarine opportunist sandy sprat (*Hyperlophus vitattus*). Sampling of fish movement through the open barrage bays and fishways captured 13 species, with catches dominated by the freshwater-estuarine opportunist Australian smelt (*Retropinna semoni*). Our results indicate the potential for substantial flow-assisted upstream movement of fish, particularly for species and life stages unable or unlikely to use fishways.
- **The upgraded hydrodynamic model can represent key salinity and velocity dynamics associated with reverse flow events.** Comparisons with logger data showed good agreement, with some over-/under-estimation likely due to the coarse representation of localised flow paths in the model and the timing/representation of gate closures.

- **Scenario modelling suggests operational rules can increase connectivity while managing salinity risk.** A "water level trigger" approach (closing gates when downstream levels exceed upstream by >0.05 m) reduced large salt ingress events relative to leaving gates open, while also supporting longer periods of openness (connectivity) than historical gate closure practices.

### Implications for management

Our findings support the feasibility of using controlled, event-based barrage operation to expand the functional estuarine mixing zone and improve freshwater–estuarine connectivity, without implying permanent opening or removal of the barrages. Further research is required but initial management recommendations are apparent, including: 1) integrating consideration of open barrage bays and facilitating reverse flows into contemporary barrage operation; and 2) progressing further automation of barrage gates to allow remote operation in response to real-time water levels.

### Future modelling, monitoring and research

- Hydrodynamic modelling results highlight a need to review methods used to estimate barrage discharge, and a need for updated bathymetry data downstream of specific barrages (e.g. Boundary Creek).
- Expand the hydrodynamic modelling undertaken in this study to include a broader range of contemporary and future barrage operating and climate scenarios.
- Foster collaboration across SA Water, DEW, CEWH, MDBA, the community and researchers: workshop current and future barrage operating and climate scenarios, and explore opportunities to adopt the concept at additional locations across the barrage network.
- Continue to collect foundational physico-chemical and biological data in association with reverse flows at the Murray Barrages, particularly under alternate hydrological conditions and across seasons. The current project forms a foundation but was a preliminary exploration.
- Expand research to consider whole-of-aquatic ecosystem response to reverse flows, including the aquatic-terrestrial interface in regions influenced by potential changes in long-term salinity regimes (e.g. current freshwater environments immediately upstream of the barrages).

# Acknowledgements

We acknowledge the cultural connections to the land and connected waters, as well as the cultural significance of waterbirds that exist between people of the Ngarrindjeri and Boandik Nations across the Coorong, Lower Lakes, and Murray Mouth region. We recognise that First Nations peoples' spiritual, social, cultural, and economic practices come from their lands and waters, and they continue to maintain their cultural heritage, economies, languages, and laws which are of ongoing importance. We are committed to fostering and nurturing ongoing relationships with First Nations communities in the CLLMM region as we collective work toward healthy, resilient and thriving lands, waters, ecosystems and communities across the region.

This project was funded by the Goyder Institute for Water Research's CLLMM Research Centre, which is funded by the Australian Government. We thank the CLLMM Research Centre staff for project initiation, support and management. We thank the Goyder Institute for Water Research, Research Advisory Committee and two anonymous reviewers for constructive feedback on the report.

Thank you to the CLLMM Research Centre management team and Advisory Forum who supported and guided this project. Field trials were made possible by the collaborative efforts of individuals from several organisations: Mark Sutcliffe, Connor Gervais and George Giatas (SARDI); Sophie Gilby (CSIRO); Garry Fyfe, Michael Shelton, Mat Irvine, Greg Bald, Dave Bishop and Luke Adderley (SA Water); Adrienne Rumbelow, Andy Harrison, Claire Sims, Damian Rowley and Renee Thompson (Department for Environment and Water, DEW); and Matt Hipsey (University of Western Australia). All sampling was conducted under an exemption (no. ME9903260) of section 115 of the *Fisheries Management Act 2007* and CSIRO Animal Ethic Committee project no. 2025-23.

# 1 Introduction

Located at the terminus of Australia's longest river system, the Murray–Darling, the Coorong, Lower Lakes and Murray Mouth (CLLMM) region encompasses the traditional lands and waters (Yarluwar-Ruwe) of the Ngarrindjeri Nation, supports extensive primary industries and tourism, and is globally recognised for its conservation values (e.g. Ramsar Convention; DEW 2023). As such, the region is of immense socio-cultural, economic and environmental importance. Historically, the River Murray flowed into the predominantly freshwater Lower Lakes which were characterised by a dynamic estuarine interface, primarily in the southern region of Lake Alexandrina (Tibby et al. 2022). In the 19th and 20th centuries, irrigated agriculture expanded across the southern Murray–Darling Basin (MDB), leading to diminished freshwater flow and increased saltwater ingress into the Lower Lakes (Mallen-Cooper and Zampatti 2018). To mitigate the impacts of saltwater intrusion, a series of tidal barriers ('barrages') were constructed in the 1940s. The barrages now restrict the physical extent of the estuary and under low–average flows, form an abrupt interface, fragmenting the freshwater Lower Lakes and the Coorong estuary, lagoons and Southern Ocean.

Connectivity is a recurring theme in Aboriginal and European culture, and in scientific understanding of ecological function (Taylor et al. 1993). Estuarine barriers and reduced river flow impact connectivity and hydrodynamics in the lower reaches and estuaries of river systems, in turn affecting ecosystem function, with accompanying cultural, environmental and economic impacts (Bice et al. 2023). Estuarine fishes are an indicator of these impacts, as is evident in the CLLMM, where barrage construction and subsequent operation influences population dynamics of diadromous and estuarine-dependent fishes (Bice et al. 2018), with flow on effects for fishery landings (e.g. mulloway, *Argyrosomus japonicus*; Ferguson et al. 2008). These impacts are caused in part by the barrages reducing the physical extent and dynamics of the estuary and also the loss of freshwater flow into the contemporary 'reduced' estuary. Climate change is predicted to exacerbate these impacts and, as sea levels rise, result in further compression of the downstream estuary (i.e. 'coastal squeeze'; Pontee 2013) and lead to more frequent overtopping of the existing barrages and ingress of saline water into the Lower Lakes (Rees et al. 2022).

Globally, to improve the health of rivers and estuaries, tidal barriers are increasingly being operated in a manner that promotes greater connectivity and more dynamic estuarine interfaces (e.g. Beeldman et al. 2018). At the Murray Barrages, promoting a more hydrologically transparent barrage interface, where two-way flux of water is facilitated under appropriate lake levels and river flows, has numerous potential benefits to the CLLMM ecosystem, and to the cultural and economic (e.g. commercial fishery) values of the region. Nevertheless, there are also considerations pertaining to upstream water quality (salinity), particularly for stock, domestic and irrigation supply, and the conservation values of freshwater habitats, mostly those around Hindmarsh and Mundoo islands, that are critical for nationally threatened fish (Wedderburn and Hammer 2003). An understanding of the risk and benefits of greater connectivity, including water quality dynamics and biological response to more transparent barrage operation, will: 1) provide knowledge to inform more flexible barrage management for ecological, cultural and economic outcomes, and 2) improve understanding of the broader impacts of climate change in the CLLMM and possible mitigation measures.

## *1.1 Project objectives*

This project aims to increase understanding of the risk and benefits of facilitating greater connectivity at the Murray Barrages, with the objectives of:

- Exploring opportunities to facilitate the bidirectional movement of water and biota through the barrages.
- Understanding the influence of 'more transparent' barrage operation on (i) the hydrodynamics and water quality of the Lower Lakes and Coorong, (ii) the ecology of key fish species, and (iii) broader ecosystem function.
- Integrating these data in a hydro-ecological model that will inform benefits and risks of more flexible barrage operation, and the potential implications of climate change and sea level rise on lake water quality and ecology.

To achieve these objectives, we pursued three broad lines of investigation, the specifics of which were guided by the CLLMM Research Centre's Advisory Forum (RCAF), DEW and SA Water.

### 1.1.1 Hydrodynamics and modelling

To assess how the risk of high salinity intrusion into the Lower Lakes can be minimised while achieving the objective of increased connectivity, we made use of a long history of hydrodynamic model development in the region. An updated and refined hydrodynamic model was used to evaluate these risks under a range of hydrological conditions, including varying River Murray inflows, lake and Coorong levels, and wind conditions. The number and location of barrage gates operated, as well as responsiveness of barrage opening and closings, were also considered, to identify how risks could be minimised.

### 1.1.2 *In situ* water quality and hydrodynamic monitoring

Water quality is a key driver of ecosystem health in the CLLMM region. Operating the barrages in a more dynamic and flexible manner comes with both risk and opportunity to water quality in the lakes and Coorong. We used *in situ* water column profiling and remote loggers to collect data on salinity and other water quality parameters, and flow velocities. These data were used to validate hydrodynamic models and investigate relationships between salinity and larval fish habitat use, and the movement and habitat use of juvenile and adult estuarine fishes.

### 1.1.3 Biology

Estuarine function and the life histories of associated biota are reliant on connectivity and a dynamic salinity regime determined by the interplay of river flows and tide (Wolanski and Elliott 2015). In the CLLMM, fish hold considerable socio-cultural and economic significance and are considered a primary indicator of ecosystem health.

In this component of the project, we investigate how more dynamic and flexible barrage operation influences the movement and habitat use of fish at the interface of the Lower Lakes and Coorong. Investigations included: 1) the active/passive movement of fish, including early life stages, in association with two-way flow through the barrages, and 2) the movement and habitat use of juvenile and adult estuarine fishes, in conjunction with the *in situ* array of water quality sensors, to gain an improved understanding of the salinities fish utilise for a range of life-history processes including foraging and potentially spawning.

# 2 Methods

## *2.1 Study site*

In consultation with SA Water and DEW, Boundary Creek and Ewe Island barrages were selected as locations where it was operationally feasible to facilitate the bidirectional movement of water through the barrages with low risk to environments immediately upstream of the barrages from temporarily increased salinity (ecologically and to consumptive water users) (Figure 1). From an operational perspective, radial gates or stop logs on the barrages are operated to release freshwater downstream, when lake water levels are higher than Coorong water levels (positive head differential). Conventionally, when Coorong water levels are higher than lake water levels (negative head differential) due to hydrological (e.g. river flow and tide), oceanographic (e.g. swell) and meteorological (e.g. storm surge, prevailing wind) drivers, barrage bays and gates are often closed to prevent the movement of higher salinity Coorong water into the lakes, Fishways, however, may remain open. These periods of negative head differential are commonly referred to as "reverse flows".

Across the period June 2025 to March 2026, when operationally feasible, one bay on each of Boundary Creek and Ewe Island barrages was opened for intermittent periods of days to weeks. At Boundary Creek Barrage, the "attractant gate" immediately adjacent the small vertical slot fishway was used. At Ewe Island Barrage all stop logs were removed from the barrage bay immediately adjacent to the dual vertical slot fishway thus facilitating a full-depth opening. Barrage bays were closed at the discretion of DEW and SA Water, particularly as flow down the River Murray diminished and lake water levels receded through spring–summer 2025–26.

## *2.2 Water physico-chemistry*

*In situ* water salinity (Electrical Conductivity (EC), µS/cm) temperature (°C), and depth (m above logger) were measured at ten sites upstream of Boundary Creek and Ewe Island barrages (Figure 1). In these locations, loggers (LeveLine model LL-CTD-ABS-010) were anchored approximately 0.5 m off the bottom and set to record at 15-minute intervals. The calibration of the EC sensor was checked using a calibrated standard solution (EC = 1412 µS/cm). A barometric pressure sensor (LL-ABS-CTD-PACKAGE) was placed in Boundary Creek on a wooden pole. This was used to correct pressure readings to depth. Data was downloaded periodically using a LeveLine Aquaread meter. Water quality profiles (EC, dissolved oxygen (mg/L), temperature, turbidity (NTU)) were also collected at time of sampling using a calibrated YSI Pro DSS meter.

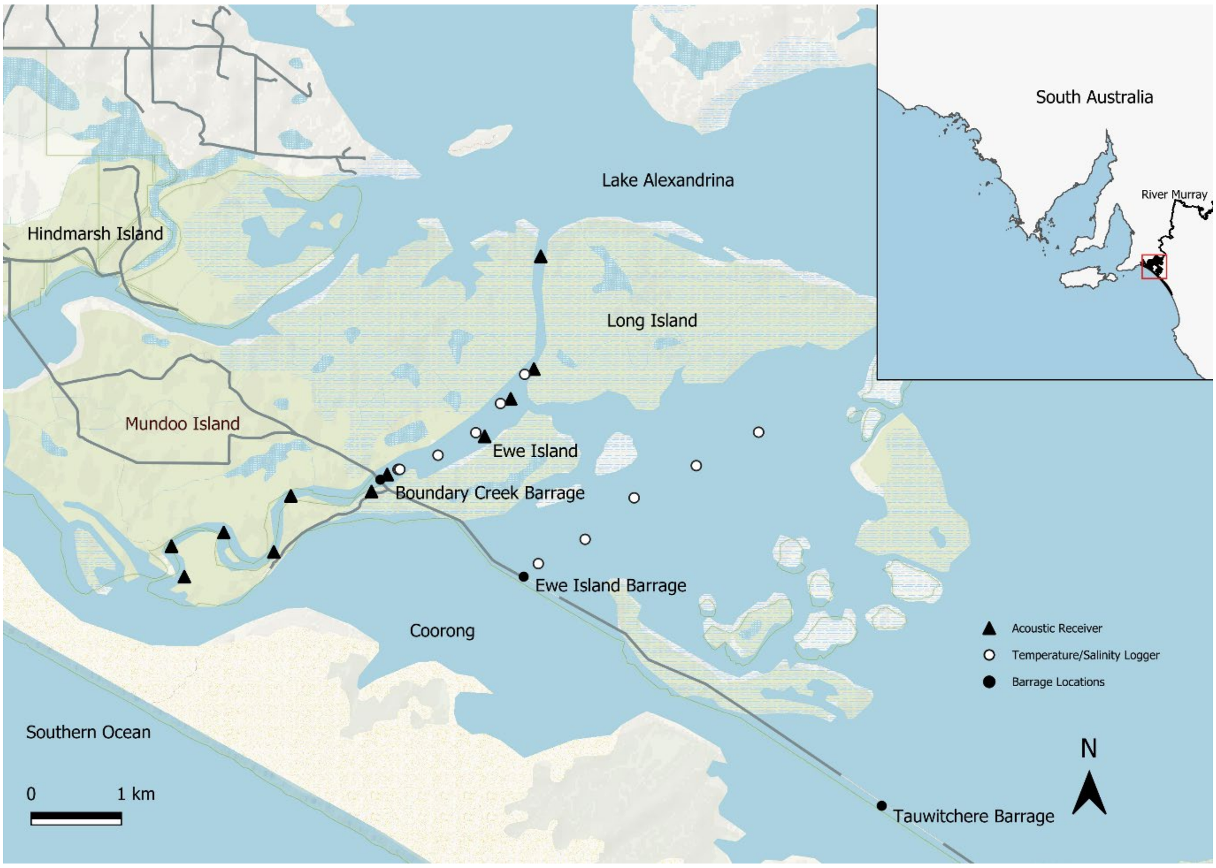


Figure 1. Map of the study region, depicting Boundary Creek and Ewe Island barrages, Lake Alexandrina (north of the barrages) and the Coorong estuary (south of the barrages). Acoustic receivers for the fish movement study shown as closed triangles. *In situ* salinity, temperature and water level monitoring sites (open circles) are numbered from closest to the barrage to furthest away, for example EW1 is the site closest to Ewe Island Barrage and EW5 the furthest.

Drag-tilt current meters (Marotte HS, Marine Geophysics Laboratory) were installed for shorter durations (1–3 months) at the salinity logger sites immediately upstream of each barrage. These collected data on water velocity, with speed (m/s) and 360° direction. Each current meter was installed using two anchor blocks, one with the logger attached, and one extending to a buoy on the surface. High-frequency (1 second) data was downloaded and processed to 20-minute intervals for comparison with hydrodynamic modelling and other datasets.

## *2.3 Biology*

In association with transparent barrage operation and reverse flows, we assessed fish movement through the barrages and fish habitat use. We used several approaches to target different species and life stages, and various aspects of spatial ecology. This specifically included: 1) sampling of upstream drift of larval fish through open bays and upstream habitat use; 2) sampling of direct upstream movement of juvenile and adult fish via open bays and fishways; 3) using high-frequency sonar to assess movement within the vicinity of open barrage bays; and 4) using acoustic telemetry to assess longitudinal habitat use of select estuarine-associated species in Boundary Creek.

### 2.3.1 Larval fish

From 5 August–2 October 2025, the upstream drift of fish eggs and larvae was assessed at Boundary Creek and Ewe Island barrages. During reverse flow events, water flowing upstream through open barrage bays and fishways at Ewe Island (*n* = 3 events), and the attraction gate at Boundary Creek (*n* = 2 events), was opportunistically sampled using a suite of three larval driftnets. Nets were 1.5 m long and 0.5 m in diameter, tapering to a removable cod end, and covered with 500 µm mesh. Nets were fixed to the barrage above open barrage bays as to sample the reverse flow and deployed for 15-min periods. The volume of water filtered through drift nets was measured by a flow meter (General Oceanics Inc. Florida, USA) fixed in the mouth of the net. The contents of each net were preserved *in situ* in 95% ethanol and returned to the laboratory for processing.

Over the same period, sites were opportunistically sampled in the immediate vicinity and further upstream (~500 and 2000 m) of Boundary Creek (*n* = 8 events) and Ewe Island (*n* = 4 events) barrages to investigate the composition of the larval fish community upstream of the barrages in association with reverse flow. This involved undertaking three replicate daytime plankton tows using the net and flowmeter apparatus, and preservation methods, described above. Initial tow duration was 15 minutes, but due to high abundance of invertebrate fauna and net fouling, tow duration was reduced to two minutes. Due to strong southerly winds and wind seiche-induced low water levels often experienced upstream of the barrages during reverse flow events, larval fish tows were typically conducted during periods of positive head differential (i.e. water discharging downstream) but immediately following reverse flow events.

Larval samples were sorted and identified in the laboratory under magnifying lamps and dissecting microscopes. Larvae were identified to the lowest possible taxonomic level using available guides and keys (Neira et al. 1998; Serafini and Humphries 2004), enumerated and assigned to estuarine-use guilds according to species life history (following Bice et al. 2018). Larval catch data are presented as raw counts and standardised for volume of water filtered (i.e. number of larvae per 1000 $m^3$ per sampling event).

Differences in catches (i.e. species identity and abundance [larvae per 1000 $m^3$ filtered water]), among barrages (i.e. Boundary Creek and Ewe Island), and sampling type (drift and tow), were assessed using non-metric multidimensional scaling (nMDS) ordination and two-factor PERMANOVA (Permutational Multivariate Analysis of Variance) ($\alpha = 0.05$). Analyses were performed on fourth-root transformed abundance data and Bray-Curtis similarity matrices in the software package PRIMER v. 6.12 and PERMANOVA (Anderson et al. 2008). When differences occurred, Similarity of Percentages (SIMPER) analysis was used to determine species contributing to differences in assemblages (a 40% cumulative contribution cut-off was applied).

### 2.3.2 Open bay and fishway trapping

From 5 August–2 October 2025, opportunistic sampling (in conjunction with reverse flow events) of upstream movement of juvenile and adult fish via open bays, and fishways, was conducted at Ewe Island and Tauwitchere barrages (Figure 1). Fish were sampled using cage traps, constructed of aluminium tube (50 x 50 mm) and clad with a combination perforated aluminium (3 mm) and knotless mesh (6 mm), specifically designed to fit open bays or fishway entrances/exits (Bice et al. 2017). The open bay adjacent the Ewe Island dual vertical-slot fishway was sampled with a cage trap 3.4 m long × 1.5 m wide × 1.4 m high and comprised three cone-shaped entrance funnels (0.5 m high × 0.15 m wide; Figure 2). The Ewe Island fishway was sampled using dual 'mirrored' traps, each measuring 0.9 m long × ~0.6 m wide × ~1.5 m high and featuring single cone-shaped entrance configurations (1.06 m high x 0.11 m wide) and designed to fit within the entrance of the fishway. The Tauwitchere trapezoidal fishway was sampled with a cage trap 3.4 m long × 1.5 m wide × 1.5 m high and comprised four cone-shaped entrance funnels (two 0.25 m high × 0.15 m wide and two 0.25 m high and 0.1 m wide) and designed to abut the upstream exit baffle of the fishway.

Figure 2. The Ewe Island open bay trap (viewed from the Coorong side) during a reverse flow.

During periods when reverse flow was predicted, traps were set for periods of 20–240 minutes. On each sampling occasion, traps were deployed by mobile crane with the assistance of SA Water staff, or manually in the case of the Ewe Island fishway. The period of sampling varied depending on the degree of mesh fouling on traps. Upon retrieval, all captured fish were transferred to aerated holding tubs before being identified to species and enumerated, and length measurements (±1 mm, fork length [FL] or total length [TL] depending on tail morphology) taken for up to 50 individuals per species per trapping event. All fish were subsequently released upstream of the barrage. The open bay and fishway at Ewe Island were sampled on seven and eight occasions, respectively, while the Tauwitchere trapezoidal fishway was sampled once.

At Ewe Island, differences in catches (i.e. species identity and abundance [fish/hour]), among sampling types (i.e. open bay versus fishway), and with regard to head differential during trapping (predominantly negative verse positive), were assessed using nMDS ordination and two-factor PERMANOVA ($\alpha$ = 0.05). Analyses were performed on fourth-root transformed abundance data and Bray-Curtis similarity matrices in the software package PRIMER v. 6.12 and PERMANOVA (Anderson et al. 2008). When differences occurred, SIMPER analysis was used to determine species contributing to differences in assemblages (a 40% cumulative contribution cut-off was applied).

### 2.3.3 High-frequency sonar

On three occasions at Boundary Creek Barrage, an Oculus M-Series multibeam imaging sonar was used as an additional means to qualitatively assess fish behaviour and movement through the open barrage bay. This was an initial trial of this technology which, if successful, may be used in future investigations. The sonar was set to an operating frequency range of 1.2 MHz and an operating distance of 3–5 m focal length; this setting has a horizontal aperture of 130° and a vertical aperture of 20°. The sonar was pole-mounted and fixed to fishway grid-mesh on the downstream sides of the barrages and positioned immediately below the water surface so as the beam covered the width and water column depth of the open barrage bay. Across the duration of reverse flow events, we used the sonar to perform a minimum of three 30-minute replicate recordings. These recordings commenced at the start of the reverse flow and continued throughout the event.

### 2.3.4 Acoustic telemetry

From 23–27 February 2026, an array of 11 VEMCO VR2W (180 kHz) acoustic receivers was deployed in Boundary Creek (Figure 1). Boundary Creek, as opposed to Ewe Island, was chosen as the location for this specific investigation due to its more confined geomorphology, which was more favourable to use of acoustic telemetry. Receivers were deployed every 500–1000 m between the upstream junction with Lake Alexandrina and the downstream junction with the Coorong. This included receivers within the immediate vicinity upstream and downstream of Boundary Creek Barrage. Receivers were deployed using marine grade rope, floats and concrete moorings or fixed to existing structures in the system. In the case of several receivers upstream of

Boundary Creek Barrage, these were deployed in conjunction with water physico-chemistry monitoring probes (see Section 2.1)

Immediately following receiver deployment, fish were captured for tagging from Boundary Creek using a seine net (180 m length, 4 m drop, 0.05 m mesh). Following capture, fish were anaesthetised using a 0.05 ml/L solution of AQUI-S in a 20 L dosing tank. When fully anaesthetised – characterised by loss of equilibrium and unresponsiveness to stimulus – fish were weighed (g), measured (mm FL/TL) and placed ventral side up in a V-shaped support. During surgery, a 0.02 ml/L solution of AQUI-S was irrigated over the gills to maintain anaesthesia. A small incision was made off-centre on the ventral surface, midway between the pelvic fins and anus, through which acoustic tags were inserted into the peritoneal cavity. All fish were fitted with a VEMCO model V5-2x (dimensions 12.7 x 5.7 mm; weight 0.77 g in air) acoustic tag. These tags have a random delay of 70–150 s, and estimated battery life of 179 days. Tag weight aimed to maintain a transmitter to fish weight ratio of <2% (Jepsen et al. 2002). Incisions were closed using a single cruciate suture. Following full recovery in an aerated tank (i.e. fish able to maintain their balance and freely swim), fish were released at their original capture location.

## *2.4 Hydrodynamic modelling*

There is a long history of hydrodynamic modelling across the CLLMM region. Early modelling efforts were undertaken using software such as RMA-2 and ELCOM, particularly to inform decision making during the Millennium Drought. Development of TUFLOW Finite Volume (TFV) hydrodynamic models for the site date back to 2011 and these models have been used to inform projects such as the Lake Albert Scoping Study (DEWNR, 2014) and to investigate the freshwater nature of Lake Alexandrina pre-development (Tibby et al. 2022). More recently different model iterations have evolved, most notably the Coorong Dynamics Model (Huang et al. 2024) and an upgraded Lower Lakes Model, developed to simulate the 2022–23 flood and scenarios of different high flow events (BMT, 2025). These models represent significant upgrades to detail and functionality over earlier models; however, they only simulate parts of the CLLMM region, i.e. only downstream or upstream of the barrages, respectively.

To make use of the most recent model developments to investigate connectivity across the barrages, these different models were integrated. For this work, the mesh of the Coorong and Murray Mouth from Huang et al. (2024) has been combined with the mesh of the Lower Lakes from BMT (2025), representing the lakes from Wellington to the barrages. To represent the seiching behaviour of water from the lakes upstream along the River Murray, the model mesh was also extended from Wellington to Lock 1. Material zones and bed roughness were adopted from the original models. This model domain also enables the recorded flow at Lock 1 to be used as a model boundary condition, as opposed to requiring an estimation of the flow at Wellington using different approaches. The resulting model mesh has 63,923 nodes with 65,891 2D cells and is seen in Figure 3.

### 2.4.1 Configuration

Initial testing found that a 3D representation of solute transport was required to more accurately represent the ingress of salt from the estuary into Lake Alexandrina. This was simulated using 5 "sigma" layers, which results in dynamic layer thickness that changes depending on the depth of the water in each model element.

Other model configuration settings were adopted based on the Coorong Dynamics Model, including second order mixing in the vertical direction, shortwave and net longwave heat exchange parameters, Elder horizontal scalar diffusivity, Smagorinsky momentum mixing and General Ocean Turbulence Model (GOTM). See Hipsey et al. (2022) for more details. For this mesh and model configuration, a runtime ratio of approximately 200 was achieved when simulated on CSIRO's Virga High Performance Computer on one NVIDIA H100 GPU.

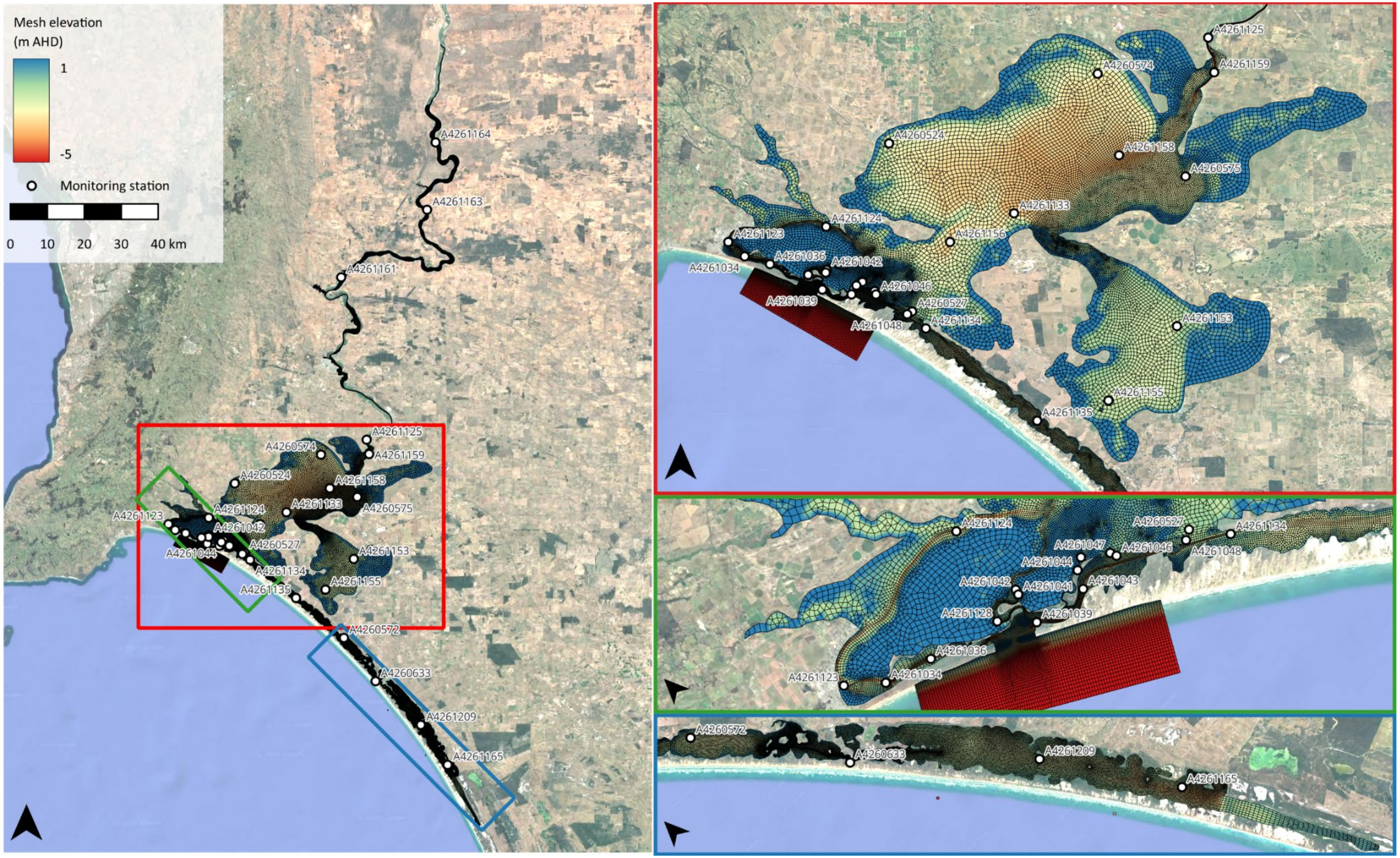


Figure 3. Model mesh and monitoring stations used for model evaluation. The coloured boxes on the main map (left) correspond to zoomed in insert maps (right). The Coorong is highlighted in the blue box, with the Coorong nominally split into the North Lagoon and South Lagoon at Parnka Point (A4260633).

### 2.4.2 Input data

#### Bathymetric updates

Given the focus on the Boundary Creek and Ewe Island barrages for operational trials in this project, the bathymetric data used to represent this part of the model was updated. SA Water surveyed this area on 11/2/2025 to provide an update to the bottom elevation data. The survey points were interpolated to a 2 m resolution raster and used to update the elevation of the model nodes using the Read Grid Zpts functionality in TFV.

The model bathymetry and underlying Digital Elevation Model (DEM) do not have accurate data downstream of the Boundary Creek Barrage, with a value of 0.3 m AHD. This is expected to be interpolated from the water surface at the time of survey, as it is too high to be an accurate representation of the bed elevation. To provide a more realistic estimate this elevation was reduced to -0.6 m AHD.

Surveys of the bathymetry directly inside the Murray Mouth are undertaken regularly to inform dredging operations managed by SA Water. These data were used where necessary to update the model depending on the simulation period. For the evaluation period, the survey from 13/1/2022 was used.

#### Meteorology

Bureau of Meteorology Atmospheric high-resolution Regional Reanalysis for Australia (BARRA) – Version 2 was used to provide most of the meteorological boundary conditions (Su et al. 2022). BARRA is an atmospheric reanalysis product using the ACCESS model and assimilates observed climate data to improve the outputs. The BARRA outputs are available at a 4 km spatial and 1 hourly temporal resolution and were collated to represent the model domain in a consistent manner. Variables of wind speed, air temperature, mean sea level pressure, relative humidity, downwelling shortwave radiation and net longwave radiation were obtained.

While BARRA also has a modelled precipitation variable, the system does not assimilate observed data for rainfall. Instead, recorded rainfall was used as the input to the model, based on the daily average from the Milang and Meninge stations as available from SILO, https://www.longpaddock.qld.gov.au/silo, applied across the model domain.

#### Flow and water level boundaries

Several time series of inflow (discharge), salinity, and water temperature were used as inputs to the model. Data were sourced from Water Data SA, water.data.sa.gov.au, unless stated otherwise. The inputs used were:

- At Lock 1, daily discharge was derived from River Murray Downstream of Lock 1, A4260903, with salinity and water temperature from River Murray at Swan Reach, A4261164.
- At Salt Creek Outlet, A2390568, for flow, salinty and water temperature into the Coorong from the south east drainage network.

- Modelled flow at each of the Eastern Mount Lofty Ranges tributaries provided by DEW, Angas, Bremer, Finniss, Currency, Marne, Saunders, Tookayerta Rivers. For these relatively small inflows nominal salinity of 0.5 g/L and water temperature of 18°C were assumed.

To represent the water balance accurately, diversions from the river and lakes were derived from aggregated monthly diversions provided by SA Water. These diversions were applied across the model domain using nominal proportions to represent offtakes at Mannum, Murray Bridge, Swan Reach and Tailem Bend.

Finally, the ocean boundary condition was represented based on the tide height encoder data at Victor Harbor maintained by Flinders Ports, applied at a 10-minute interval. A constant salinity of 35 g/L was assumed, and water temperature recorded in the Coorong Channel at Barker Knoll, A4261039.

#### Barrage flow

Hydraulic relationships representing the different barrages, and different gates and sill heights at each barrage, were derived from DEW (2021). In previous TFV models, these relationships have been used to determine the flow through fully open barrages for different combinations of upstream and downstream water level, and a time series of the fraction of the barrage open (based on the number of gates) used to scale the total flow. This approach makes it difficult to represent the fine scale of barrage operations; for example, the differences between stop log and radial gate bays, or the number of stop logs removed for a given bay.

To enable this level of detail to be represented, the equations used in DEW's barrage calculator were used to derive hourly time series of flow through each barrage based on the gate settings, either the historical record for evaluation or adapted for specific scenarios. The equations were modified to calculate reverse flow from the estuary back into the lakes, which the current calculator, focused on flow over the barrages, ignores.

The upstream and downstream water levels must be input to the barrage flow calculation prior to model simulation. This is a limitation of this offline approach, with the water levels specified outside of the model rather than using the modelled levels dynamically. If the modelled levels were different to those assumed (typically from observations), the barrage flow calculations and model simulation were rerun.

### 2.4.3 Model evaluation

The underpinning models, including model meshes and configuration, have been developed and tested over many years, with calibration results documented in past reports (including BMT 2025; Brookes et al. 2022; Hipsey et al. 2022; Huang et al. 2024). To ensure that salt movement into Lake Alexandrina was represented adequately, the model was tested over a period where this process was apparent in the historical observed data. The simulation period selected was 1/5/2022 – 1/9/2022, with main period of reverse for 44 hours from 30/5/2022, where the high tide and storm surge increase in the Coorong water level above 0.9 mAHD coinciding with the wind direction decreased the lake level directly upstream of Tauwitchere Barrage to below 0.4 mAHD at times. The resulting salinity in Lake Alexandrina increased from less than 0.2 g/L (333 EC) at the start of the simulation to peak at 0.8 g/L (1400 EC) at Milang Jetty (A4260524), 3.9 g/L at Beacon 95 3 km west of Point McLeay (A4261156) and 2.1 g/L at Beacon 97 offshore Raukkan (A4261133). Monitoring sites with salinity, water temperature and/or water level were identified to test the model performance. The sites used are outlined in Table 1 and shown on Figure 3.

Table 1. Monitoring stations used for hydrodynamic model evaluation. All data sourced from water.data.sa.gov.au. See Figure 3 for locations. temp = temperature.

| ZONE | STATION | NAME | WATER LEVEL | SALINITY & TEMP. |
|---|---|---|---|---|
| River Murray | A4261125 | River Murray at Wellington Pontoon (AMTD 77.8km) | ✓ | ✓ |
| | A4261159 | River Murray 2km downstream Wellington Ferry | ✓ | ✓ |
| | A4261161 | River Murray adjacent Mannum Town Wharf | ✓ | ✓ |
| | A4261163 | River Murray at Walker Flat (AMTD 207 km) | ✓ | ✓ |
| | A4261164 | River Murray 3km downstream Swan Reach Ferry | ✓ | ✓ |
| Lake Albert | A4261153 | Lake Albert Near Causeway at Waltowa Swamp | ✓ | ✓ |
| | A4261155 | Lake Albert 2km North Warringee Point | ✓ | ✓ |
| Lake Alexandrina | A4260524 | Lake Alexandrina at Milang Jetty (Recorder) | ✓ | ✓ |
| | A4260574 | Lake Alexandrina near Mulgundawa (Recorder) | ✓ | ✓ |
| | A4260575 | Lake Alexandrina at Poltalloch Plains (Recorder) | ✓ | ✓ |
| | A4261123 | Goolwa Channel at Signal Point (Beacon 23) | ✓ | ✓ |
| | A4261124 | Goolwa Channel 2km West Clayton | ✓ | ✓ |
| | A4261133 | Lake Alexandrina at Beacon 97 (Offshore Raukkan) | ✓ | ✓ |
| | A4261156 | Lake Alexandrina 3km West Point McLeay | ✓ | ✓ |
| | A4261158 | Lake Alexandrina 4km West Pomanda Point | ✓ | ✓ |
| Upstream of Barrages | A4260527 | Lake Alexandrina at Tauwitchere Barrage | ✓ | |
| | A4261034 | Lake Alexandrina at Goolwa Barrage | ✓ | ✓ |
| | A4261042 | Lake Alexandrina at Mundoo Barrage | ✓ | |
| | A4261045 | Lake Alexandrina at Boundary Creek Barrage | ✓ | ✓ |
| | A4261047 | Lake Alexandrina at Ewe Island Barrage | ✓ | ✓ |
| Estuary | A4261036 | Goolwa Channel at Beacon 12 (Adjacent Reedy Island) | | ✓ |
| | A4261039 | Coorong Channel adjacent Barker Knoll | ✓ | ✓ |
| | A4261041 | Mundoo Channel at Mundoo Barrage | ✓ | |
| | A4261043 | Coorong Channel near Beacon 1 (Ewe Island Shacks) | ✓ | ✓ |
| | A4261044 | Boundary Creek downstream Boundary Creek Barrage | ✓ | ✓ |
| | A4261046 | Coorong at Ewe Island Barrage | ✓ | ✓ |
| | A4261048 | Tauwitchere Channel at Tauwitchere Barrage | ✓ | ✓ |
| | A4261128 | Mundoo Channel at Channel Drive Boat Ramp | ✓ | ✓ |
| North Coorong | A4260572 | The Coorong at Robs Point | ✓ | ✓ |
| | A4261134 | The Coorong at Pelican Point | ✓ | ✓ |
| | A4261135 | The Coorong at Long Point | ✓ | ✓ |
| South Coorong | A4260633 | Coorong at Parnka Point | ✓ | ✓ |
| | A4261165 | The Coorong NW Snipe Island | ✓ | ✓ |
| | A4261209 | Coorong near Woods Well | ✓ | ✓ |

Data from these stations were used to generate initial conditions for the model, using inverse distance weighting separately for each zone defined in Table 2.

Table 2. Volume of barrage flow (GL) in each model simulation

| SIMULATION PERIOD | HISTORICAL GATES | NO CLOSURE | WATER LEVEL TRIGGER |
|---|---|---|---|
| 1May – 1 Sept 2022 | 3312 | 3342 | 3601 |
| 20 Jun – 27 Oct 2025 | 553 | 574 | 609 |

The results in Appendix A, along with the long history of evaluation of the TFV models of the CLLMM site, suggest the model is a suitable tool for the evaluation of short-term salinity dynamics across the barrages.

### 2.4.4 Barrage scenarios

Along with the 2022 simulation period used to test the ability of the model to represent reverse flow events, the period overlapping the physico-chemical and biological sampling in this study was also simulated. The model period commenced on 20/6/2025 and ended on 27/10/2025, aligned to the end of the BARRA climate data available at the time of model simulations (there is typically a 3–4-month lag in reanalysis data becoming available). The two 4-month simulations provide two different inflow periods to compare, with the average Lock 1 flow 6980 ML/d for the 2025 period and 33,640 ML/d over the 2022 period.

The barrage flow applied in the scenarios was calculated using:

- *Historical gates*: barrage flow was calculated based on recorded gate openings and recorded water levels upstream and downstream of the barrages for the relevant climate period.
- *No closure*: removes periods where the gates were closed to prevent reverse flow. If gates were closed for less than 7 days, this scenario keeps the gates open. This scenario does not open additional gates, i.e. it does not represent the barrages fully open.
- *Water level trigger*: this is based on the *No closure* scenario but all gates at a barrage are closed if the observed water level on the Coorong side of the barrage is more than 0.05 m higher than the observed water level on the lake side. This allows connectivity across the barrage as long as possible but prevents large salt ingress events when there is a substantial negative head difference across the barrage. This scenario represents an upgrade to barrage automation capability, where currently barrages can be operated electronically remotely or on a timer, adding additional functionality to be operated based on water level sensors.

The barrage flow used for each barrage in each period is shown in Figure 4 and Figure 5. The changes to the barrage gate settings results in minor differences in barrage flow volumes (Table 1).

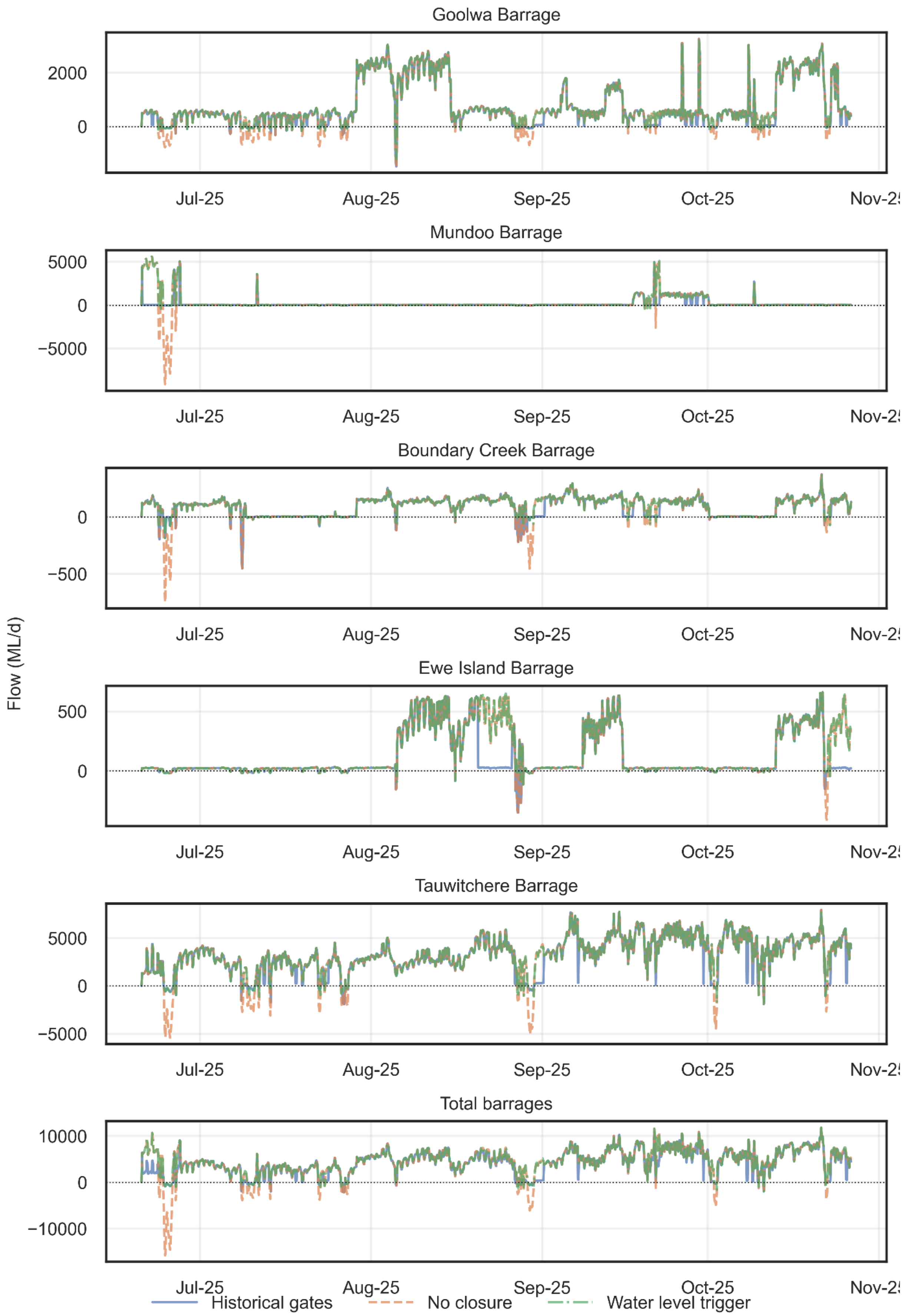


Figure 4. Barrage flow (ML/d) time series for each barrage and combined total flow for the 2025 scenarios. Negative flow indicates reverse flow.

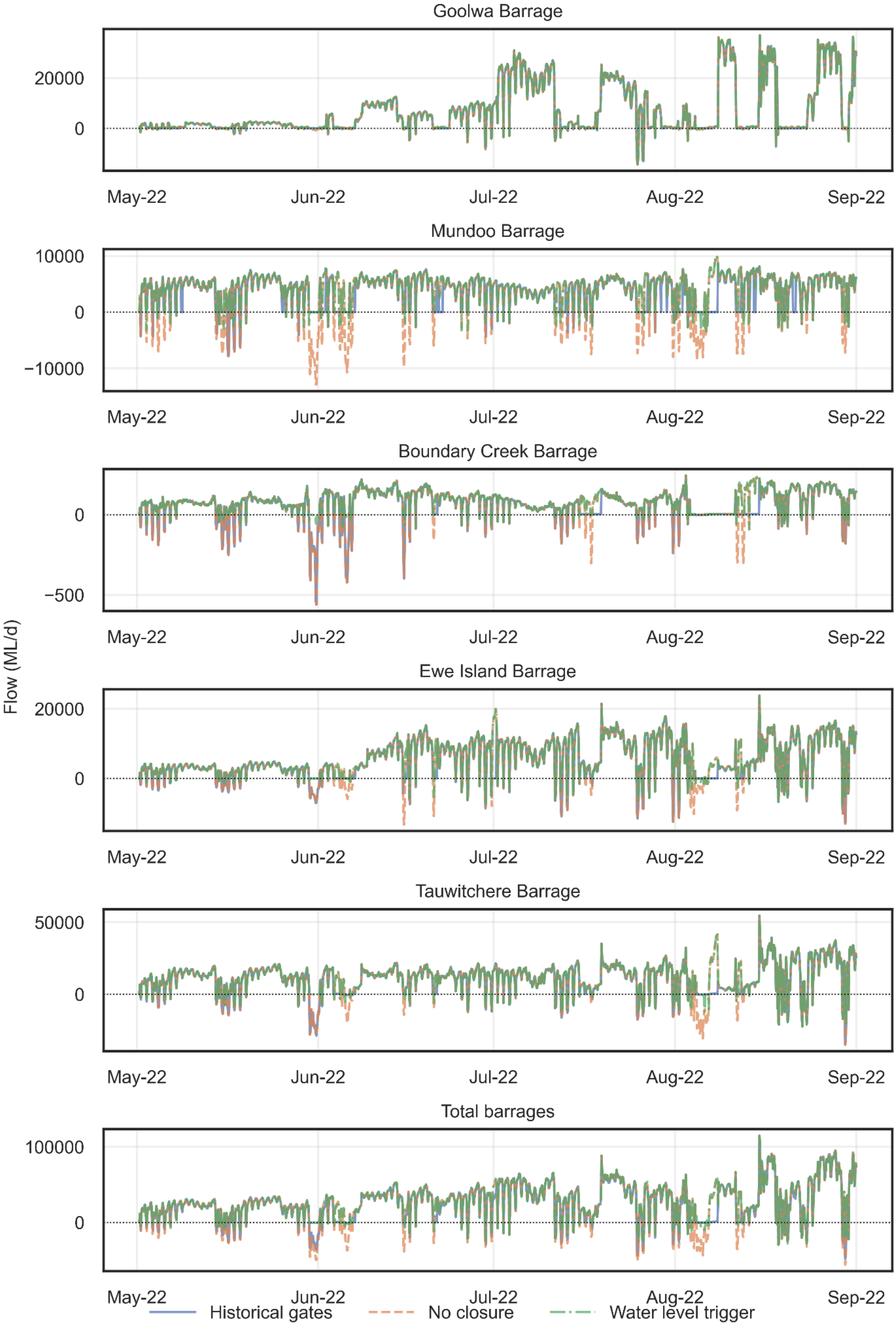


Figure 5. Barrage flow (ML/d) time series for each barrage and combined total flow the 2022 scenarios. Negative flow indicates reverse flow.

# 3 Results

## *3.1 Observed hydrological and operational context for the study*

Over the course of this study (June 2025–March 2026), River Murray flow into the Lower Lakes, as recorded at Lock 1, was generally low (<8,000 ML/d), with small flow pulses (12,000–15,000 ML/d) in September, October and November 2025 (Figure 6). Flow from the barrages was prioritised at Tauwitchere Barrage to direct freshwater flow toward the Coorong North Lagoon, with 6–16 radial gates open between July and October 2025, with some short periods of closure to prevent salt ingress into the lakes during reverse flow events (Figure 7). The number of gates open at Tauwitchere peaked at 40 for a 5-day period at the end of November 2025.

At our study sites, Ewe Island and Boundary Creek Barrages, discharge was considerably less than Tauwitchere (Figure 6), with only one gate in addition to fishways open at each barrage. Barrage gates were also closed more frequently, particularly at Ewe Island (Figure 7). Following the peak flow in late November 2025, all barrage gates were closed by 15 December 2025, in association with low River Murray inflows. All barrage gates, except for fishways, remained closed for the majority of summer 2025–2026, with a period of closure of 71–88 days at Goolwa, Ewe Island and Tauwitchere barrages. On 6 February 2026, the modified attractant gate at Boundary Creek was reopened, with a small number of gates reopening at Goolwa, Ewe Island and Tauwitchere barrages over 24 February to 4 March 2026.

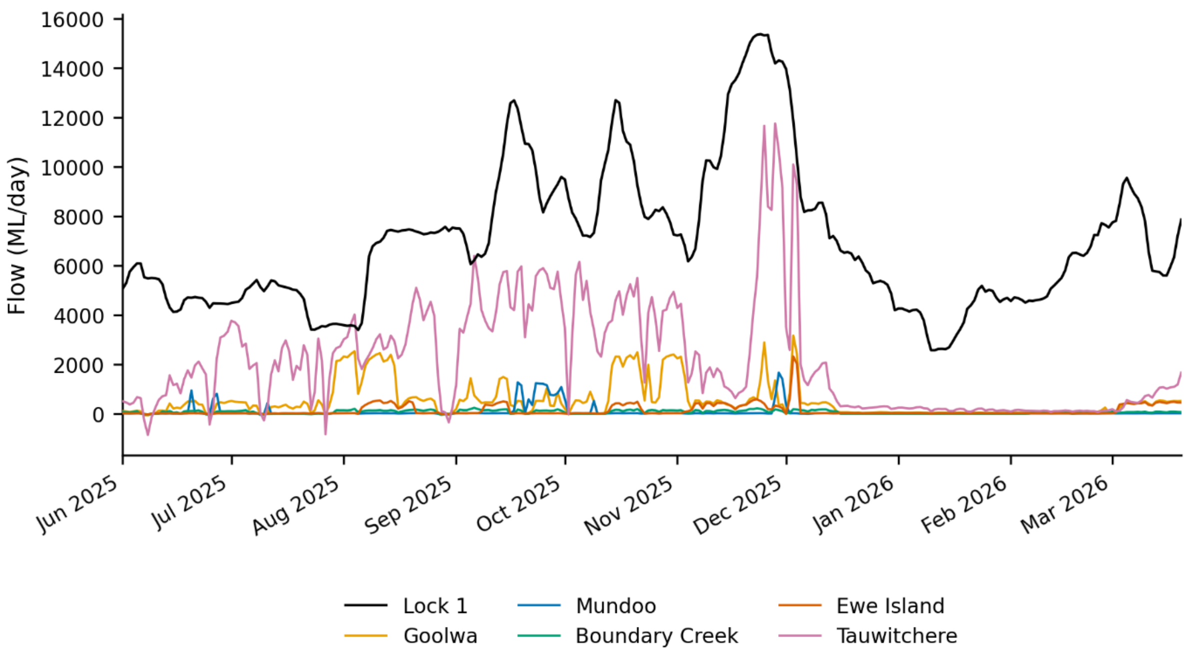


Figure 6. Flow (ML/d) at Lock 1 and across each of the barrages during the study period.

Potential for reverse flow at all barrages can be seen as the negative flow rates, most noticeable at Tauwitchere (Figure 6), and in water level data, where water levels downstream of the barrages exceed those upstream (Figure 7), predominantly from June–August 2025. These events also coincide with barrage closure, as displayed in

Figure 7. These events tend to reduce in frequency and magnitude moving into spring and summer, as a lack of storm events, as well as high pressure systems, result in lower water levels in the Coorong, even as the lake levels reduce over summer.

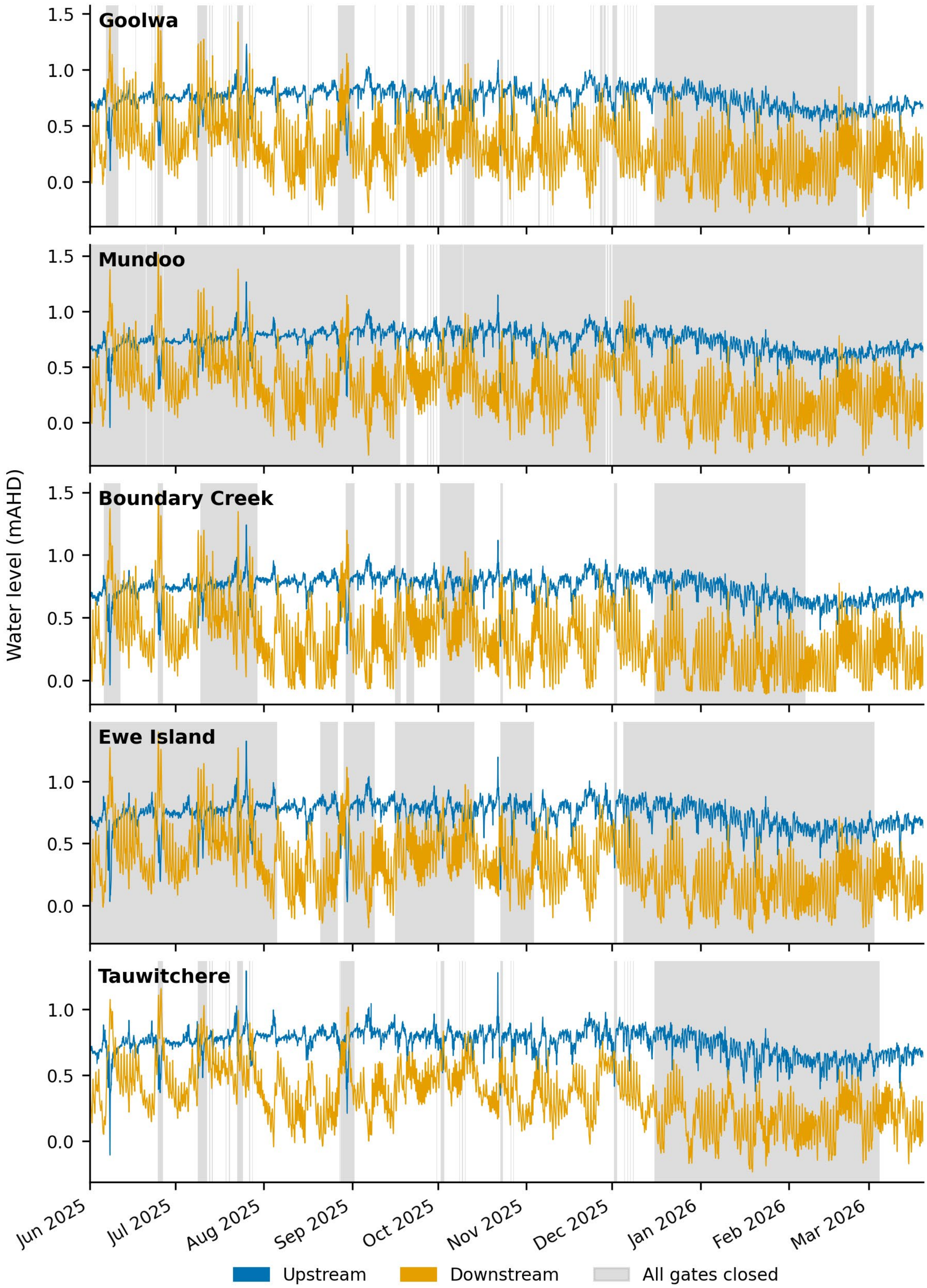


Figure 7. Hourly water level (mAHD) upstream and downstream of each barrage, and periods where all gates were closed shaded grey (excluding fishways). Periods when downstream levels exceed upstream levels indicate potential reverse flow.

## *3.2 Biology*

### 3.2.1 Larval fish

Across five drift sampling events at Boundary Creek and Ewe Island barrages, a total of 1009 larval fish were captured from 11 species, comprising a diversity of life history strategies (Table 3). The overall catch was dominated by the catadromous common galaxias (*Galaxias maculatus*, 74%) and the marine-estuarine opportunist sandy sprat (*Hyperlophus vittatus*, 21%). The freshwater bony herring (*Nematalosa erebi*, 2%) and Australian smelt (*Retropinna semoni*, 1%) made notable smaller contributions, while the remaining 11 species comprised ~2% of the catch. Peak abundance was recorded at Boundary Creek on 27 August, when 566 common galaxias were sampled from a single net over a 20-minute period. Across 12 tow sampling events immediately upstream of Boundary Creek and Ewe Island barrages, a total of 144 larvae were sampled from five species, with common galaxias representing ~95% of the catch.

Table 3. Summary of fish species and total number of larvae captured from drift-net sampling of open bays and tow-net sampling of areas immediately upstream of Boundary Creek and Ewe Island barrages in August–October 2025. Species are categorised using estuarine use guilds from Potter et al. (2015) and designations presented by Bice et al. (2018). Numbers of older life stages (e.g. juveniles) are presented in brackets.

| COMMON NAME | SCIENTIFIC NAME | GUILD | DRIFT | | | TOW | | |
|---|---|---|---|---|---|---|---|---|
| | | | BOUNDARY CREEK | EWE ISL. | TOTAL | BOUNDARY CREEK | EWE ISL. | TOTAL |
| | | *N* events | 2 | 3 | 5 | 8 | 4 | 12 |
| | | *N* species | 8 | 8 | 11 | 4 | 4 | 5 |
| Australian smelt | *Retropinna semoni* | Freshwater estuarine opportunist | 0 (2) | 1 (10) | 1 (12) | 0 | 0 | 0 |
| Bony herring | *Nematalosa erebi* | Freshwater estuarine opportunist | 2 | 18 | 20 | 2 | 1 | 3 |
| Flat-headed gudgeon | *Philypnodon grandiceps* | Freshwater estuarine opportunist | 7 | 1 | 8 | 2 | 1 | 3 |
| Congolli | *Pseudaphritis urvillii* | Catadromous | 3 | 0 | 3 | 0 | 0 | 0 |
| Common galaxias | *Galaxias maculatus* | Semi-catadromous | 725 | 33 | 758 | 123 | 14 | 127 |
| Smallmouth hardyhead | *Atherinosoma microstoma* | Solely estuarine | 1 | 0 | 1 | 0 | 0 | 0 |
| Tamar river goby | *Afurcagobius tamarensis* | Solely estuarine | 0 | 1 | 1 | 0 | 0 | 0 |
| Gobiidae sp. | *n/a* | Solely estuarine, estuarine and marine | 1 | 1 | 2 | 0 | 1 | 1 |
| Yelloweye mullet | *Aldrichetta forsteri* | Marine estuarine-opportunist | 0 | 0 (2) | 0 (2) | 0 (1) | 0 | 0 (1) |
| Sandy sprat | *Hyperlophus vittatus* | Marine estuarine-opportunist | 210 | 0 | 210 | 0 | 0 | 0 |
| Soldierfish | *Gymnapistes marmoratus* | Marine estuarine-opportunist | 0 | 5 | 5 | 0 | 0 | 0 |
| | | **Total** | **949 (2)** | **60 (12)** | **1009 (14)** | **127 (1)** | **17** | **144 (1)** |

nMDS of assemblage data exhibited groupings of larval fish assemblages by barrage (i.e. Boundary Creek or Ewe Island) and sampling type (i.e. drift verse tow; Figure 8). PERMANOVA revealed significant differences among barrages (*Pseudo-*$F_{1, 33}$ = *6.85, p = 0.003*) and sampling types (*Pseudo-*$F_{1, 33}$ = 6.87, *p* = 0.003), and a significant interaction between factors (*Pseudo-*$F_{1, 33}$ = 2.82, *p* = 0.041), indicating differences in assemblages among sampling types were not consistent across the two barrages. Pairwise comparisons indicated samples from drift- and tow-nets were significantly different at Boundary Creek (*t* = 2.37, *p* = 0.004) but not Ewe Island (*t* = 1.43, *p* = 0.083). SIMPER revealed the difference among drift and tow samples was primarily driven by greater abundances of sandy sprat and common galaxias (65.7% cumulative contribution) in drift samples.

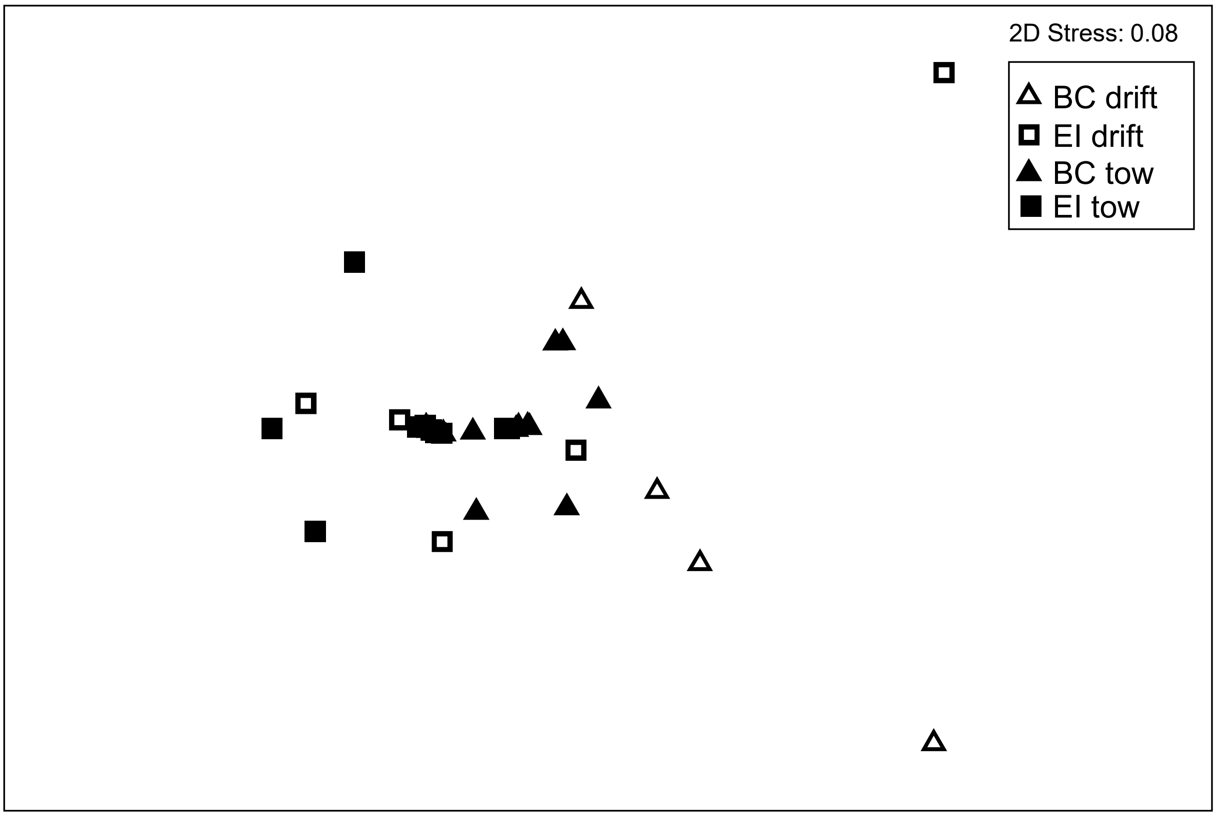


Figure 8. Non-Metric Multidimensional-Scaling (nMDS) plot of larval fish assemblages sampled from drift-net sampling of open bays and tow-net sampling of areas immediately upstream of Boundary Creek (BC) and Ewe Island (EI) barrages in August–October 2025.

### 3.2.2 Open bay and fishway trapping

Across the three sites and 16 sampling events, a total of 831 fish were sampled from 13 species (Table 3). The overall catch was dominated by the freshwater Australian smelt (*Retropinna semoni*, 87%) with smaller contributions from the estuarine smallmouth hardyhead (*Atherinosoma microstoma*, 4%), catadromous congolli (*Pseudaphritis urvillii*, 3.6%) and common galaxias (*Galaxias maculatus*, 1%), and marine-estuarine opportunist sandy sprat (*Hyperlophus vittatus*, 1%). The remaining eight species collectively comprised 2% of the total catch.

nMDS of assemblage data from Ewe Island exhibited some grouping of assemblages by sampling site and negative/positive head differential during trapping (i.e. predominantly downstream discharge or predominantly reverse flow) (Figure 9). PERMANOVA indicated there was no significant difference among sites ($Pseudo\text{-}F_{1,\,14} = 0.54$, $p = 0.87$) but a significant difference among sampling events undertaken during positive and negative head differential ($Pseudo\text{-}F_{1,\,14} = 4.01$, $p < 0.001$), with no interaction among factors ($Pseudo\text{-}F_{1,\,14} = 0.55$, $p = 0.87$). SIMPER indicated the primary difference among catches during negative and positive head differential was primarily driven (43% of variation) by greater abundances of Australian smelt during trapping events with positive head differential.

Table 4. Summary of species and total number of fish sampled from the open bay and dual-vertical-slot fishway on Ewe Island Barrage, and the trapezoidal fishway on Tauwitchere Barrage in August–October 2025. Species are categorised using estuarine use guilds from Potter et al. (2015) and designations presented by Bice et al. (2018).*Non-native species.

| COMMON NAME | SCIENTIFIC NAME | GUILD | EWE ISL. OPEN BAY | EWE ISL. FISHWAY | TAUWITCHERE TRAP. FISHWAY | TOTAL |
|---|---|---|---|---|---|---|
| | | *N* events | 7 | 8 | 1 | |
| | | *N* species | 10 | 10 | 5 | |
| Australian smelt | *Retropinna semoni* | Freshwater estuarine opportunist | 264 | 459 | 3 | **726** |
| Bony herring | *Nematalosa erebi* | Freshwater estuarine opportunist | 1 | 1 | 0 | **2** |
| Flat-headed gudgeon | *Philypnodon grandiceps* | Freshwater estuarine opportunist | 2 | 3 | 1 | **6** |
| Redfin perch | *Perca fluviatilis** | Freshwater straggler | 1 | 1 | 0 | **2** |
| Congolli | *Pseudaphritis urvillii* | Catadromous | 0 | 30 | 0 | **30** |
| Common galaxias | *Galaxias maculatus* | Semi-catadromous | 1 | 9 | 0 | **10** |
| Smallmouth hardyhead | *Atherinosoma microstoma* | Solely estuarine | 1 | 1 | 0 | **2** |
| Lagoon goby | *Tasmanogobius lasti* | Solely estuarine | 1 | 1 | 1 | **3** |
| Blue-spot goby | *Pseudogobius olorum* | Solely estuarine | 0 | 0 | 1 | **1** |
| Yelloweye mullet | *Aldrichetta forsteri* | Marine estuarine-opportunist | 1 | 1 | 0 | **2** |
| Sandy sprat | *Hyperlophus vittatus* | Marine estuarine-opportunist | 9 | 0 | 0 | **9** |
| Greenback flounder | *Rhombosolea tapirina* | Marine estuarine-opportunist | 2 | 1 | 0 | **3** |
| Velvet leatherjacket | *Meuschenia scaber* | Marine straggler | 0 | 0 | 1 | **1** |
| | | **Total** | **316** | **508** | **7** | **831** |

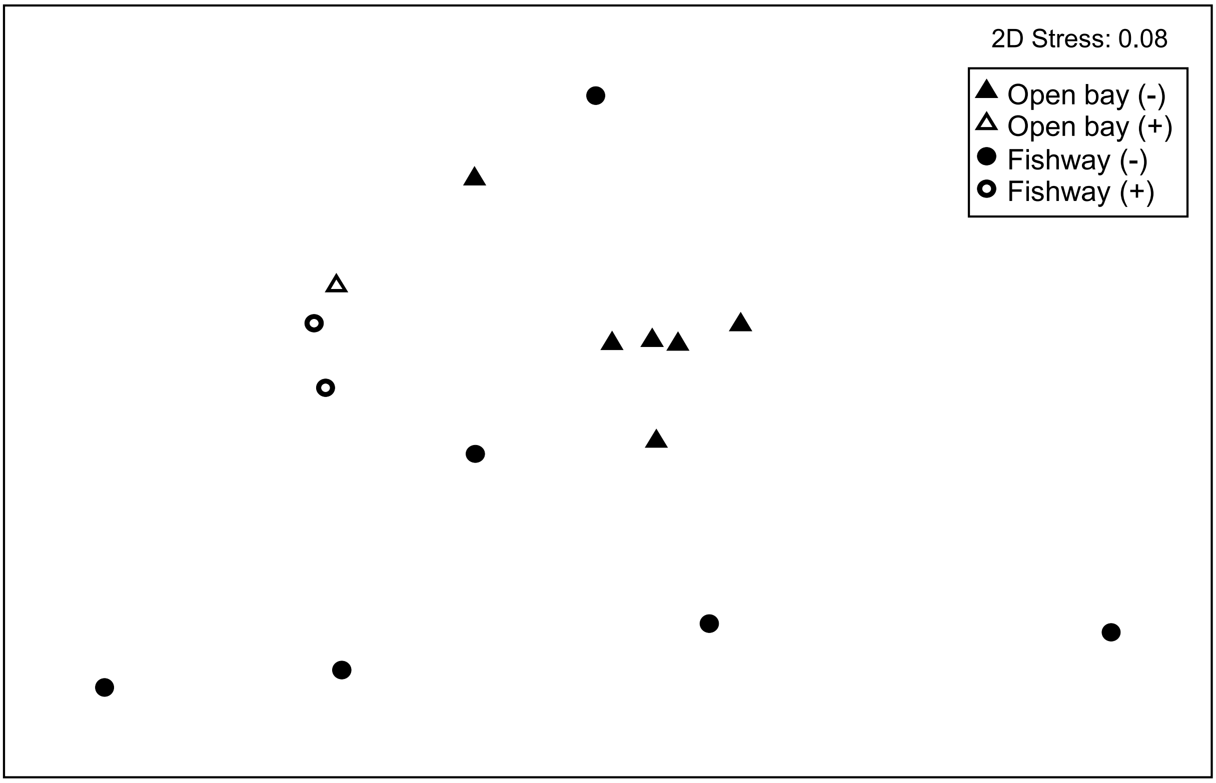


Figure 9. Non-Metric Multidensional-Scaling (nMDS) plot of fish assemblages sampled from the Ewe Island open bay (triangles) and dual vertical-slot fishway (circles). Sampling events when reverse flow predominated (i.e. negative [-] head differential) are indicated by closed symbols and when downstream flow predominated (i.e. positive [+] head differential) are indicated by open symbols.

### 3.2.3 High-frequency sonar

An initial trial of high-frequency sonar image recording was undertaken predominantly at Boundary Creek Barrage during reverse flow. At the time of reporting, these data are yet to be quantitatively analysed but on several occasions schools of large-bodied (~300–500 mm TL) fish were observed swimming in the vicinity of the open gate, adjacent the fishway (Figure 10). The species in Figure 10 remain unverified.

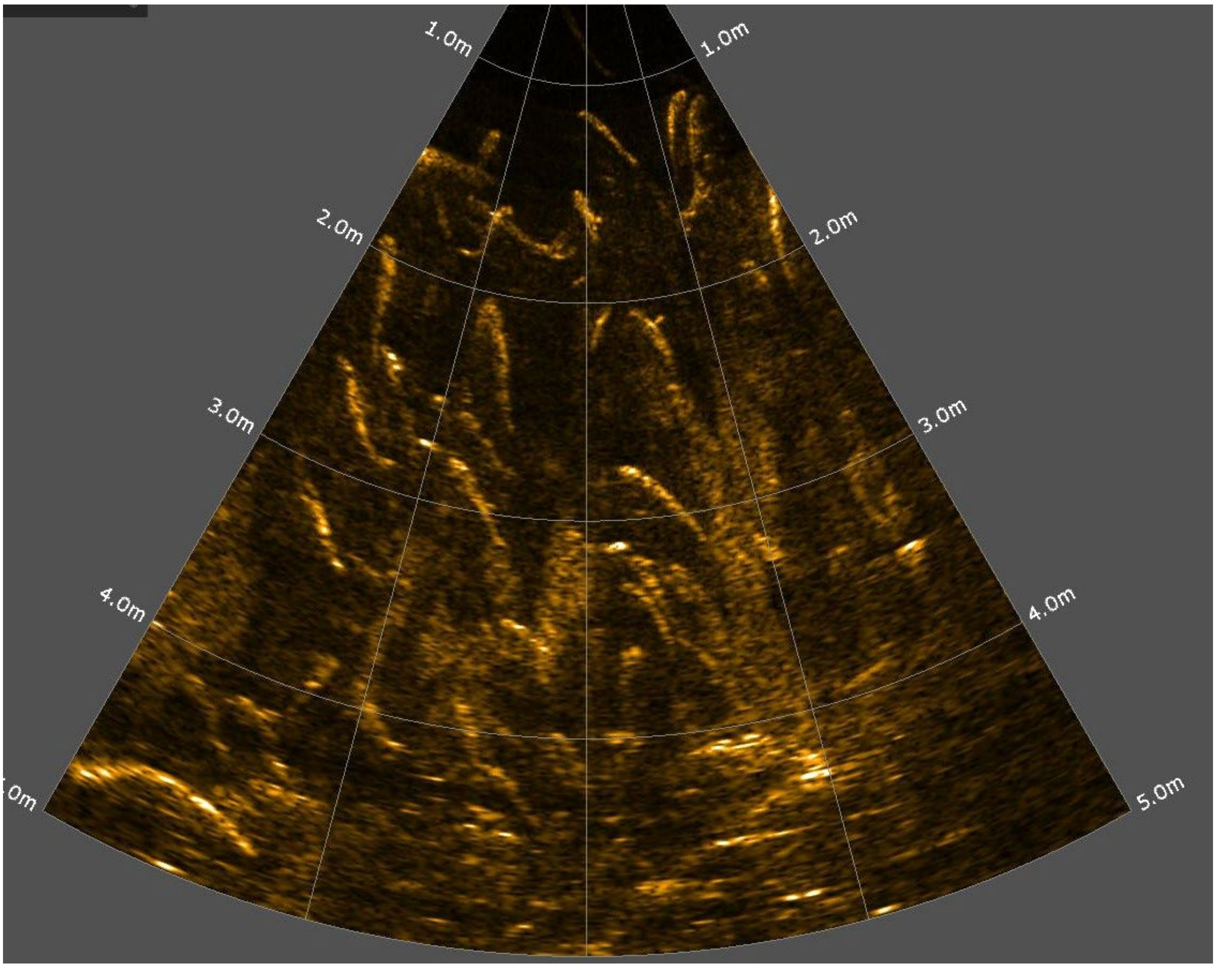

Figure 10. Fish observed with the Oculus M-Series multibeam imaging sonar immediately upstream of the Boundary Creek Barrage at the start of a reverse flow event.

### 3.2.4 Acoustic telemetry

A total of seven adult black bream (*Acanthopagrus butcheri*, mean FL = 308 ± 0.9 mm, mean weight = 643 ± 4.3 g) and ten juvenile mulloway (*Argyrosomus japonicus*, mean TL = 271 ± 0.3 mm, mean weight = 187 ± 0.9 g) were captured and tagged in Boundary Creek downstream of the barrage (Table 5). At the time of reporting, this investigation of fish movement and habitat use in association with bi-directional flow at Boundary Creek Barrage remains ongoing.

Table 5. Summary of information for fish tagged in Boundary Creek, downstream of the barrage. Fish lengths were recorded as total length for mulloway and fork length for black bream.

| COMMON NAME | SCIENTIFIC NAME | DATE TAGGED | FISH LENGTH (MM) | FISH WEIGHT (G) | ACOUSTIC TAG ID | |
|---|---|---|---|---|---|---|
| Mulloway | *Argyrosomus japonicus* | 4/02/2026 | 258 | 181 | ID8306 | 1663762 |
| Mulloway | *Argyrosomus japonicus* | 4/02/2026 | 278 | 198 | ID8301 | 1663757 |
| Mulloway | *Argyrosomus japonicus* | 4/02/2026 | 293 | 244 | ID8317 | 1663773 |
| Mulloway | *Argyrosomus japonicus* | 4/02/2026 | 274 | 193 | ID8312 | 1663768 |
| Mulloway | *Argyrosomus japonicus* | 4/02/2026 | 281 | 190 | ID8307 | 1663763 |
| Mulloway | *Argyrosomus japonicus* | 4/02/2026 | 273 | 191 | ID8302 | 1663758 |
| Mulloway | *Argyrosomus japonicus* | 4/02/2026 | 267 | 184 | ID8322 | 1663778 |
| Mulloway | *Argyrosomus japonicus* | 4/02/2026 | 261 | 156 | ID8303 | 1663759 |
| Mulloway | *Argyrosomus japonicus* | 4/02/2026 | 264 | 178 | ID8308 | 1663764 |
| Mulloway | *Argyrosomus japonicus* | 4/02/2026 | 263 | 158 | ID8327 | 1663783 |
| Black bream | *Acanthopagrus butcheri* | 5/02/2026 | 286 | 489 | ID8304 | 1663760 |
| Black bream | *Acanthopagrus butcheri* | 4/02/2026 | 274 | 423 | ID8318 | 1663774 |
| Black bream | *Acanthopagrus butcheri* | 4/02/2026 | 345 | 904 | ID8311 | 1663767 |
| Black bream | *Acanthopagrus butcheri* | 4/02/2026 | 326 | 748 | ID8321 | 1663777 |
| Black bream | *Acanthopagrus butcheri* | 4/02/2026 | 293 | 536 | ID8316 | 1663772 |
| Black bream | *Acanthopagrus butcheri* | 4/02/2026 | 279 | 458 | ID8326 | 1663782 |
| Black bream | *Acanthopagrus butcheri* | 4/02/2026 | 350 | 946 | ID8313 | 1663769 |

## *3.3 Hydrodynamics and water quality during the experimental period*

### 3.3.1 Water physico-chemistry

Salinity (measured by EC) at the logger sites upstream of the barrages is shown in Figure 11 and Figure 12 (see observed data) for the Boundary Creek and Ewe Island sensors respectively. Several salinity spikes were observed corresponding to periods when gates were open (see Figure 7) and reverse flows occurred, particularly in July–August 2025. Salinity increases during reverse flow events were attenuated with distance away from the barrages.

Some salinity stratification occurred during reverse flow events. Specifically, a narrow (<0.5 m) zone of more saline water was detected near the bed at some sites near the barrages. Averaged across all the profiles the bed water EC was approx. 600 µS/cm higher than the surface water EC. Often, however, the water column was well mixed.

Measured water velocity in the vicinity of the barrages showed typical low levels, with a median velocity of 0.02 m/s and 0.04 m/s at Boundary Creek and Ewe Island, respectively. Higher velocities into the lakes (indicated by negative values in the bottom panel of Figure 14 and Figure 15) were experienced in at the time of reverse flow events. For example, during an event in early September 2025, water velocities reached >0.5 m/s upstream of Boundary Creek Barrage and >0.15 m/s from the Ewe Island Barrage.

Water temperature showed seasonal changes but did not appear significantly affected by reverse flow events. Water quality profiling showed temperature stratification was minimal (i.e. <0.04°C average difference between top and bottom of water column). Dissolved oxygen averaged 95.8% saturation while turbidity averaged 96.4 NTU, with minimal stratification apparent at time of profiling (daytime).

### 3.3.2 Model comparison to loggers

The model output for 2025 conditions is compared to the data recorded from the *in situ* salinity and velocity sensors upstream of Boundary Creek and Ewe Island barrages (see Figure 1). At the time of modelling, climate data available to input into the model were current to October 2025. The model results have been presented in a number of ways to represent the variability through the water column, with the model output for the top layer, bottom layer and the average across the 5 layers used by the model.

The model provides a reasonable representation of the salinity dynamics in Boundary Creek, considering the coarse representation of the creek in this model that covers the region from Lock 1 to the Murray Mouth, including all of the Coorong. The first event in July is overestimated, with higher salinities at BCK1 in the model and the influence of this reverse event persisting up to BCK5, whilst the observed data suggest this signal is largely attenuated by BCK3 (Figure 11). The second event later in July is accurately represented by the model, particularly when focusing on the bottom layer of the model results (dotted line in Figure 11). The August event is again overestimated by the model, with observed data indicating that raised salinities were again largely attenuated by BCK3. Both events that are overestimated may be a result of the model simulating reverse flow through an open gate which, in reality, appears to have been shut just prior to the modelled increase in salinity (see grey shading in Figure 11).

The same two reverse flow events are observed in the Ewe Island sensor data (Figure 12). The model starts with a higher salinity than observed by the sensors, with a larger reverse flow event earlier in the model simulation, and hence the July salinities are overestimate at EWE1 (Figure 12). At EWE2 and EWE3 for the July event, there is good agreement between modelled and observed data, particularly the bottom layer of the model (dotted line in Figure 12). For the August event, the model underestimates EWE1 and EWE2, but provided an accurate representation of the salinity recorded at EWE3. These results could be a function of the representation of the flow through the barrage in the model, which is distributed across the barrage compared to focused through one gate (the setting in our trials).

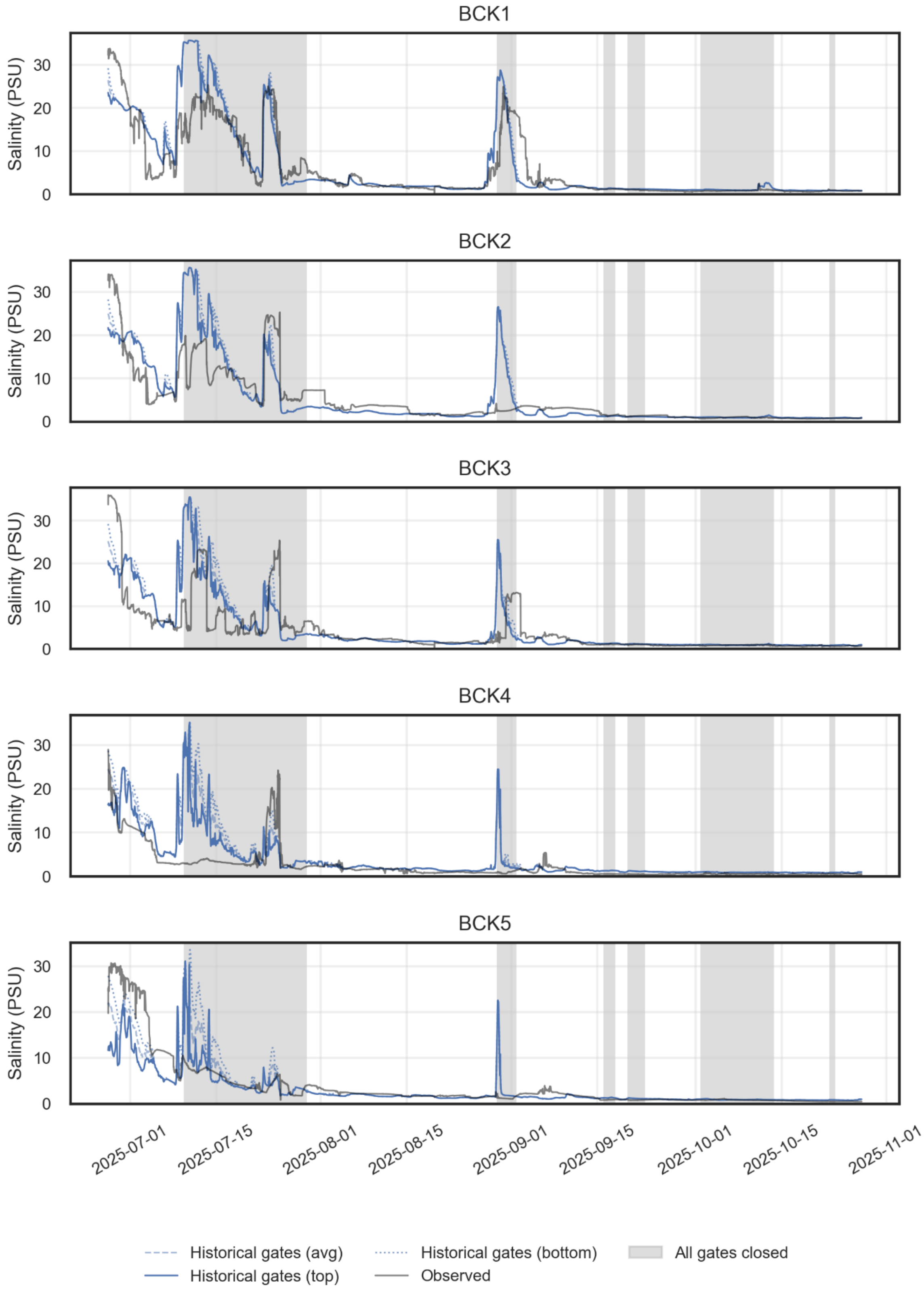


Figure 11. Modelled (Historical gates scenario) and observed salinity in boundary creek, from closest (BCK1) to furthest from the barrage (BCK5, see Figure 1). The 3D model results are presented from the top layer of the model (top), bottom layer (bottom) and the average across the 5 model layers (avg).

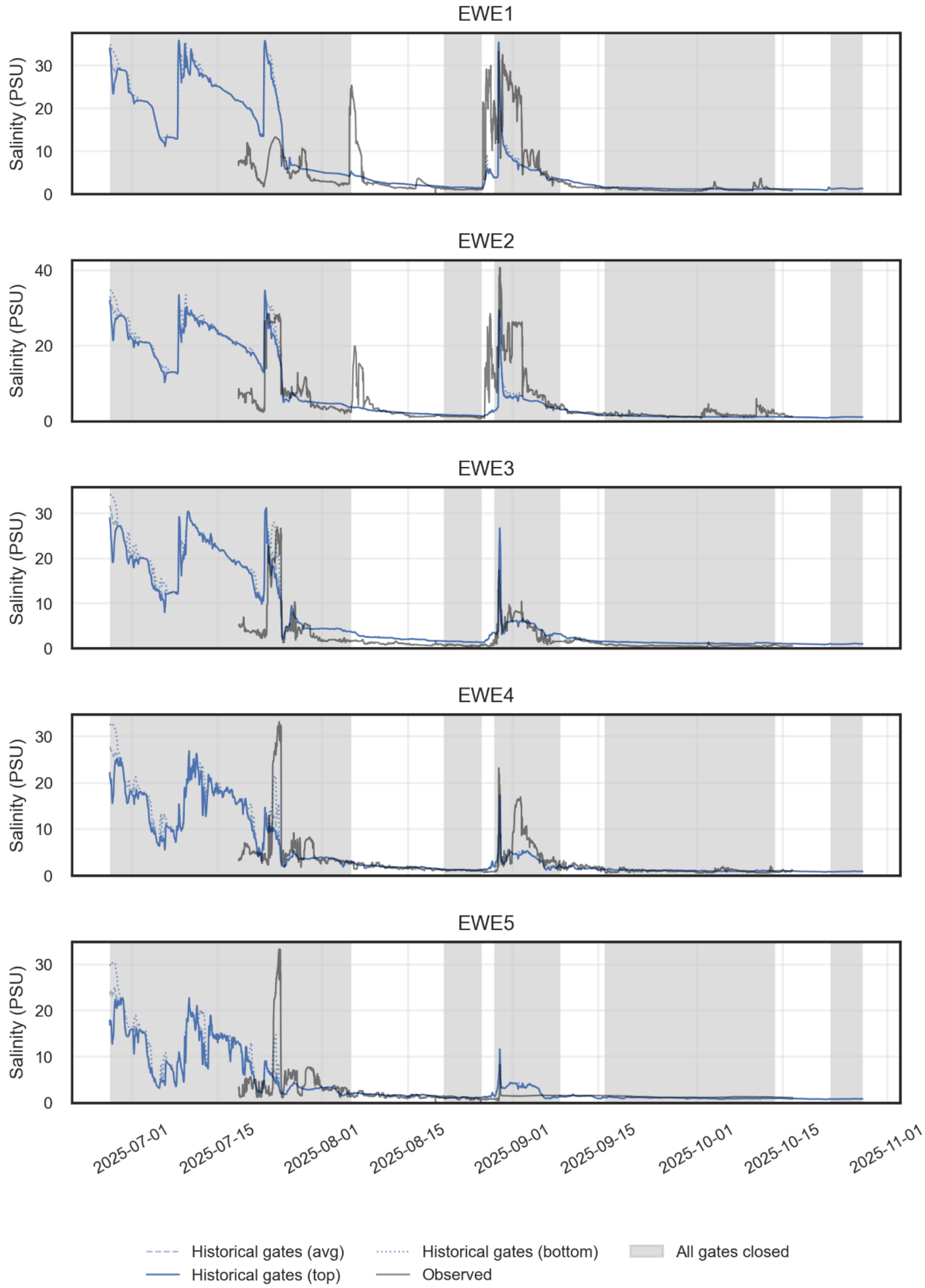


Figure 12. Modelled (Historical gates scenario) and observed salinity in Ewe Island embayment, from closest (EWE1) to furthest from the barrage (EWE5, see Figure 1). The 3D model results are presented from the top layer of the model (top), bottom layer (bottom) and the average across the 5 model layers (avg).

Velocity dynamics upstream of Boundary Creek (BCK1) and Ewe Island (EWE1) barrages are well represented by the model (Figure 13 and Figure 14), albeit at a smaller magnitude in the model compared to the *in situ* data. This difference is expected to be due to the resolution of the model, averaging the velocity over a much larger area than recorded by the sensor. Nonetheless, the flow directions in the west–east (x direction), south–north (y direction) and of out of the barrage (210º from north) align well, even when the barrage gates are closed and any water movement is driven by wind (indicated by grey shaded areas in Figure 13 and Figure 14).

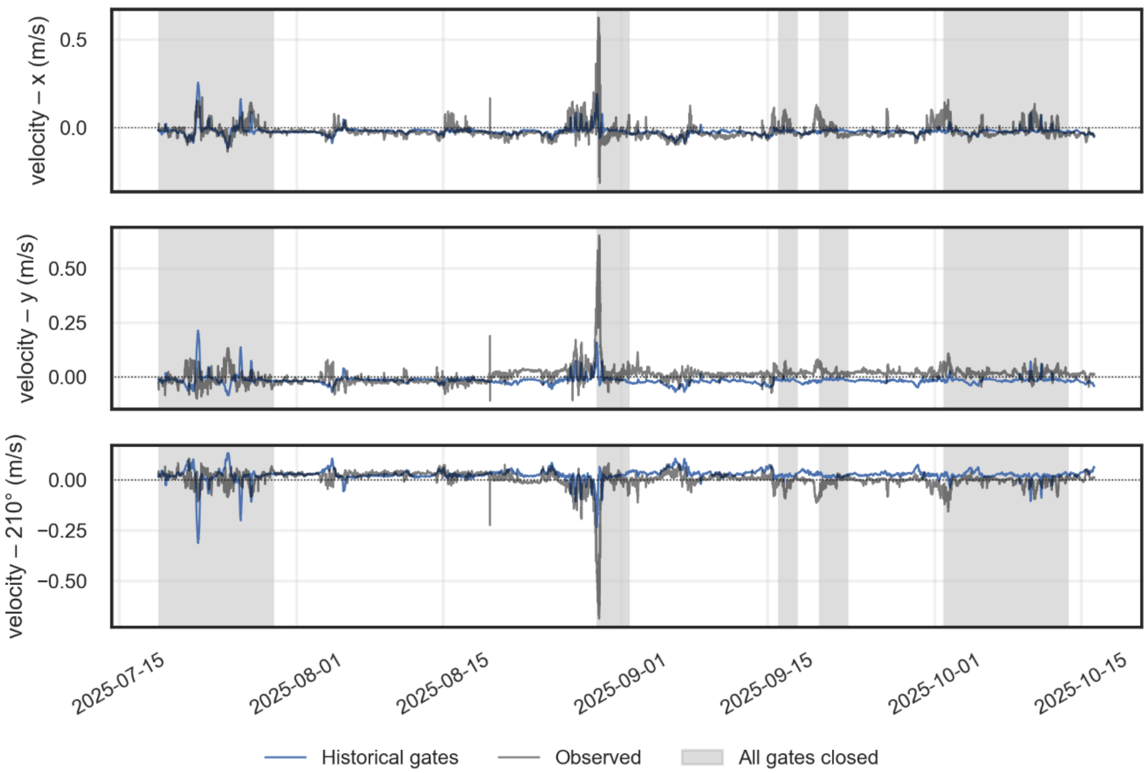


Figure 13. Modelled and observed velocity upstream of Boundary Creek Barrage. Velocity is recorded in the x (positive east) and y (positive north) direction. The component of the velocity in the direction 210º from north (bottom panel) represents the direction out of the barrage. On the bottom panel negative velocities indicating reverse flow events.

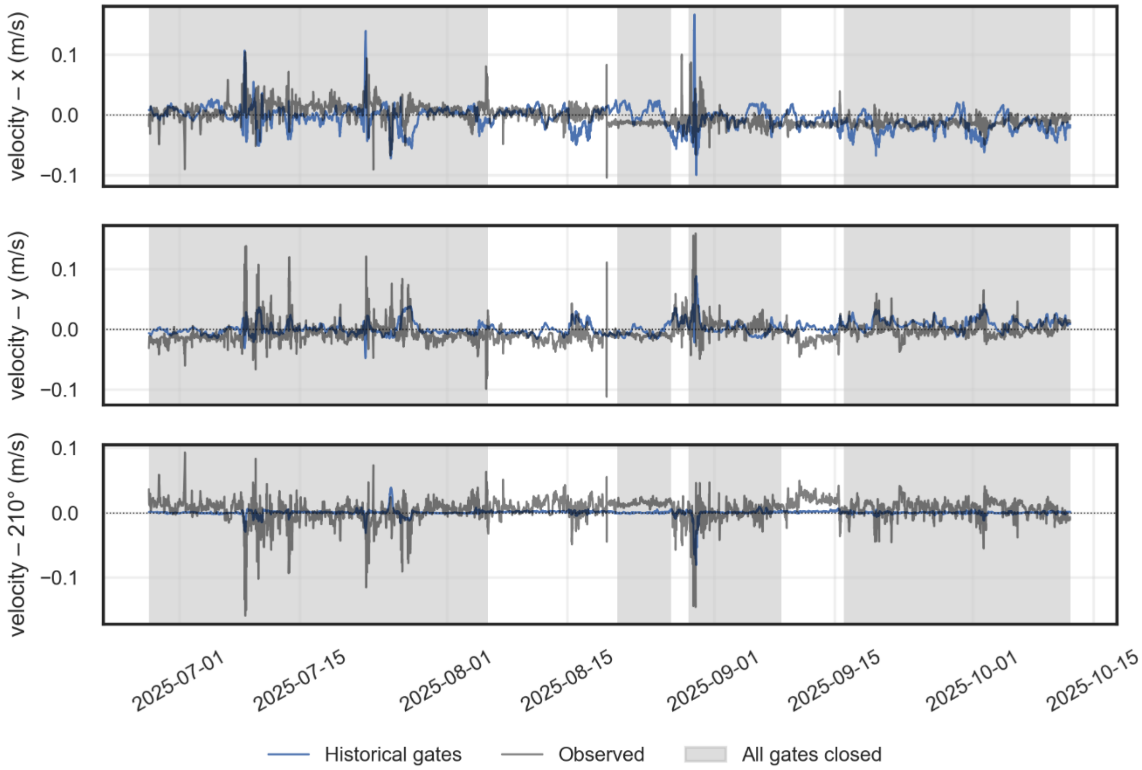


Figure 14. Modelled and observed velocity upstream of Ewe Island Barrage. Velocity is recorded in the x (positive east) and y (positive north) direction. The component of the velocity in the direction 210º from north (bottom panel) represents the direction out of the barrage. On the bottom panel negative velocities indicating reverse flow events.

### 3.3.3 Barrage scenarios

Modelled salinity and water level at existing monitoring stations have been reported for the barrage scenarios for the 2022 and 2025 climate conditions (see Section 2.4.4), with the stations considered presented in Figure 15. To provide further insights into the movement of salt around the model domain the cumulative flux across sections of the domain is considered at each of the barrages (red lines in Figure 15) as well as other locations of interest (yellow lines in Figure 15). The arrowhead indicates the direction of positive cumulative flux and for all barrages positive direction is assumed to be from Lake Alexandrina to the Coorong.

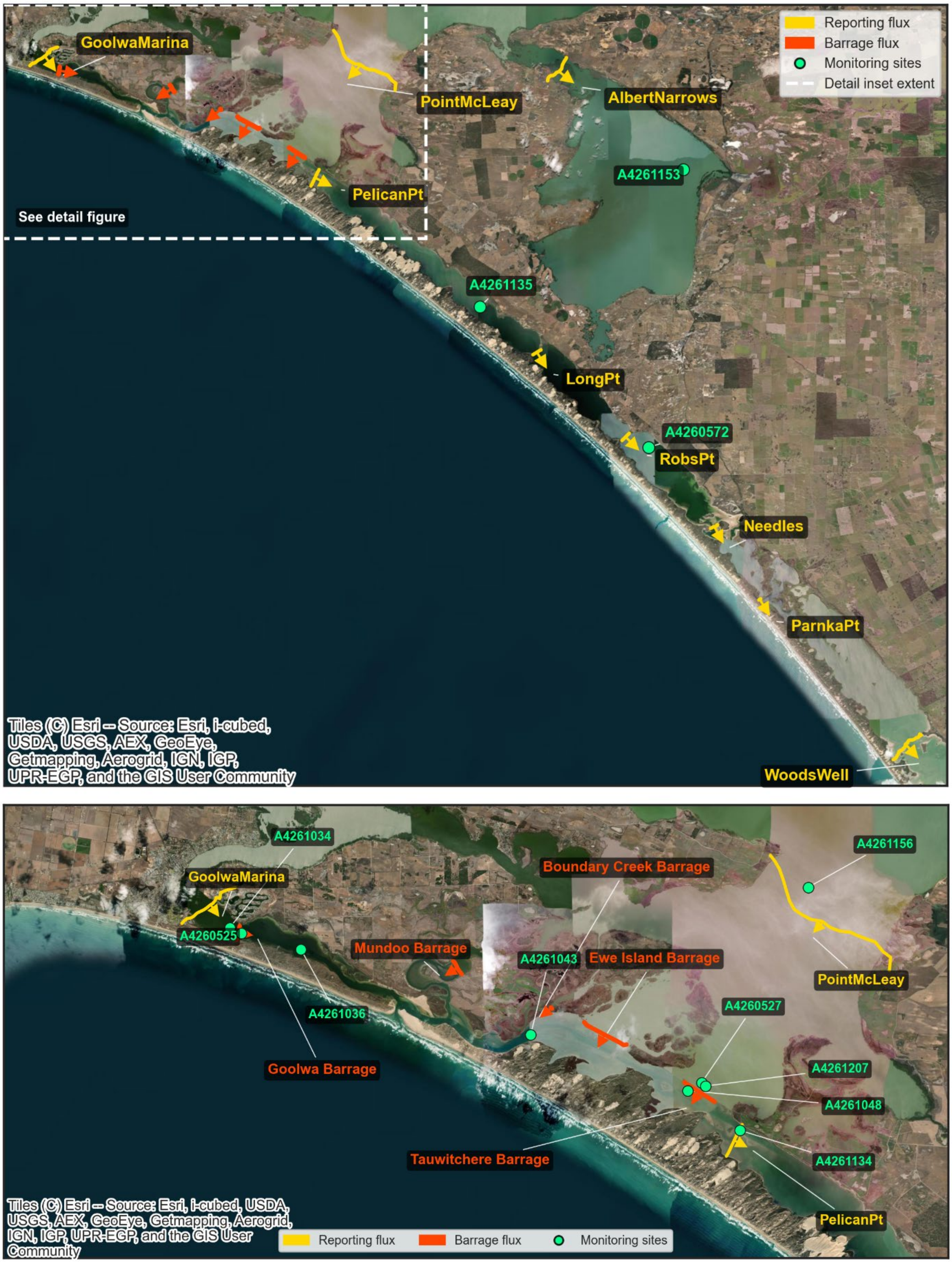

Figure 15. Model output reporting locations, for all reporting locations (top) and detail insert around the barrages (bottom). Flux is calculated across the reporting and barrage flux lines, with positive direction indicated by the arrowheads.

### 2025 conditions

For 2025 conditions, the model represents well the wind driven seiche events in the Lower Lakes, as well as the tidal signal in Goolwa and Coorong channels (Figure 16). Differences in water level between the scenarios are small, particularly in the Coorong. Small differences in lake levels occur between the scenarios, most likely due to the different barrage flow time series and volumes adopted (see Section 2.4.4).

The modelled salinities in the Lower Lakes for 2025 conditions are higher than observed due to a modelled reverse flow event in June having an influence on salinities in the lakes that was not actually observed to penetrate into the lake as far as A4261156 (Figure 17). Given barrages gates were closed at this time in the historical gates scenario (Figure 7), this is most likely due to the coarse representation of spillways adjacent to the barrages simulating too much flow, and hence salt flux, into the lakes. By closing gates (historical gates) compared to leaving them open (no closure) this did prevent additional salt from entering Lake Alexandrina and to a lesser extent Lake Albert (A4261153, Figure 18). The water level trigger scenario reduced salinities slightly compared to the historical gates scenario, by avoiding larger reverse flow events. This scenario also allowed the gates to reopen earlier, with lower salinities in the Goolwa channel at some times (A4261036, Figure 17). Differences between scenarios in the Coorong were negligible due to the overall relatively small total barrage volumes modelled for each scenario (Table 1).

The salt flux results also indicate minimal difference between salt movement in the Coorong between the scenarios (Figure 18). The water level trigger scenario results in less salt imported into the main body of Lake Alexandrina (at Point McLeay) over the first half of the scenario, resulting in a net export of salt from the lake by the end of the scenario. The salt imported into the lake under this scenario was more than in the historical gates scenario and there was a net import of salt in the no closure scenario. There was a net import of salt into Lake Albert in all scenarios, which was smallest in the water level trigger scenario. The relative results across the barrages were variable, with more salt exported by the no closure scenario at Goolwa Barrage (Figure 19, also indicated by the Goolwa Marina reporting point in Figure 18), however this may represent salt that was imported across other barrages, with a large import of salt through Mundoo and Tauwitchere barrages in June 2025 (Figure 19). As a total across all barrages, the water level trigger scenario exported the most salt over the barrages, however this may be in part a function of more barrage flow in this scenario (553, 574 and 609 GL for the historical gates, no closure and water level trigger scenarios, respectively).

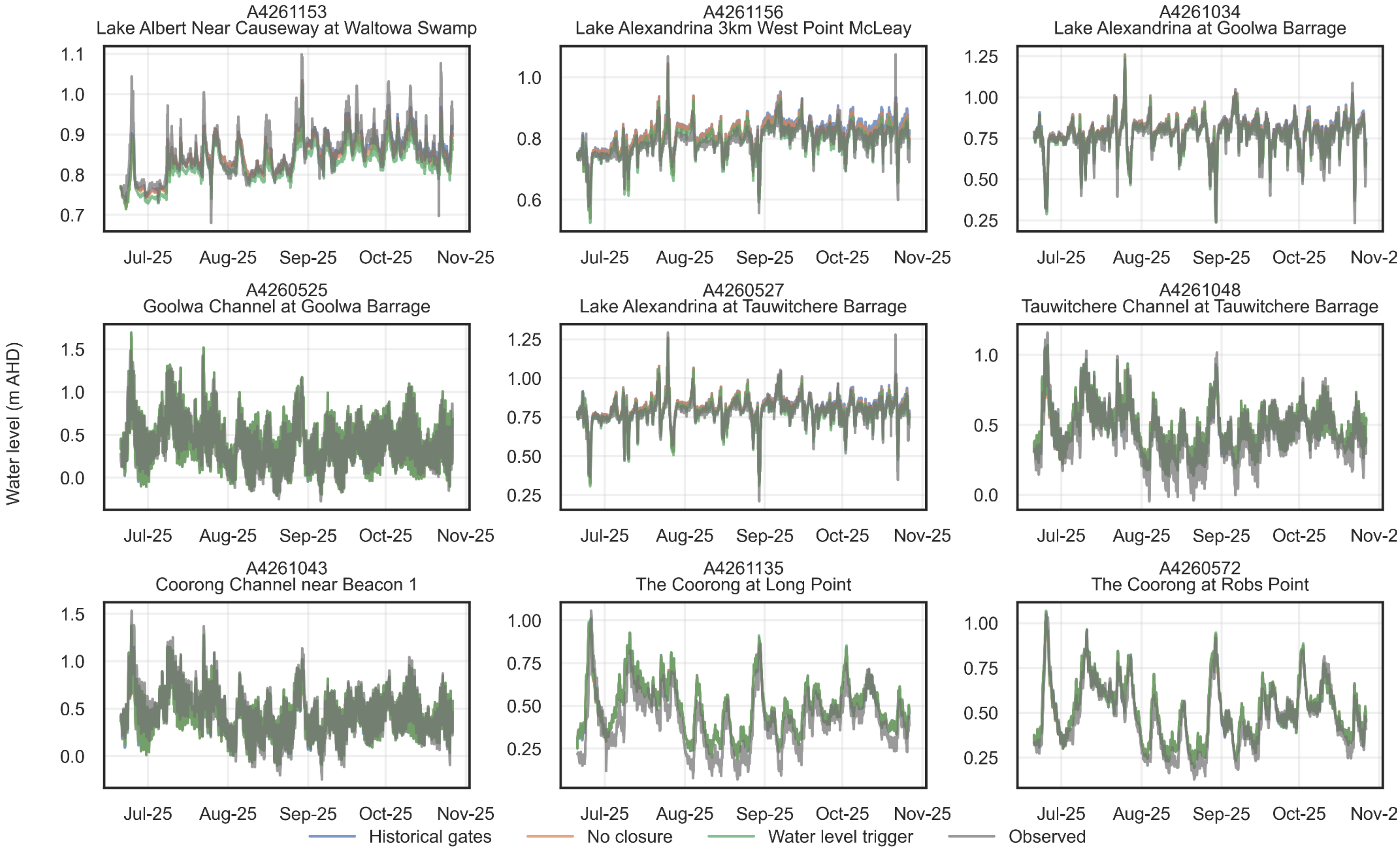


Figure 16. Modelled water levels at reporting points for the three barrage scenarios and 2025 conditions

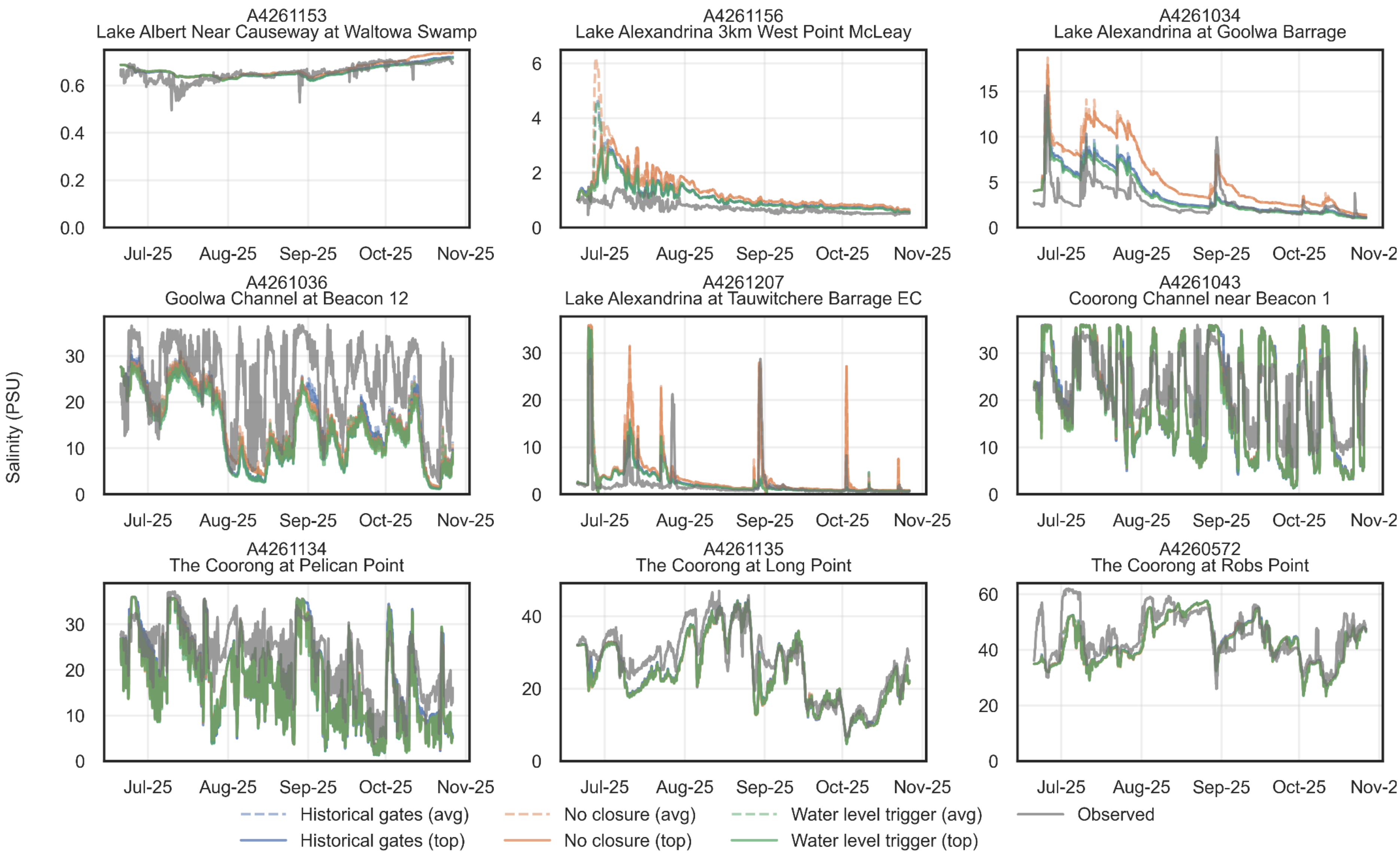


Figure 17. Modelled salinity at reporting points for the three barrage scenarios and 2025 conditions

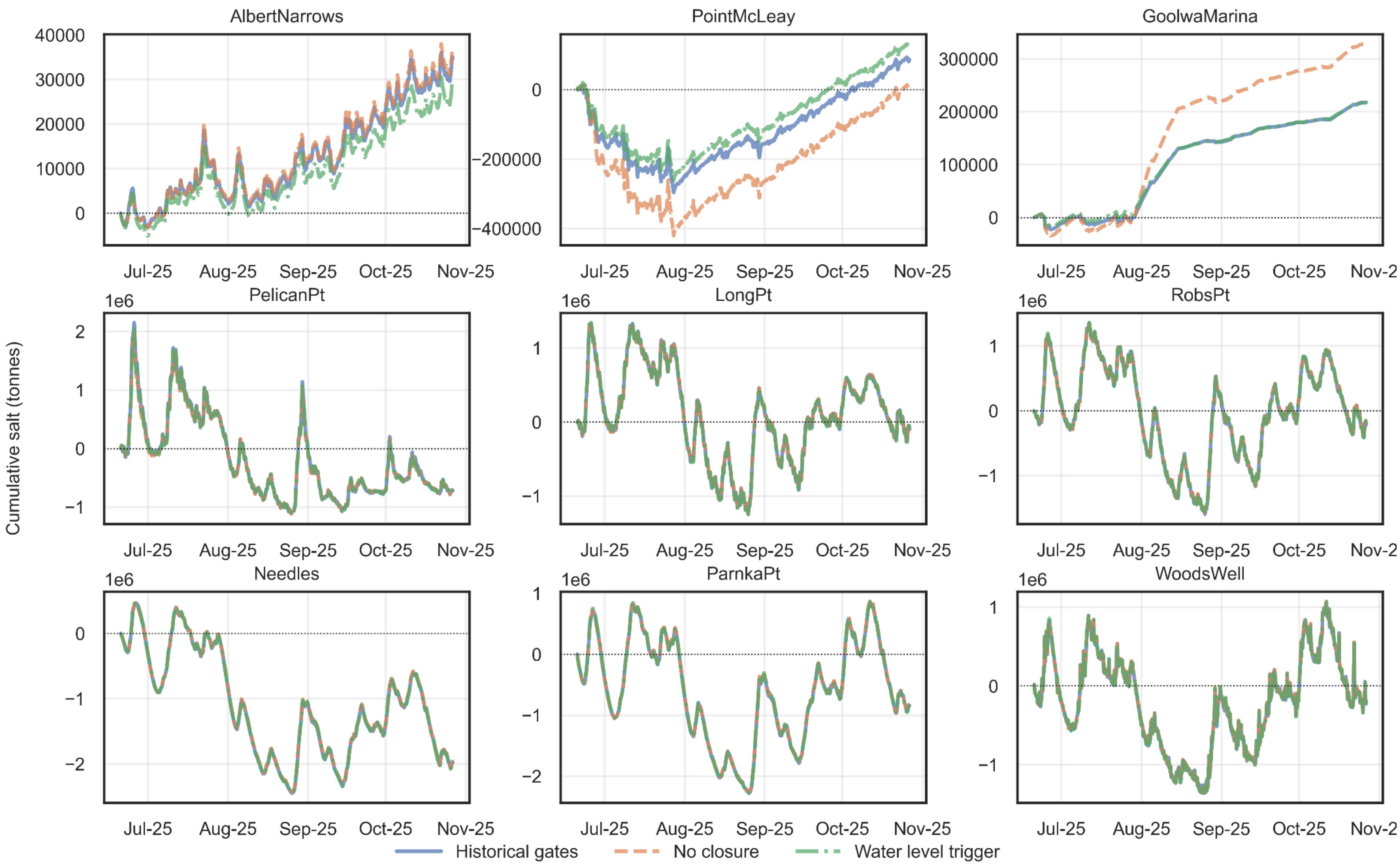


Figure 18. Modelled cumulative salt flux (see Figure 16 for locations and positive direction) for the three barrage flow scenarios and 2025 conditions

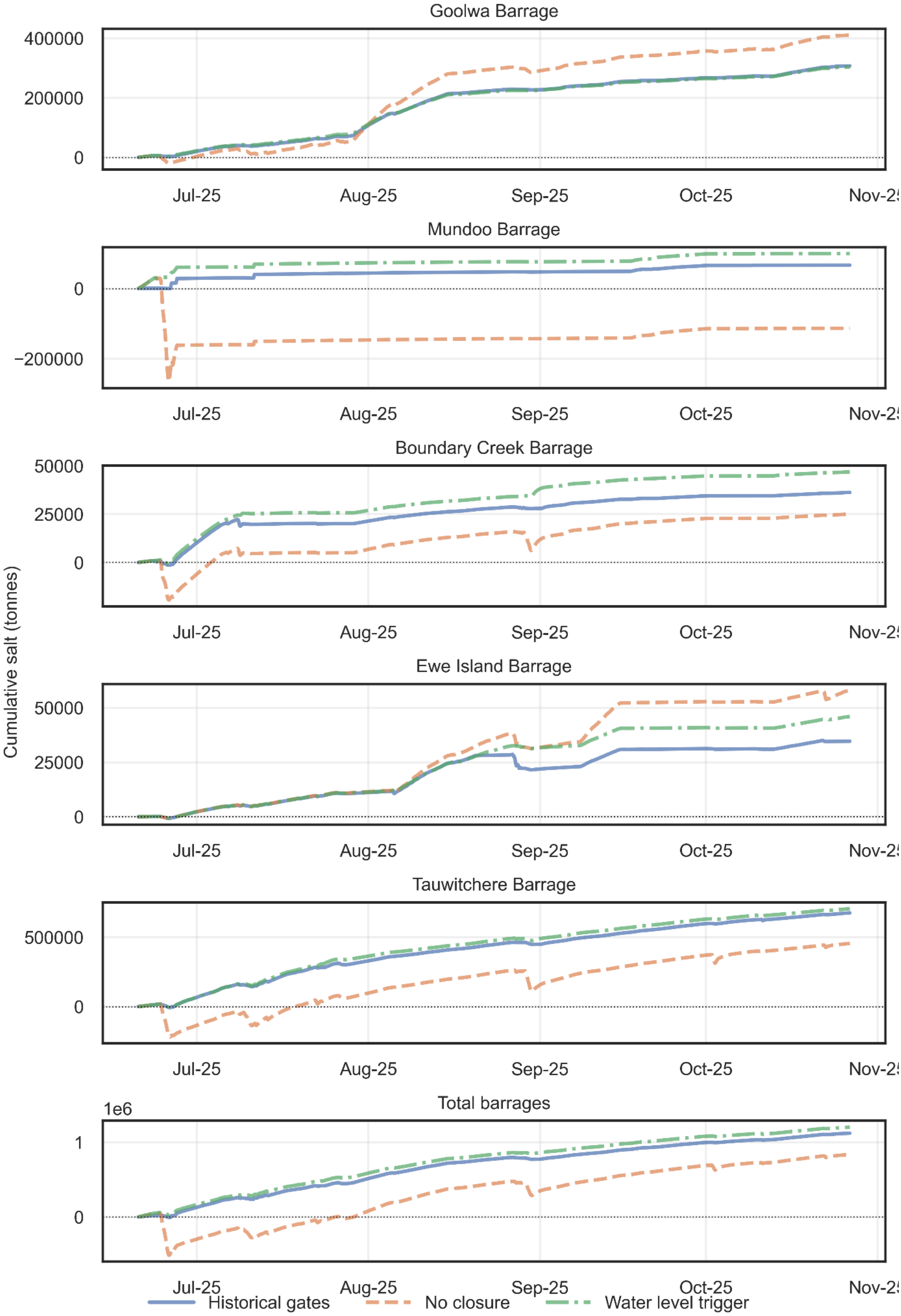


Figure 19. Modelled cumulative salt flux at each barrage, and the total across all barrages, for the three flow scenarios and 2025 conditions. Note different axis scales for different barrages.

## 2022 Conditions

To enable the barrage flow for the scenarios to be calculated using the barrage calculator equations, the 2022 scenarios did not apply the same barrage scaling as the calibration comparison undertaken over the same period (see Appendix A). Hence, the modelled water levels in the Lower Lakes are overestimated compared to observed for the 2022 conditions (Figure 20). There are some differences between the scenarios in lake levels, with a reverse flow event in late May 2022 resulting in higher lake levels for the historical gates and no closure scenarios (see Figure 6). By the end of the simulation, the differences in lake level are relatively small, driven by the differences in barrage flow volume over the simulation (3312, 3342 and 3601 GL for the historical gates, no closure and water level trigger scenarios, respectively). With these larger volumes of barrage flow compared to the 2025 conditions, there are discernible differences in water level in the Coorong. Typically, water levels are higher in the historical gates scenario, followed by the water level trigger scenario, and lowest in the no closure scenario. However, this is not always the case (for example during the reverse flow event in late May–June 2022), and generally the differences are relatively small, typically less than 0.05 m.

The water level trigger scenario removes the high salinity from a reverse flow event that did occur (Figure 21) by responding to the reverse water level head difference and closing any open barrage gates as a model behaviour. These events can be hard to forecast in advance and the water level trigger scenario represents additional real-time control functionality compared to the current barrage automation. By avoiding this reverse flow event, and the slightly higher barrage flow volume overall, salinities in Lakes Alexandrina and Albert are lowest in the water level trigger scenario.

With more barrage flow during the 2022 conditions compared to the 2025 conditions, the different barrage scenarios result in differences in the salinity in the Coorong. It is difficult to interpret the changes in salinity at individual point locations in the highly variable and dynamic system, however the cumulative salt flux provides a clearer indication of the movement of salt across the domain (Figure 22). For the Coorong sites, a positive value indicates salt movement into the Coorong (see Figure 15), so smaller values indicate less salt imported, or negative values a net movement of salt toward the Murray Mouth. Over the simulation there is a net import of salt into the Coorong based on the cumulative salt flux at Pelican Point, which is largest in the historical gates scenario. The no closure and water level trigger scenarios result in approximately half the salt mass imported to the Coorong from the ocean by the end of the simulation (Figure 22), with a net salt imported into the Coorong of 101,269 tonnes, 47,100 tonnes and 58,187 tonnes, for the historical gates, no closure and water level trigger scenarios, respectively. In the case of the no closure scenario, the difference in salt load into the Coorong is instead directed through the barrages (Figure 23).

Salt movement in the Coorong North Lagoon, at Long Point and Robs Point, is variable with the cumulative salt flux switching between positive and negative. The lowest (most net export or least import) salt flux results from the water level trigger and no closure scenarios. Over the scenario, there is a net export of salt out of the Coorong south lagoon into the north lagoon (based on the Needles and Parnka Point locations), with similar patterns to that seen in the north lagoon. Hence, for the 2022 conditions, the more consistent and hence slightly higher volumes of barrage flow (approximately 10% higher) resulted in more salt exported from the Coorong South Lagoon, and less salt imported to the Coorong north lagoon from the ocean.

Across the barrages, the no closure scenario resulted in a net import of salt to Lake Alexandrina over the model period due to two large reverse flow events in June and August (Figure 23), even in this period with elevated barrage flow (average flow of 33,640 ML/d). The historical gates scenario also imported salt at Boundary Creek, Ewe Island and Tauwitchere Barrage during the first reverse flow event, however most of this salt appears to have been exported back over the barrages, where by the end of the scenario the difference between the historical gates and water level trigger scenarios is relatively small, and mostly likely explained by the higher barrage flow volume in water level trigger scenario (3601 GL compared to 3312 GL). The water level trigger scenario avoids the larger salt import events by closing barrages automatically if the water level differences indicate potential for larger flow into the lakes (based on a head difference of greater than 0.05 m) and facilitates longer periods of barrage opening by reopening gates as soon these water level conditions end.

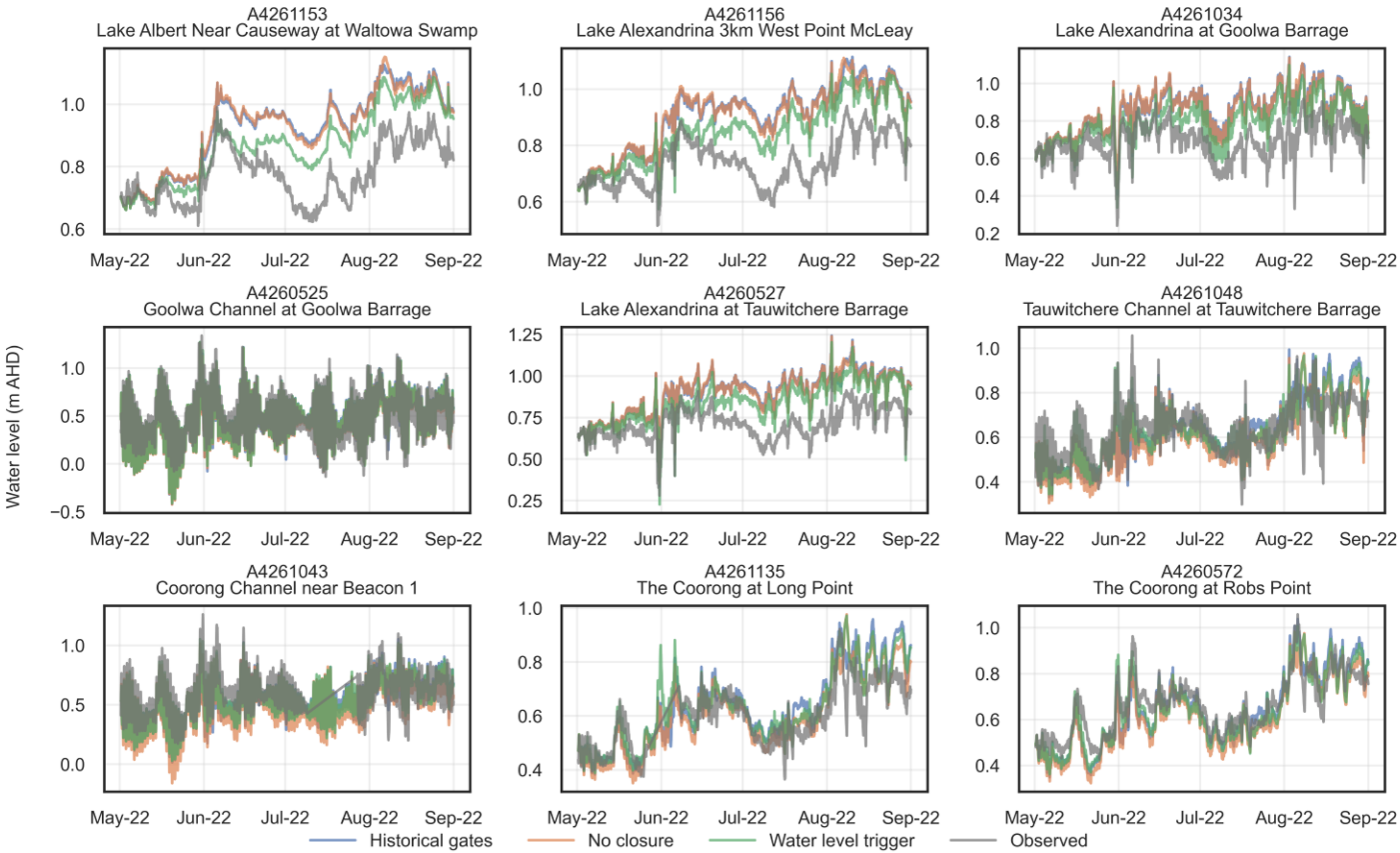


Figure 20. Modelled water levels at reporting points for the three barrage scenarios and 2022 conditions

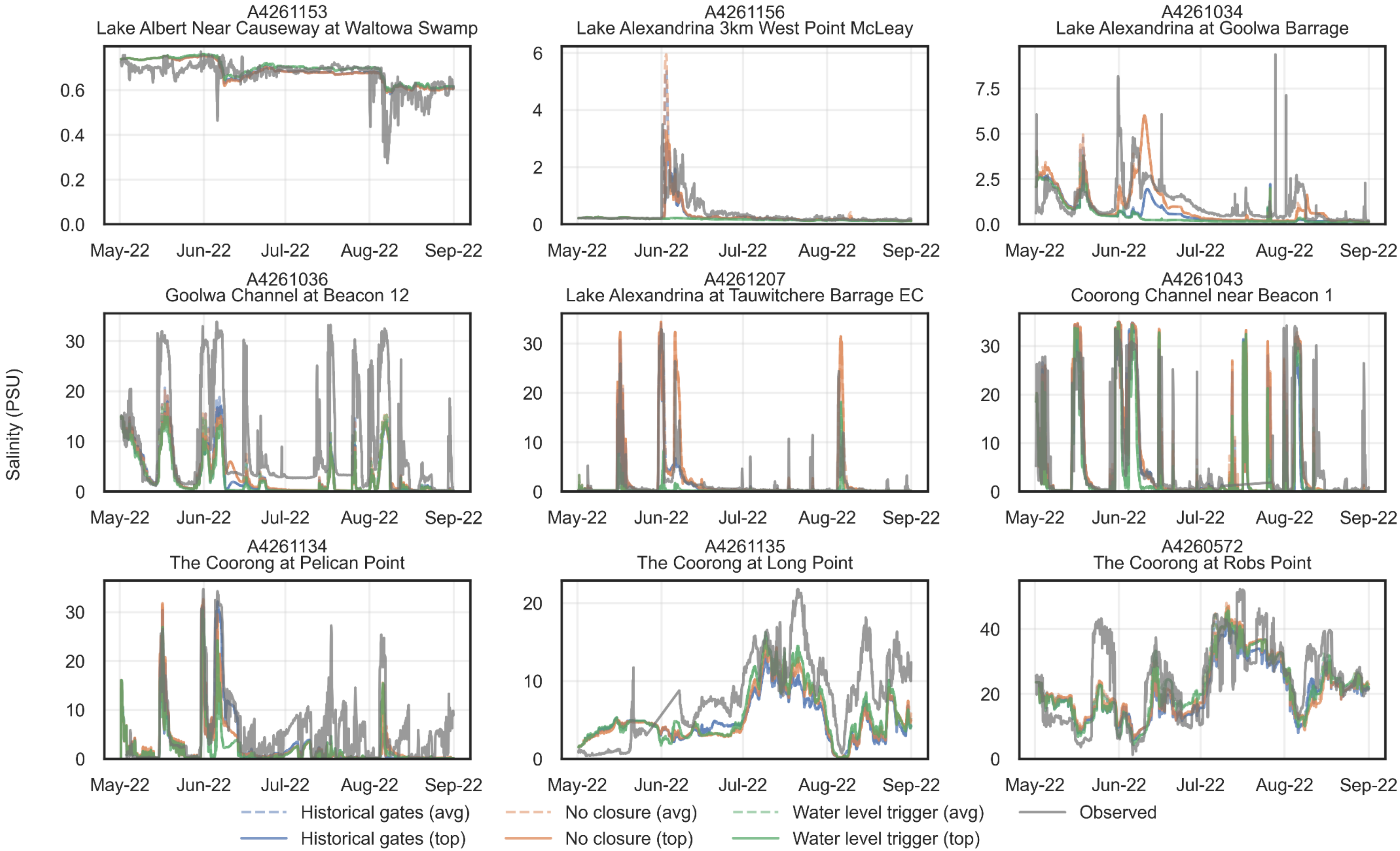


Figure 21. Modelled salinity at reporting points for the three barrage scenarios and 2022 conditions

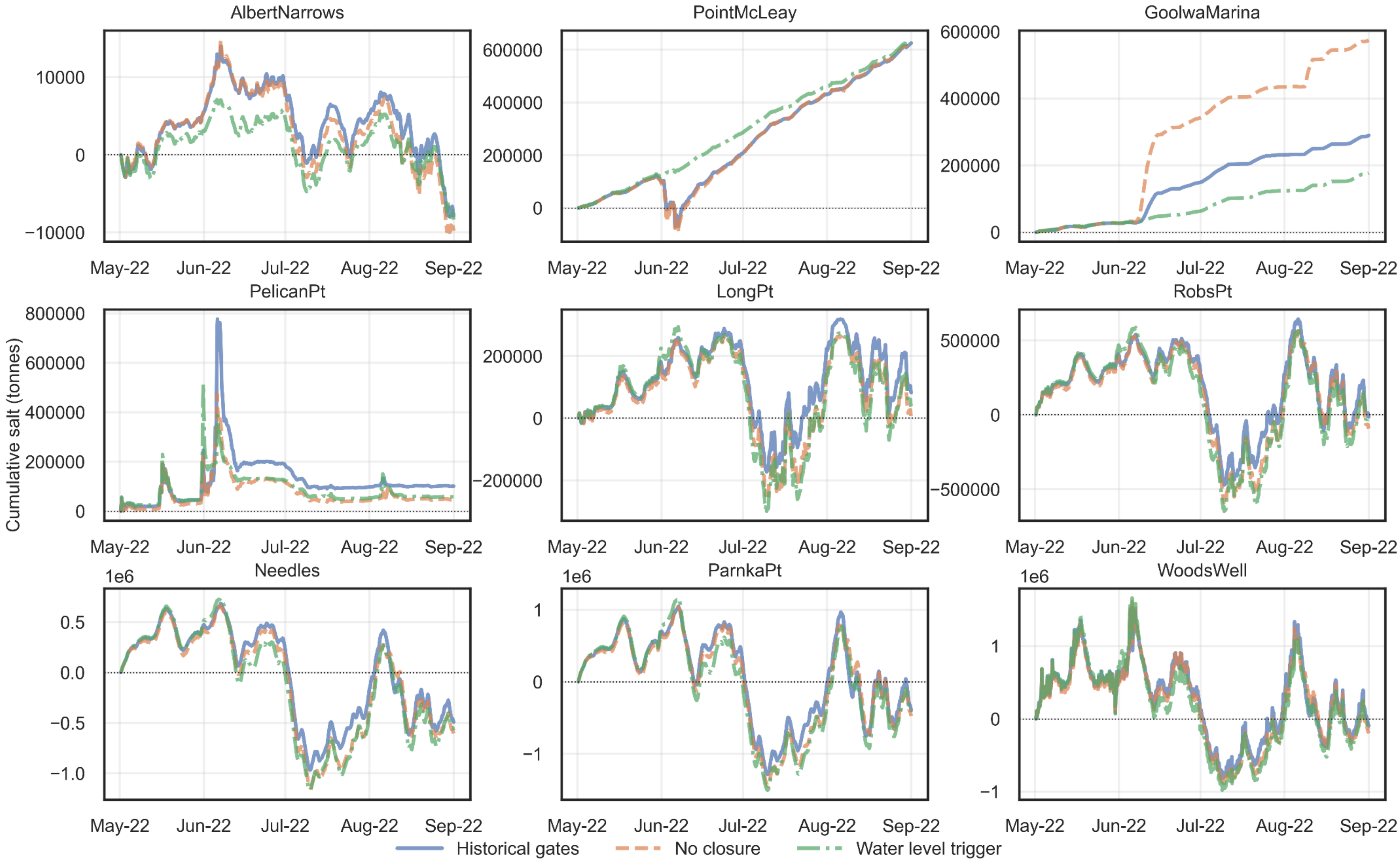


Figure 22. Modelled cumulative salt flux at reporting flux locations (see Figure 16) for the three barrage flow scenarios and 2022 conditions

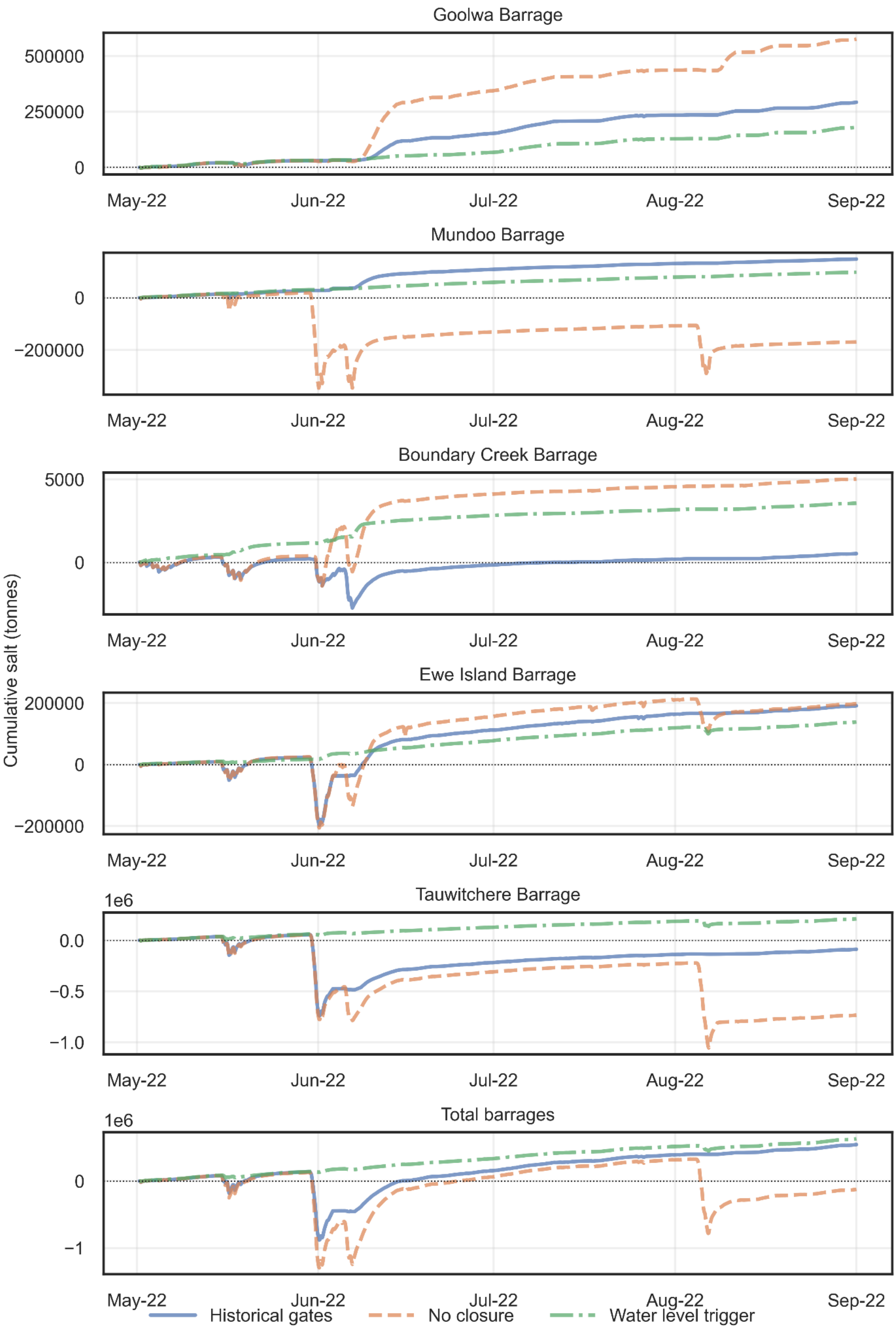


Figure 23. Modelled cumulative salt flux at each, and the total across all, barrages for the three barrage flow scenarios and 2022 conditions

### Area of estuarine conditions

The model results have been post-processed to investigate changes in the area of estuarine conditions across the full model domain, both upstream and downstream of the barrages. The estuarine conditions have been defined based on the depth averaged salinity being between fresh (nominally assumed to be 1 g/L, above the salinity of both Lower Lakes) and sea water (35 g/L). The results for all barrage flow and climate conditions considered are presented in Figure 24.

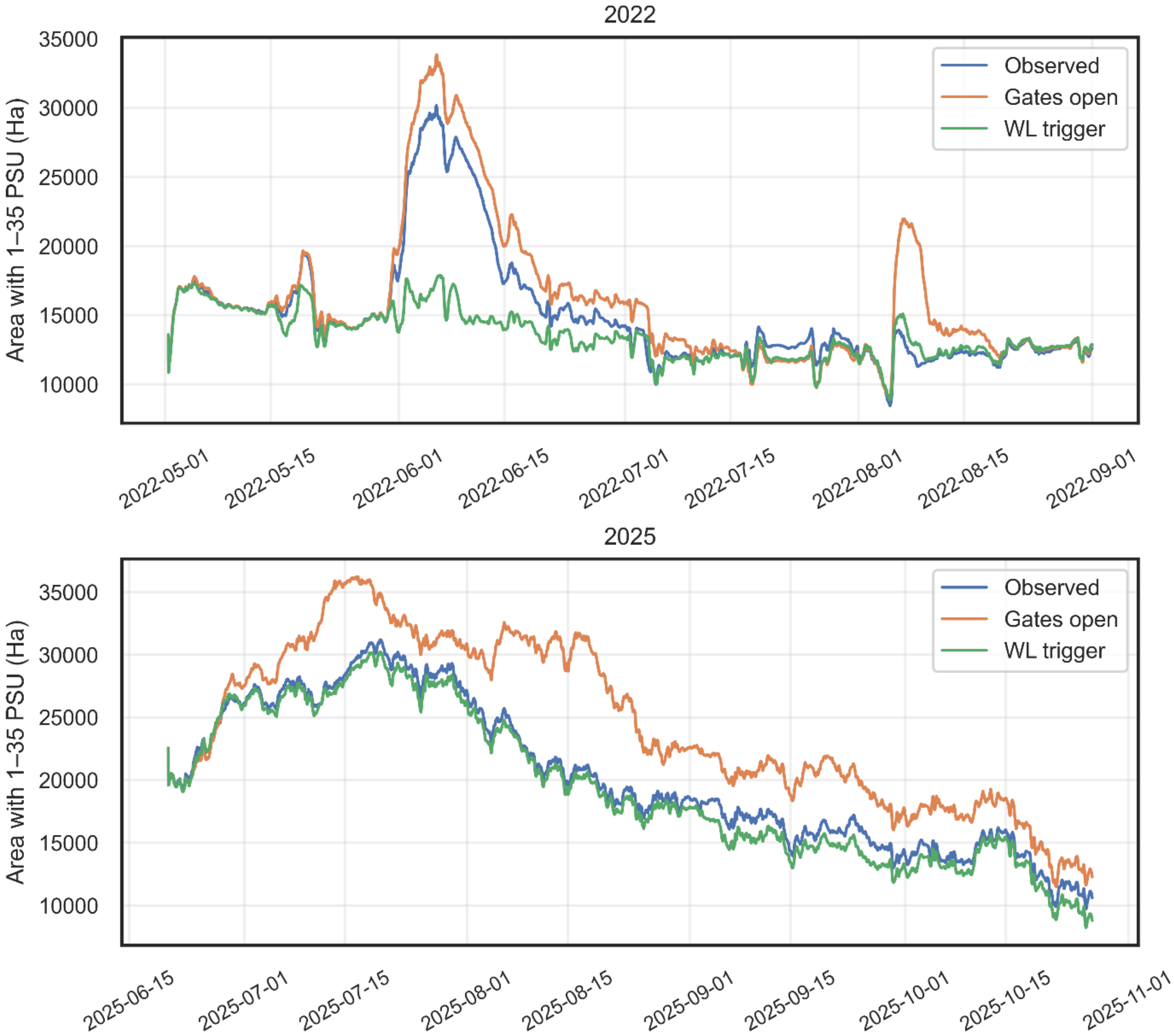


Figure 24. Area across the full model domain with estuarine conditions (1–35 g/L) for the three barrage flow scenarios for 2022 climate (top) and 2025 climate (bottom).

The 2022 period had a smaller average area of estuarine conditions over the model simulation compared, 15,045 Ha over the 2022 period with observed barrage options, compared to the 2025 period (20,250 Ha for the 2025 period). The change in area of estuarine conditions between the barrage scenarios typically occurs upstream of the barrages, with the reverse flow event in late May 2022 doubling the area with salinity between 1 and 35 g/L across the region, which does not occur in the water level trigger scenario that prevents this salt ingress. This is also the case over the lower flow 2025 period, with the water level trigger scenario resulting in the lowest estuarine area by preventing salinities greater than 1 g/L upstream of the barrages. Further work is required to continue this analysis, for example to consider more potentially ecologically relevant salinity thresholds, at different times of the year or a more refined spatial scale (estuarine conditions in only the ocean domain to trigger movement, for example).

# 4 Discussion

In human-modified river systems worldwide, tidal barriers and reduced flows can alter connectivity and disrupt the function and health of estuarine ecosystems. In response, tidal barriers are increasingly being operated to enhance connectivity and reinstate a more dynamic estuarine interface (e.g. Beeldman et al. 2018). In the CLLMM region, at the terminus of the Murray–Darling Basin, reduced river flows and the Murray Barrages act together to fragment a historically dynamic estuarine interface, with profound environmental, cultural, and economic consequences (Bice et al. 2023).

In winter–spring 2025, we worked in collaboration with SA Water and DEW to explore opportunities to enable the two-way flux of water through Boundary Creek and Ewe Island barrages during periods of reverse flow (i.e. Coorong water levels higher than lake water levels). Due to low River Murray inflows, diminishing lake water levels, and operating and water security constraints, opportunities across this period were limited. Nevertheless, when reverse flow could be facilitated through open barrage gates, we collected invaluable data on physico-chemical and biological response that will inform future barrage management and investigations.

## *4.1 Water physico-chemistry*

This study provided high resolution (hourly) data on salinity, water temperature and water velocity during reverse flow events at Ewe Island and Boundary Creek barrages. Fine-scale data had not previously been collected in this context and the results showed, as expected, that salinity increases occurred on the Lake Alexandrina side when barrage gates remained open and suitable head conditions to create reverse flow occurred. Salinity diminished with distance (2–3 km) away from the barrages and with time once positive head differential was reestablished, and salt was flushed back out from the lakes. It took approximately 1–2 weeks for salinity to return to baseline conditions. Some salinity stratification was observed upstream of the barrages in association with reverse flow, and typically this was confined to a narrow zone near the bottom of the water column, at sites in closer proximity to the barrages. Overall, the water quality results indicate an increased estuarine zone, extending upstream of the barrages, was created by controlled barrage gate openings, and that the size and persistence of this zone can be managed via gate manipulation. No adverse ecological events (e.g. fish kills) were observed during the reverse events that were monitored, and other ecologically relevant parameters such as dissolved oxygen and temperature were maintained within acceptable ranges.

## *4.2 Biology*

Fish hold considerable socio-cultural and economic significance in the CLLMM region and are considered a primary indicator of ecosystem health. As such, in association with facilitating improved transparency and two-way flow through the barrages, we investigated: 1) the active/passive movement of fish, including early life stages, through the barrages, and 2) the movement and habitat use of juvenile and adult estuarine-associated fishes concurrent with spatio-temporal variation in salinity.

In association with reverse flows, we collected 11 species of fish as larvae and 13 species as juveniles/adults passing upstream through the barrages. These fishes represent a diversity of life histories from across the freshwater-estuarine-marine spectrum, including freshwater-estuarine opportunist (e.g. Australian smelt), catadromous (e.g. common galaxias and congolli), solely estuarine (e.g. lagoon goby, *Tasmanogobius lasti*) and marine-estuarine opportunist species (e.g. sandy sprat and greenback flounder, *Rhombosolea tapirina*). The most abundant species, represented as larvae, were the catadromous common galaxias and marine-estuarine opportunist sandy sprat. In the CLLMM, common galaxias migrate from freshwater to the estuary to spawn from late autumn–early spring, and juveniles develop in estuarine/marine waters before migrating back to freshwater in spring–summer (Bice et al. 2018). Connectivity between these habitats across these early life stages (larval and juvenile upstream migrant) is critical for recruitment and population persistence. While considered a marine-estuarine opportunist, sandy sprat demonstrates a strong relationship with estuarine nursery habitats across its range (Gaughan et al. 1996; Bice et al. 2016). Abundances of both species were variable among trapping events, with a peak catch of 566 common galaxias from one drift net over a period of just 20 minutes on 27 August 2025. This suggests that numbers of individual larvae transiting the barrages during such events could be substantial.

The mostly passive movement of high abundances of early life stage common galaxias and sandy sprat in association with reverse flow represents a fundamental process in the recruitment of juvenile fishes in estuaries (Elliott and Whitfield 2025). The mixing zones of estuaries, where freshwater and saltwater interact, are of paramount importance for the growth and survival of fish early life stages (Arevalo et al. 2023). In these regions, the interaction of tide, freshwater inflow, turbidity and nutrients, concentrate larval fish and their all-important food resources. Globally, interruption of these processes and fragmentation of habitats threaten fishes with estuarine associated life stages, particularly diadromous fishes and marine estuarine opportunists (Whitfield et al. 2023). This was evident in the CLLMM during the Millenium drought when closed barrages and disconnection of marine and freshwater habits for over 1200 days was associated with >90% decreases in the abundances of sandy sprat and upstream migrating juvenile common galaxias (Zampatti et al. 2010). Facilitating connectivity and a dynamic estuarine interface over a greater spatial area will benefit populations of diadromous, estuarine and marine-estuarine opportunist species in the CLLMM.

Overall, in our study, species richness of larval fishes was generally low and may reflect the winter-early spring timing of our investigations. Bucater et al. (2013) monitored larval fish in the Coorong in the winter-spring of 2008 and found similarly low diversity, with gobies (several species) and sandy sprat dominating catches; sandy sprat larvae were also prevalent in this study. If we had the opportunity to collect ongoing data through spring–summer, species richness and abundance may have been higher as the incidence of spawning is likely to be greater through this period across a range of species in temperate southern Hemisphere estuaries (Neira et al, 1992; Kruger and Strydom, 2010). Nonetheless, in general terms, estuaries are considered low diversity/high abundance/high biomass environments with minimums in diversity often observed in the oligohaline zone (0.5–5 g.$L^{-1}$)

Of the species collected in open bay trapping, the freshwater-estuarine opportunist Australian smelt was by far the most abundant species and is commonly sampled in high abundance at fishways on the barrages (Gervais et al. 2025). In coastal rivers of Victoria and Tasmania, Australian smelt exhibit high levels of facultative diadromy, whereby substantial proportions of populations use downstream estuaries as nursery habitats (Crook et al. 2008; Hughes et al. 2014). In the CLLMM, the level of diadromy has not been ascertained for Australian smelt, yet the presence of 'freshwater' and 'diadromous' population contingents appears likely, with persistence of these contingents likely reliant on connectivity between the Coorong and lakes. Also collected in open bay trapping were juveniles of species that constitute important components of the commercial fishery in the CLLMM, e.g. yellow-eye mullet (*Aldrichetta forsteri*) and greenback flounder (Ferguson et al. 2018). Temperate estuaries worldwide form key nursery habitats for juvenile flat fishes like flounder with juveniles of some species specifically inhabiting oligohaline regions (Martinho et al. 2007). In the CLLMM, the habitat use and autecology of these juvenile life stages of species important to the commercial fishery remain little studied and warrant further investigation.

Of the larval and juvenile fish, we collected, across a range of species and life histories, many do not have the swimming ability (i.e. due to small size), or potentially motivation (e.g. preference for brackish rather than truly freshwater salinities), to use conventional fishways at the barrages. Thus, during reverse flows, open barrage bays may facilitate unique connectivity more akin to the natural estuarine interface (Bice et al 2023), enabling fish to passively or actively move along an estuarine gradient and access nutrient and food rich habitats that are likely transitory and dynamic. To further explore the movement and habitat use of fish in association with improved transparency at the barrages and corresponding spatio-temporal variation in salinity, we initiated an ongoing study of habitat use of acoustically tagged juvenile and adult estuarine fishes (black bream and mulloway) in Boundary Creek. Data from this study will be collected across late summer to spring 2026 in association with facilitating reverse flow at Boundary Creek Barrage and the ongoing collection of *in situ* water quality data.

## *4.3 Hydrodynamics – foundational and extension*

The model evaluation results for the 2022 and 2025 climate scenarios demonstrate an accurate representation of salt movement around the CLLMM, including ingress into the main body of the lakes. These results provide confidence that salinity dynamics associated with more permeable barrage operation, including risks of increasing salinity in the Lower Lakes, will be simulated adequately by the model. The 2025 scenarios represented a period of low flow, with only one barrage bay open at each of Boundary Creek and Ewe Island. The results indicate the transport of salt is relatively confined for the climate and tides assumed, with limited influence on the main body of the lake. This may be partially due to the constrained nature of these barrages, with islands on the upstream side of the barrage preventing extensive mixing. Longer simulations that include higher flow events may be required to investigate flushing of salt back out of the lakes following regular reverse flow events that permit some ingress of salt. Ultimately, the water level trigger approach mitigates the risk of large salt ingress events, while maximising the period of connectivity across the barrages, by reopening as soon as reverse flow events subside. These events can be very dynamic, changing with the wind and tides, with variability in timing and magnitude across the barrages.

Our modelling of three operational scenarios, across two historical climatic periods, provides insight to alternative barrage operating scenarios to achieve multiple objectives, including: transparency and connectivity at the barrages, a more dynamic salinity regime in the vicinity of the barrages, expanding the area of estuarine habitat across the CLLMM, mitigating high salinities in the lakes and influencing salinity dynamics in the north and south lagoon of the Coorong. Previously, it has been hypothesised that times of higher river flows may present lower risk of increasing salinity in the main body of the lakes from reverse flows, as there is more flow to flush any salt that does enter the lakes back to the estuary. Nevertheless, more flow also means there are more barrage gates open, resulting in a higher risk of higher loads of salt entering the lakes through the barrages during storm events, as head difference across the barrages can be large. Conversely, under low flows there are only a small number of barrage bays open, with a small flow and hence potential salt load. Obviously, closing gates in response to reverse flow head events reduces the flux of salt into the lakes.

Having the functionality to respond to water level differences upstream and downstream of the barrages automatically (water level trigger scenario) enabled increased periods of connectivity across the barrages compared to the historical conditions (i.e. barrage closure) while ensuring events that could import large salt loads into the lakes were avoided. The water level trigger scenario resulted in the highest salt export out of Lake Alexandrina, and in the 2022 conditions with higher barrage flow rates, reduced salt imported to the Coorong North Lagoon and increased salt moving from the Coorong South Lagoon to the North Lagoon. These results, particularly the salt export from Lake Alexandrina, may be in part due to higher barrage flow volume created by having gates open for longer in the water level trigger scenario, approximately 10% higher than the historical gates scenario in both conditions considered.

## *4.4 General discussion*

This study enabled characterisation of biological and physicochemical responses to trials of facilitating the two-way flow of water through the Murray Barrages to reconnect the Lower Lakes and Coorong. In concert, we refined and validated a hydrodynamic model that can predict salinity patterns and hydrodynamic parameters in the Lower Lakes and Coorong in association with contemporary and potential future barrage management, including under a changing climate although this was not explored in this work. Our study represents initial steps to reestablishing a more dynamic and connected estuarine interface in the CLLMM, whilst mitigating overt salinity impacts in the main body of the Lower Lakes.

The concept of enabling two-way flow at the barrages, by leaving barrage bays open during reverse flows (under specific climatic and hydrological conditions), does not promote the removal or permanent opening of the barrages. The weight of evidence suggests that the Lower Lakes have been predominately freshwater for at least the past 10,000 years (see Bourman et al. 2022) but there was historically a spatio-temporally variable estuarine interface between the Murray Mouth and approximately Point Sturt (Tibby et al. 2022). In a heavily flow-modified system, where end-of-system flows are ~40% of natural, removing the barrages and retaining the hydro-ecological character of the CLLMM is not feasible. Nevertheless, our study demonstrates there is potential to introduce flexibility into barrage operation that improves two-way flow and reinstates some of the physical, chemical and biological characteristics of a more connected and dynamic estuarine interface.

The future for the CLLMM likely entails less freshwater flow from the River Murray and higher sea levels, leading to more frequent overtopping of the barrages (Mosley et al. 2024). In this project, we demonstrate that more nuanced operation of the barrages and increasing 'openness' during specific upstream and downstream water levels can increase the area of estuarine habitat and improve connectivity in the absence of additional freshwater (i.e. River Murray flow). This suggests there are opportunities to expand environmental outcomes with existing volumes of environmental water through: improving freshwater–estuarine–marine connectivity and the salinity dynamics of the Lower Lakes and Coorong, increasing the area of estuarine habitat and in turn, decreasing estuarine squeeze. Maintaining the status quo of a hard barrage interface, with one-way (downstream) flow, impedes the dynamic processes which are essential to estuarine function and health, and may render the CLLMM's freshwater and estuarine ecosystems more susceptible to the impacts of a changing climate.

Operating the barrages in a more transparent manner, however, is not without risks to water quality and freshwater ecosystems immediately upstream of the barrages. Nevertheless, regardless of barrage operations, overtopping of the barrages due to sea level rise is occurring and is predicted to increase (Brookes et al. 2026). Our refined hydrodynamic model can be used to predict impacts on water quality and as discussed, guide potential mitigation through barrage operations. Undoubtedly though, current freshwater environments immediately upstream of the barrages, and the threatened freshwater fishes they support (e.g. southern pygmy perch, *Nannoperca australis*), will be impacted by increasing salinities. The management of these fish populations, in light of future climate scenarios, is considered by Zukowski et al. (2026) who suggest that populations may need to be bolstered or established in alternative freshwater habitats in the Lakes and lower River Murray. In the context of our study, more flexible barrage operation may assist in the transition of these near barrage freshwater habitats to a brackish aquatic ecosystem that will be more resilient in the long term to the interaction of rising sea levels and diminished freshwater flows. Furthermore, reconnection of a dynamic estuarine interface, whereby tidal flux is restored to previously impounded freshwater habitats, can have positive implications for carbon sequestration and methane emissions (Kroeger et al. 2017). This is a consideration for climate change adaptability in the CLLMM region and presents an important avenue for future research.

## *4.5 Future directions*

### 4.5.1 Modelling

- Review the methods used to calculate barrage flow. The need to scale the calculated barrage flow to match the observed conditions suggests it may be timely to review the weir equations used to derive barrage flow as suggested in DEW (2021). The period from July 2015–March 2020 was used for calibration, commencing based on the availability of sufficient records of barrage gate openings. Now there is double the length of data available to test and update the weir equations. The water balance used to derive barrage flow to calibrate the weir equations is likely to be influenced by the change in SILO evaporation and solar radiation data made in November 2023, when all data after 1990 was replaced by satellite data from Bureau of Meteorology, rather than the previous, less reliable, estimates derived from cloud oktas and sunshine hours.
- Bathymetric survey downstream of Boundary Creek Barrage. The DEM, and previous TFV models, adopt a water level of 0.3 m AHD in Boundary Creek downstream of the barrage, which is clearly too high. However, it is noted access through the downstream part of Boundary Creek can be difficult with shallow water. The need for updated bathymetric data upstream and downstream other barrages (e.g. Mundoo) should also be considered.
- Workshop current and future barrage operating and climate scenarios. The hydrodynamics model presents a powerful tool to consider barrage operating scenarios under a range of inflow and climate conditions. Workshop operational scenarios with DEW, SA Water, MDBA, Commonwealth Environmental Water Holder (CEWH) and the community.

### 4.5.2 Management

- Formally integrate consideration of open barrage bays and facilitating reverse flows into contemporary barrage operation. An upcoming Barrage Operating Strategy (BOS) review and update provide a timely mechanism for this.
- Progress automation of gates to enable remote operation in response to real time upstream and downstream water levels. Explore priority locations and develop, through hydrodynamic models, water level triggers that maximise ecological outcomes whilst mitigating salinity risks (ecologists, SA Water, DEW, CEWH).
- Continue to work collaboratively across SA Water, DEW, CEWH, MDBA, the community and researchers to explore opportunities to adopt the concept at additional locations across the barrage network. Boundary Creek and Ewe

Island barrages proved suitable trial sites but the concept could now be trialled at one of the larger barrages (see Research below).

### 4.5.3 Research

- Mundoo Barrage presents as a promising option to further investigate water quality and ecological response to more transparent barrage operation. The geographic vicinity of Mundoo Barrage to the Murray Mouth increases opportunities for connectivity across the barrage interface (e.g. more reverse events in Figure 8 in Section 3.1). From an operational perspective, Mundoo Barrage is easily accessible and has gates that can be automated. Furthermore, Mundoo Island is to become part of the National Parks systems, so is an excellent candidate for integrated aquatic and terrestrial ecosystem restoration. There is also community support in this region for barrage management options that will help promote ecosystem resilience to future climate scenarios of sea level rise and diminishing freshwater flow.
- Continue to collect foundational physico-chemical and biological data in association with reverse flows at the Murray barrages, particularly under alternate hydrological conditions and across seasons. The current project forms a foundation but was a preliminary exploration.
- Additional modelling scenarios could be used to develop rules around the magnitude and duration of reverse events at each barrage and forecast conditions that would inform a decision to shut or leave gates open.
- Expand research to consider whole-of-aquatic ecosystem response to reverse flows, including the aquatic-terrestrial interface in regions influenced by potential changes in long-term salinity regimes (e.g. current freshwater environments immediately upstream of the barrages).

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# Appendix A

## *2022 model validation time series*

Water temperature results (Figure A1) suggest the model represents heat exchange, and hence evaporation from the water surface, accurately. This representation of evaporation, combined with the boundary condition data sourced (inflows and extractions from best available information) is expected to represent the overall water balance well.

Using the hourly barrage flows calculated using the weir equations of DEW (2021) resulted in water levels in Lake Alexandrina higher than observed, suggesting the barrage flow was low (assuming the other water balance terms were reasonable). The calculated barrage flows were scaled by a factor of 1.27 to provide a closer match between the modelled and observed water levels across the domain (Figures A9-A15).

Salinity dynamics are also well represented across the model domain (Figures A2-A8). At Point McLeay in Lake Alexandrina, between Point Sturt and Raukkan, it can be seen that the depth averaged salinity (purple in the bottom left plot of Figure A1) is higher than in the surface layer only (black) for a short period during the peak salinity at this site, due to salt ingress from a reverse flow event. The salinity sensor is at the surface (blue), and hence the modelled surface layer provides a close representation of the recorded salinity event. When the model was run in 2D (not shown) the salinity dispersed too quickly and did not penetrate into the lake body at the observed concentrations (for example at sites A4260524 and A4261133). A more accurate representation of the salt movement was obtained with 3D, and hence this was deemed necessary for the purposes of evaluating salinity risks from reverse flow events.

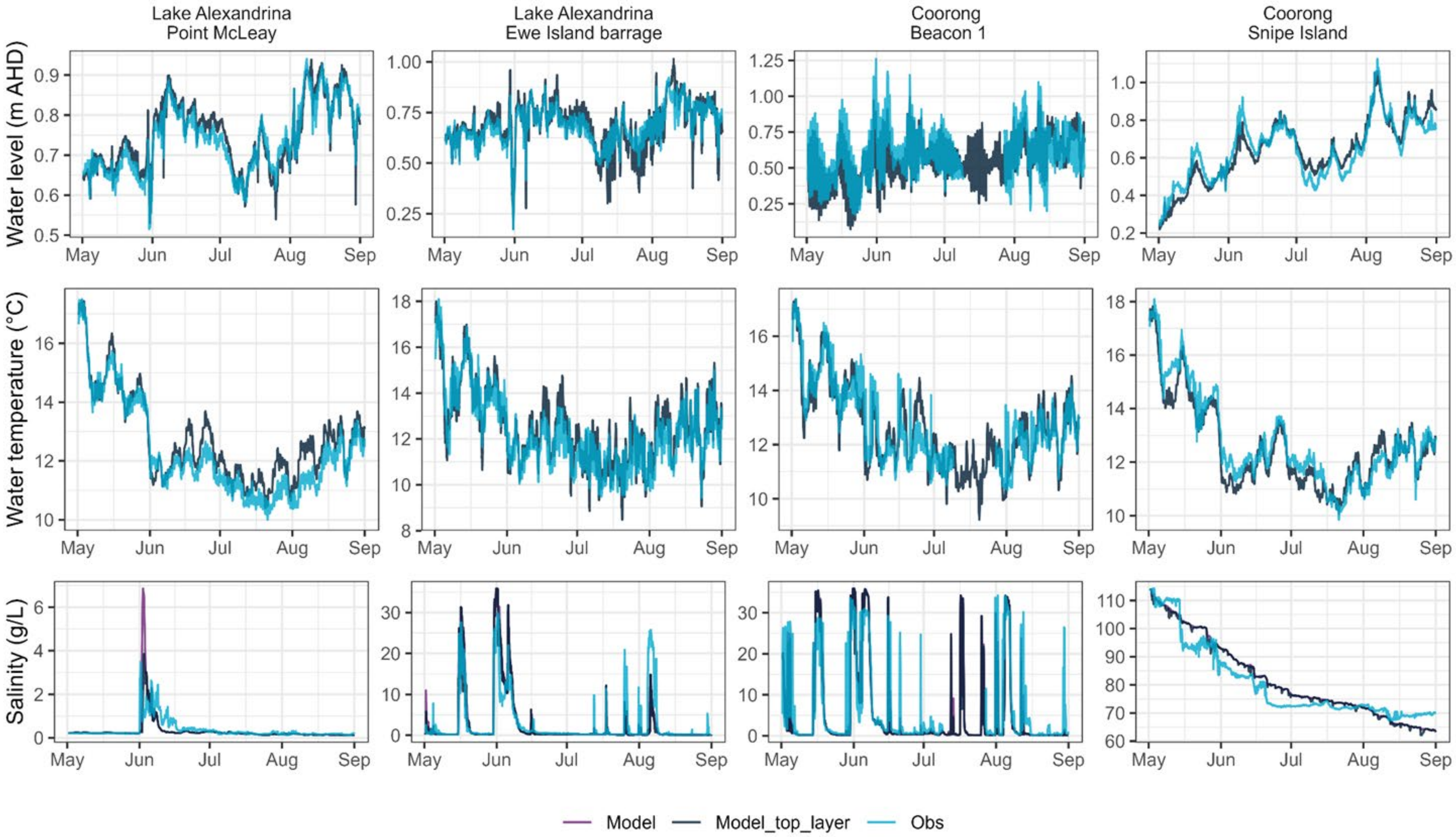


Figure A1. Model and observed results for water level, water temperature and salinity for example sites over a reverse flow event in 2022

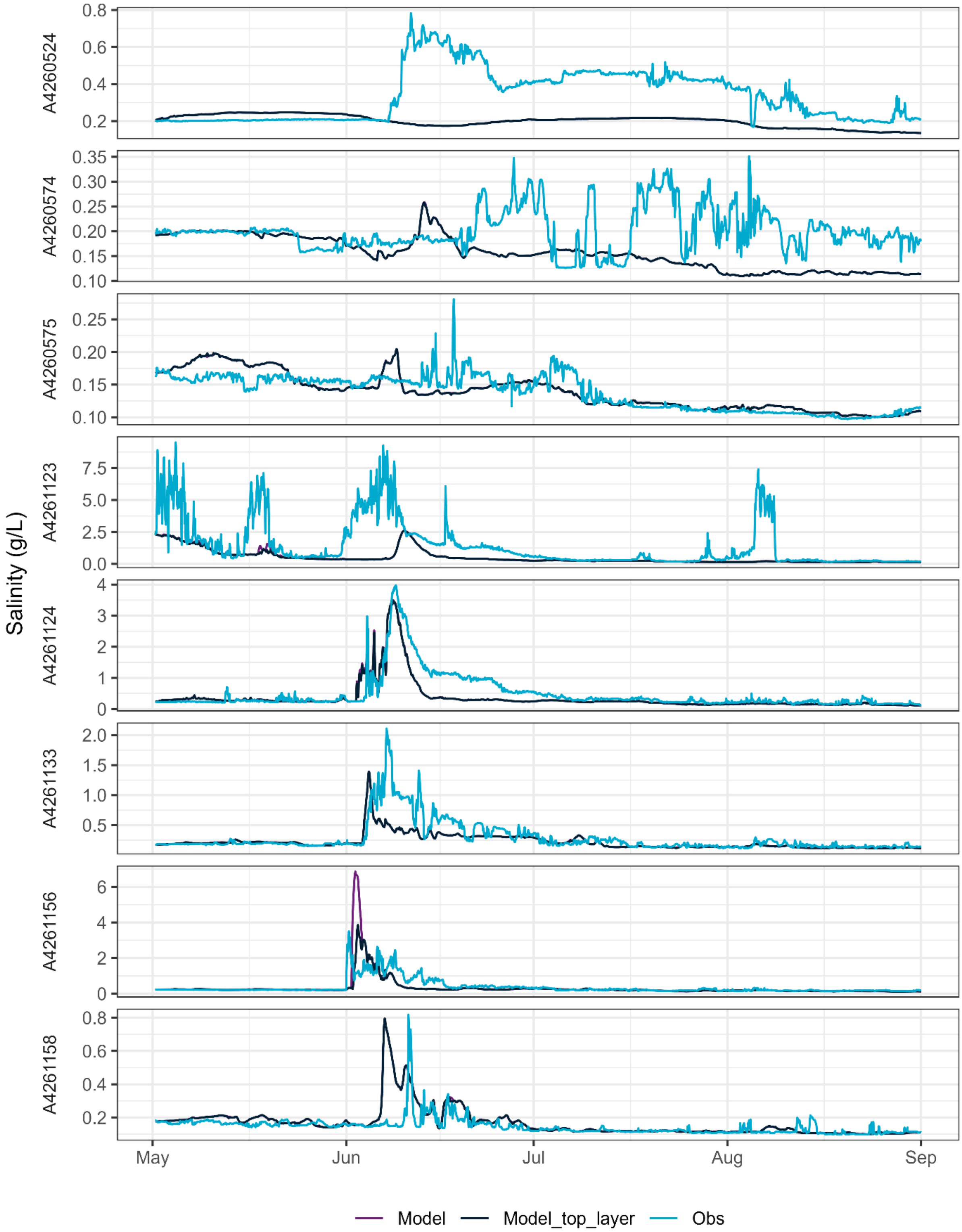


Figure A2. Modelled and observed Lake Alexandrina salinity

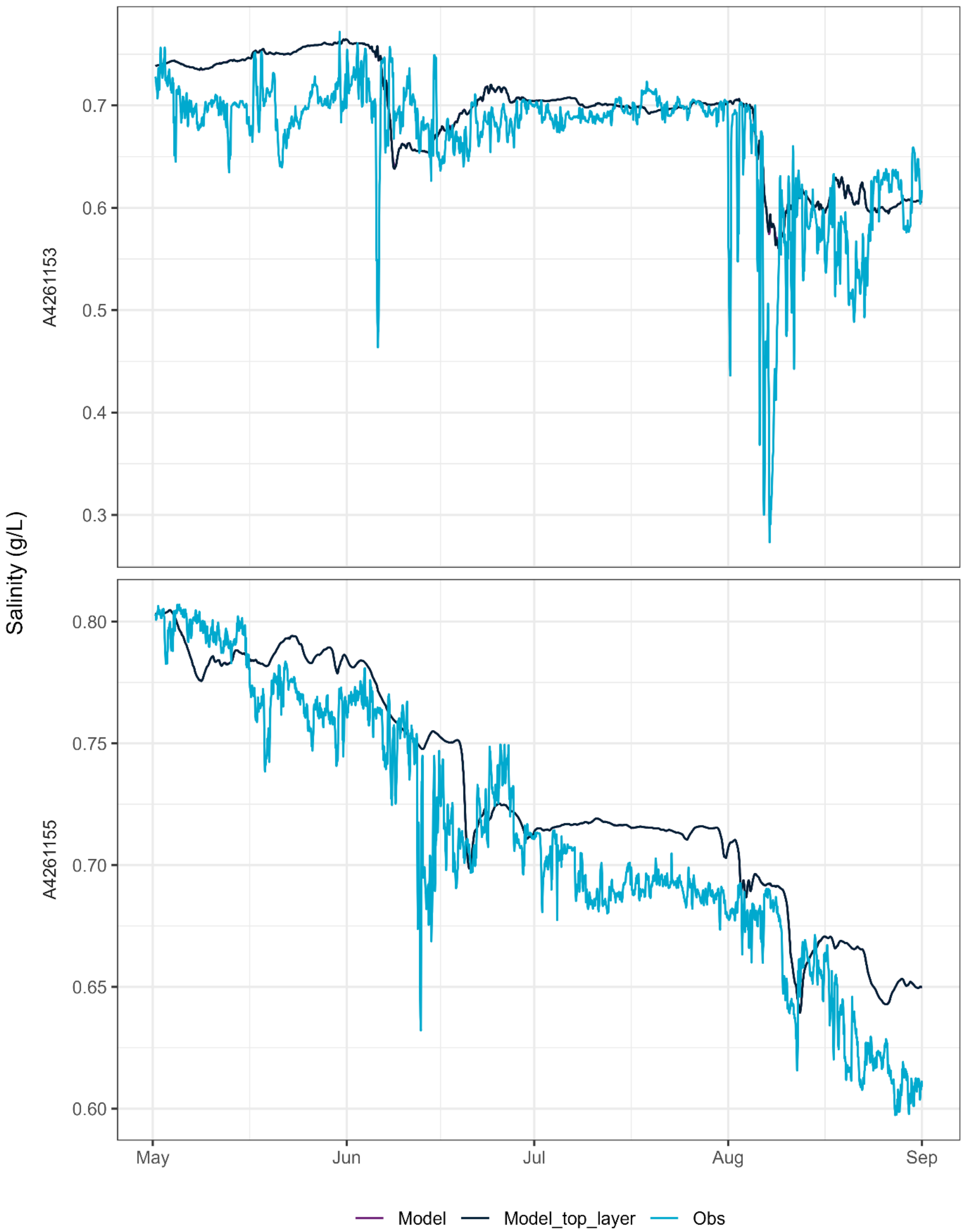


Figure A3. Modelled and observed Lake Albert salinity

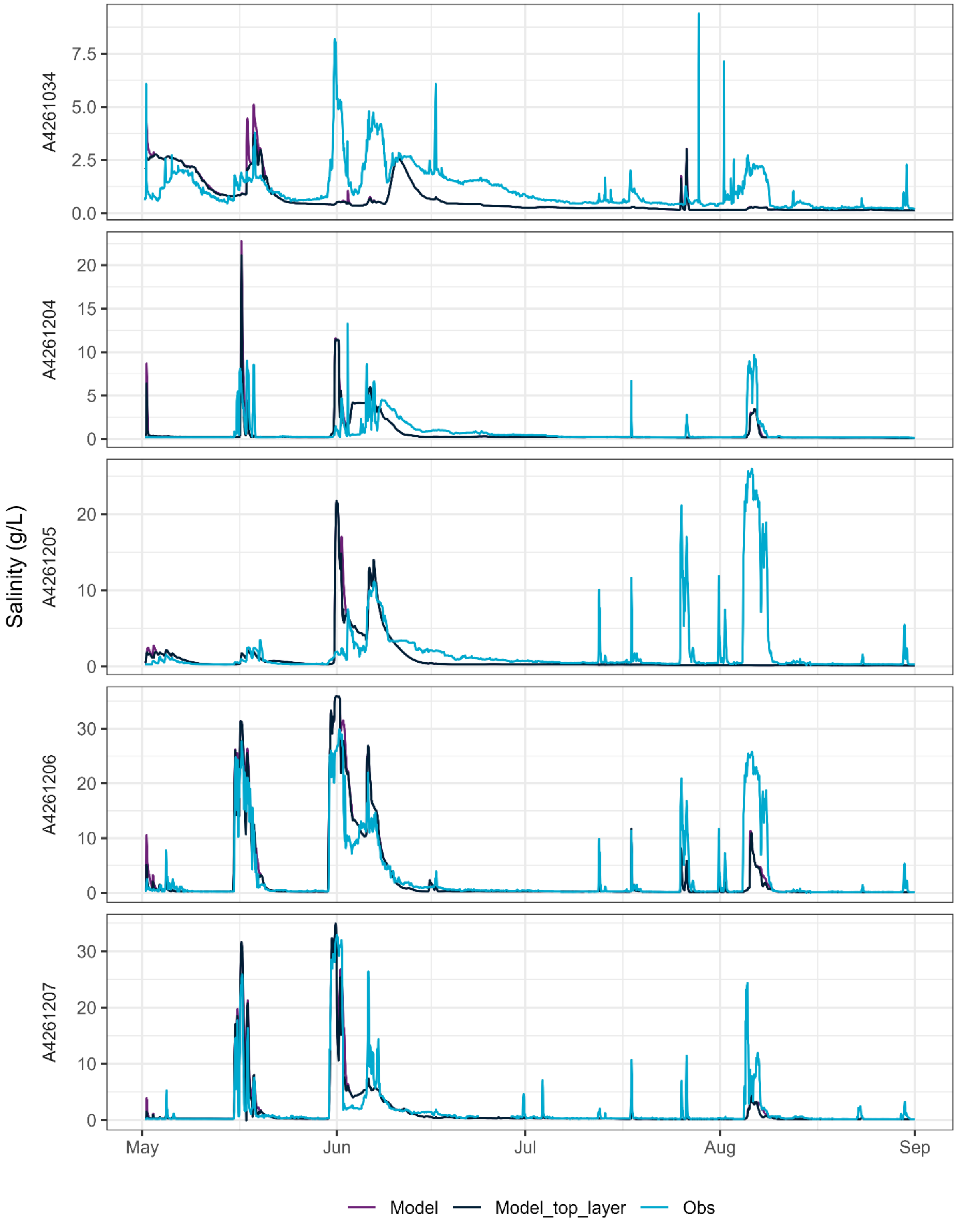


Figure A4. Modelled and observed salinity at upstream of barrages

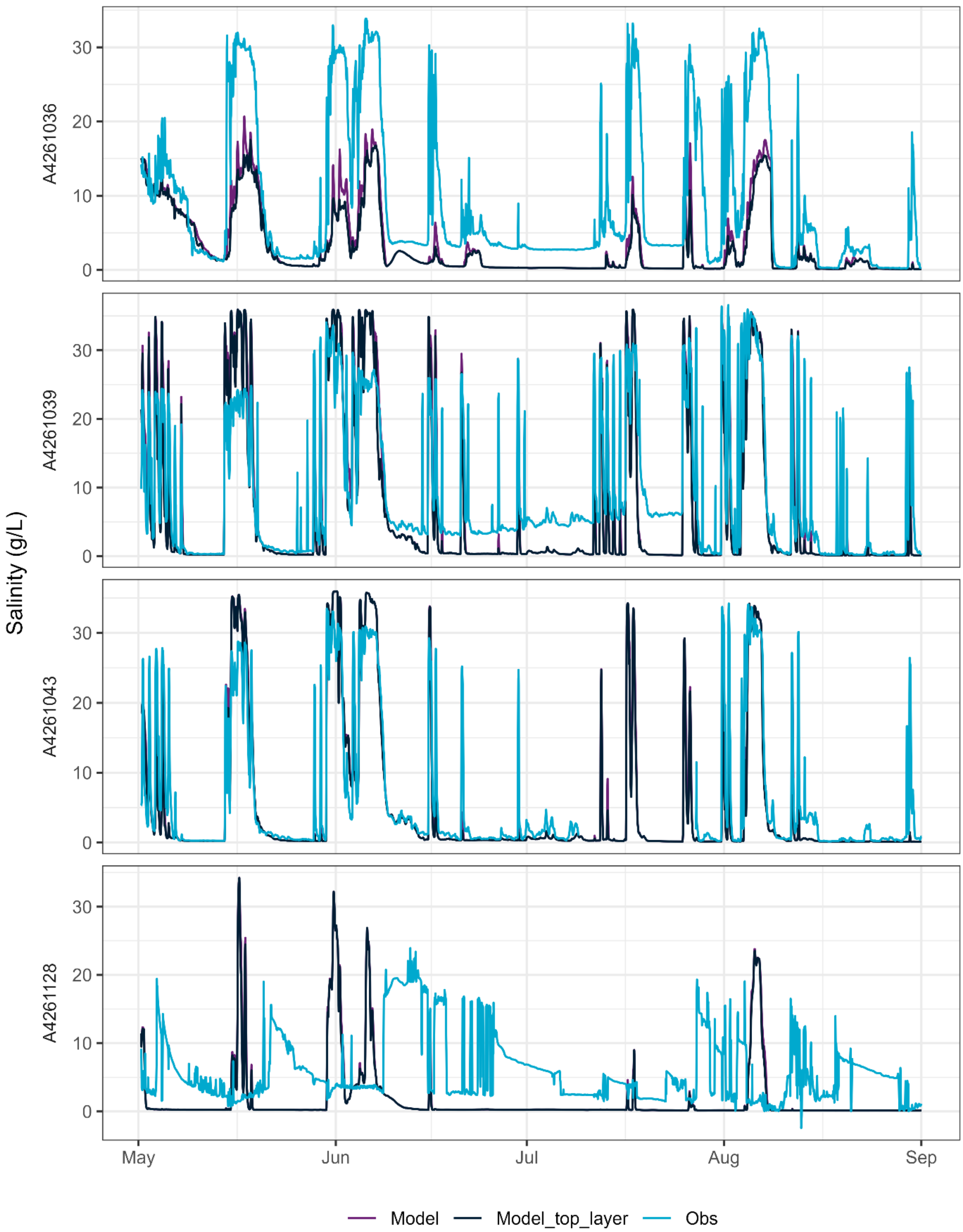


Figure A5. Modelled and observed Coorong estuary salinity

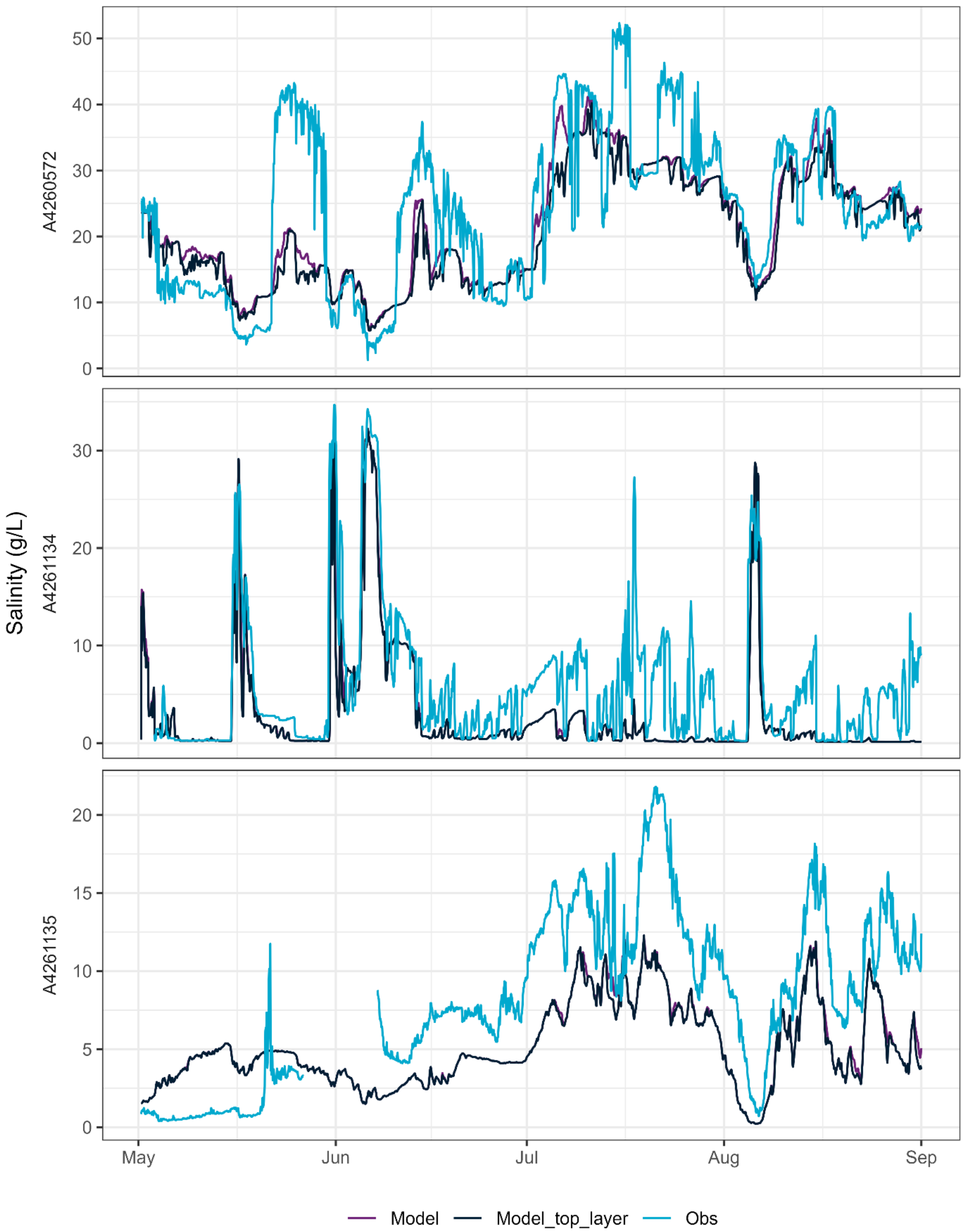


Figure A6. Modelled and observed Coorong North Lagoon salinity

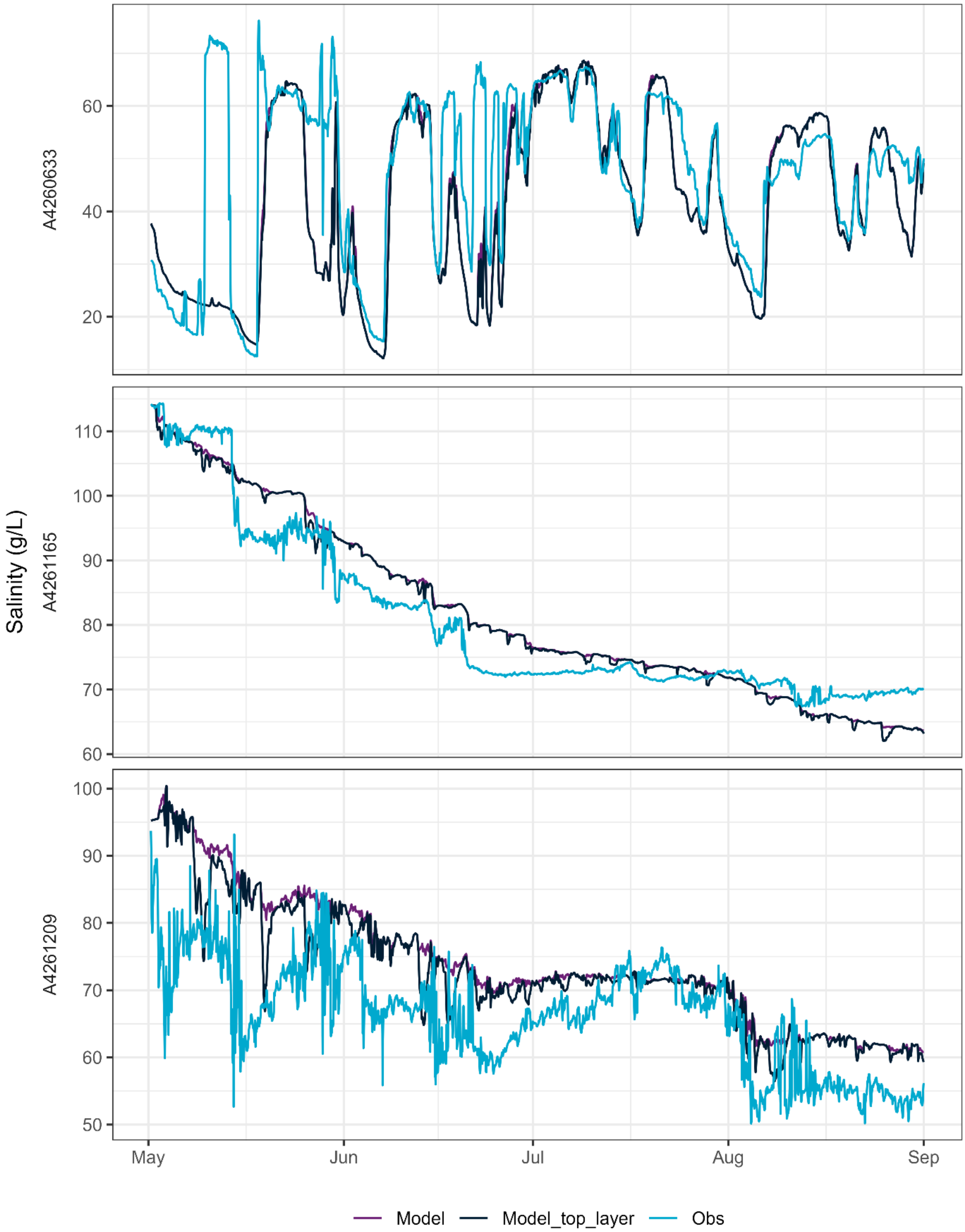


Figure A7. Modelled and observed Coorong south Lagoon salinity

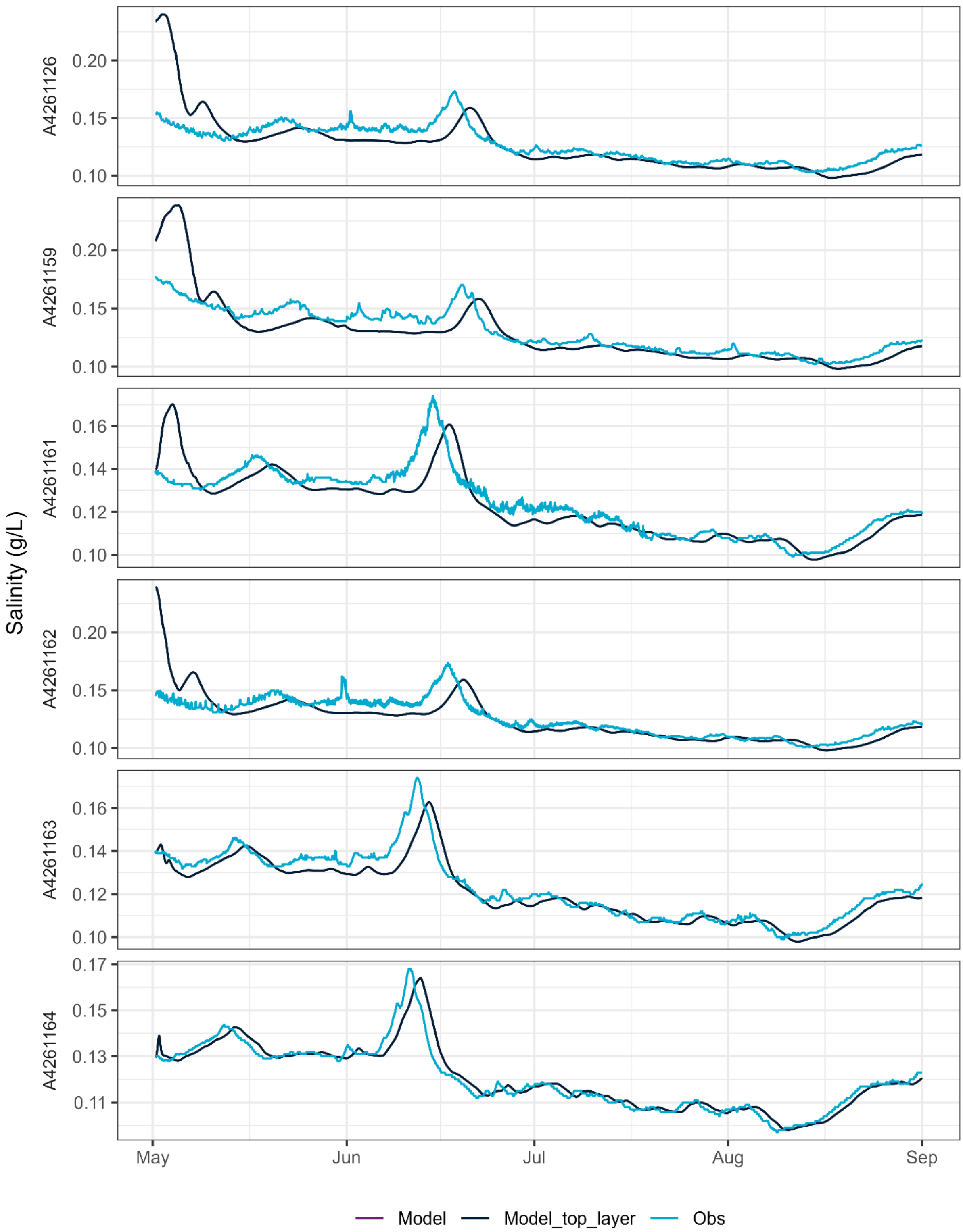


Figure A8. Modelled and observed River Murray salinity

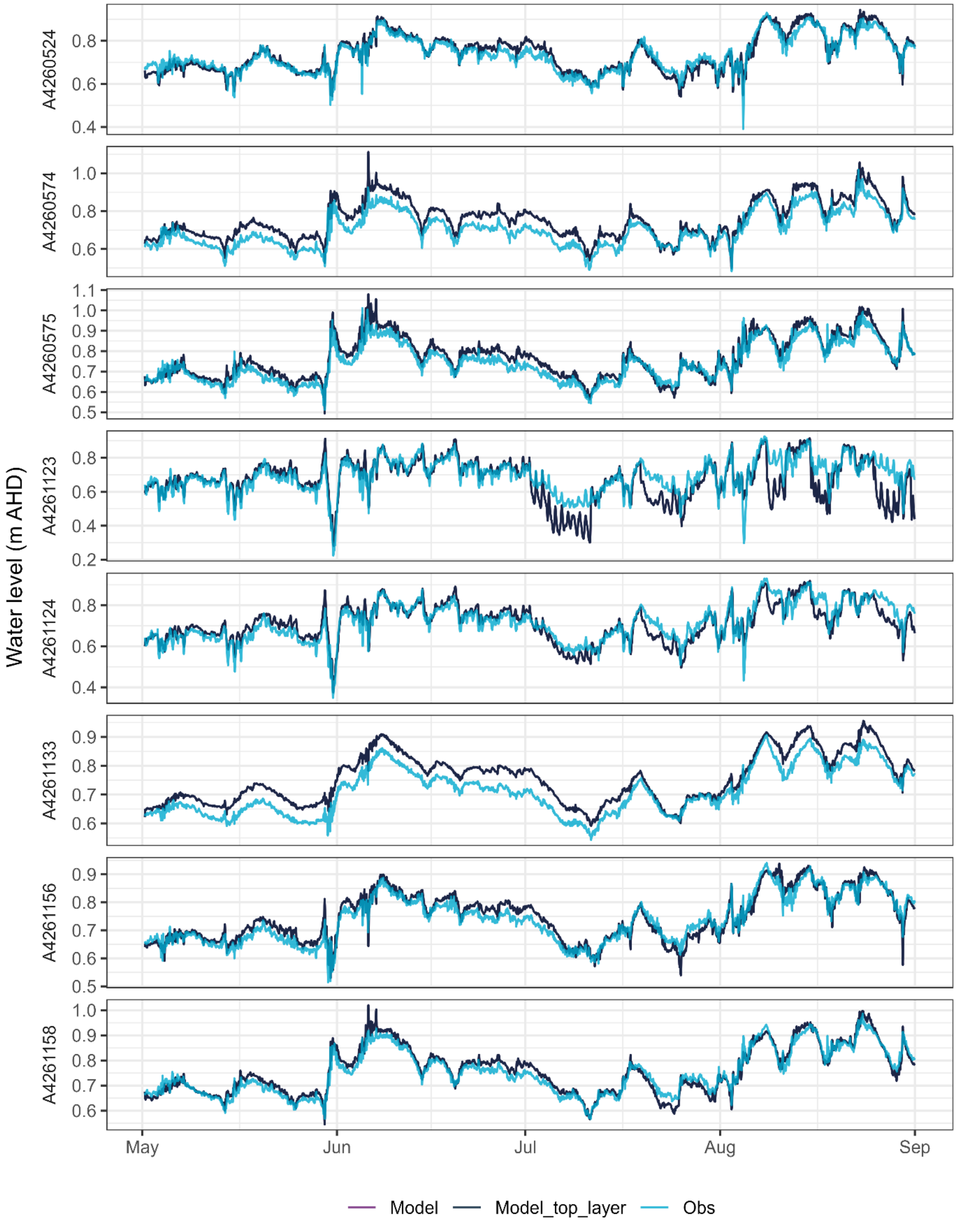


Figure A9. Modelled and observed Lake Alexandrina water level

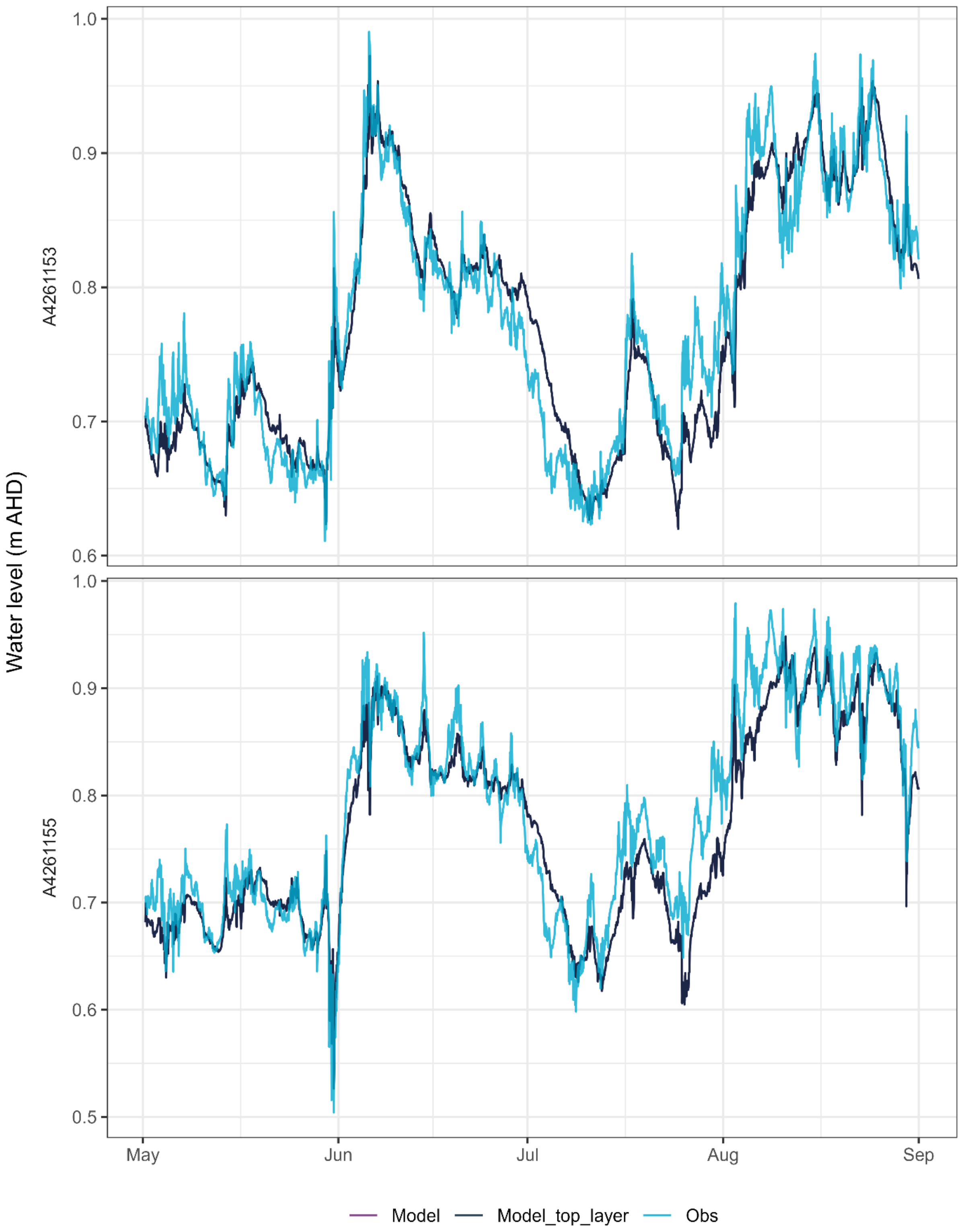


Figure A10. Modelled and observed Lake Albert water level

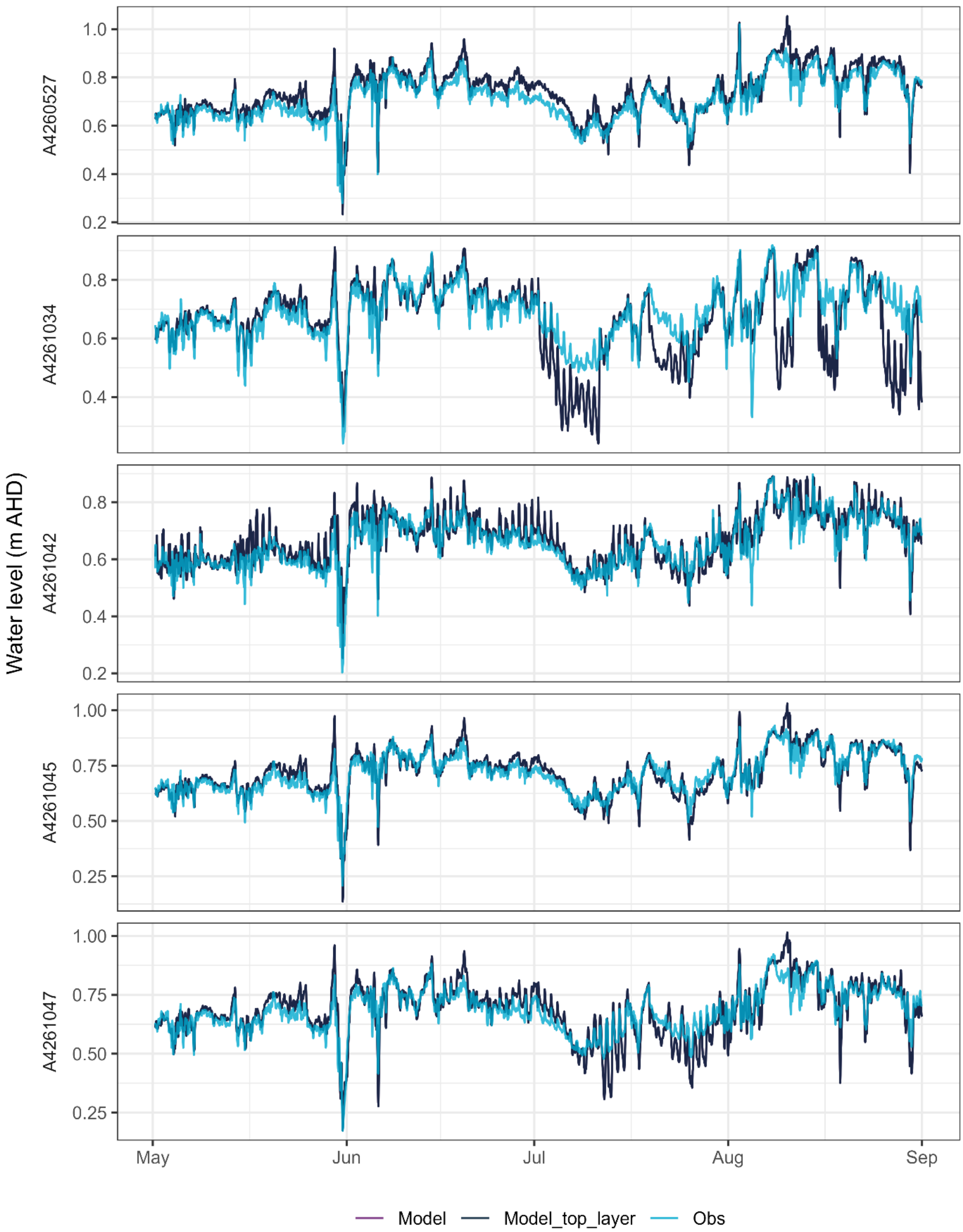


Figure A11. Modelled and observed water level upstream of barrages

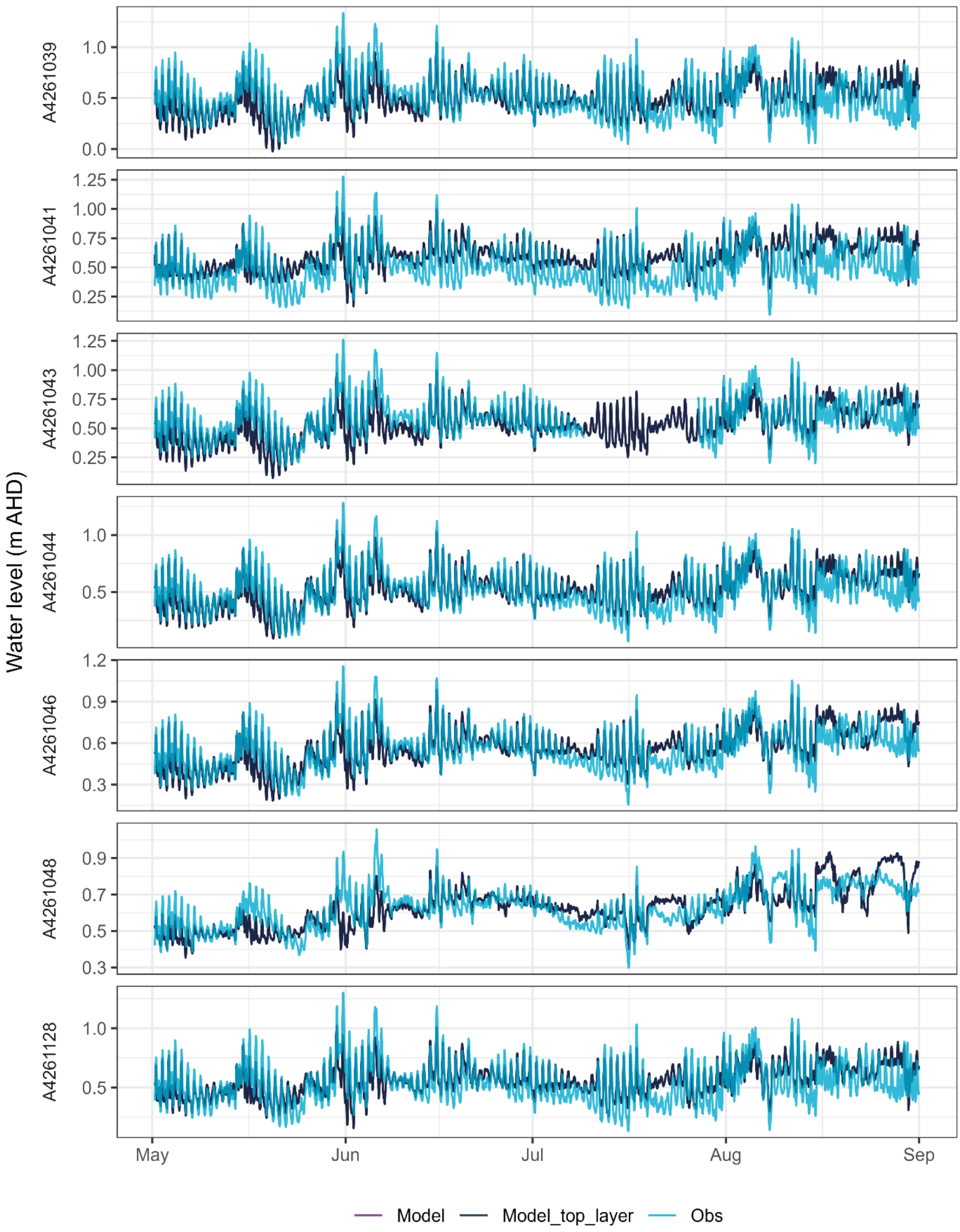


Figure A12. Modelled and observed Coorong estuary water level

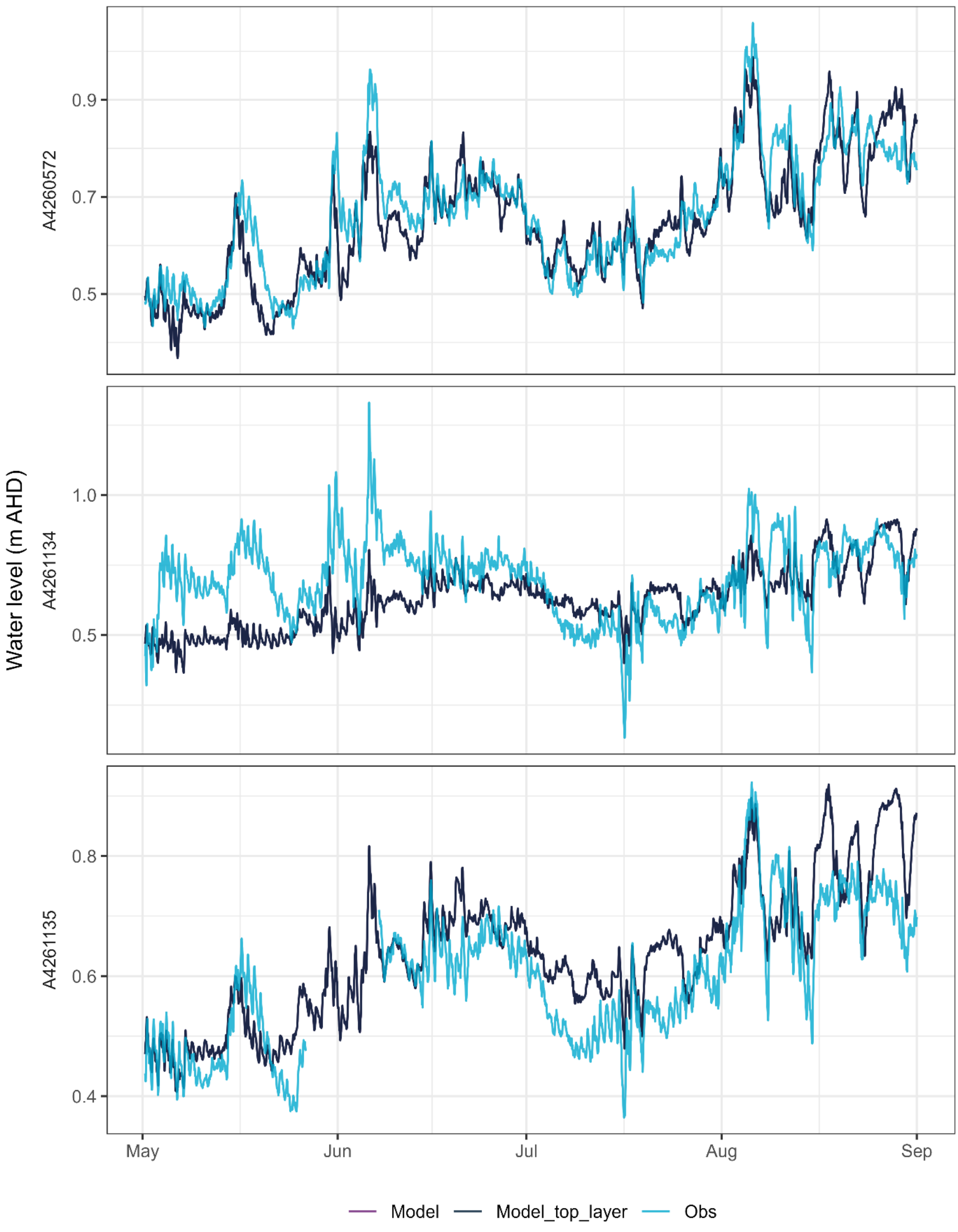


Figure A13. Modelled and observed Coorong North lagoon water level

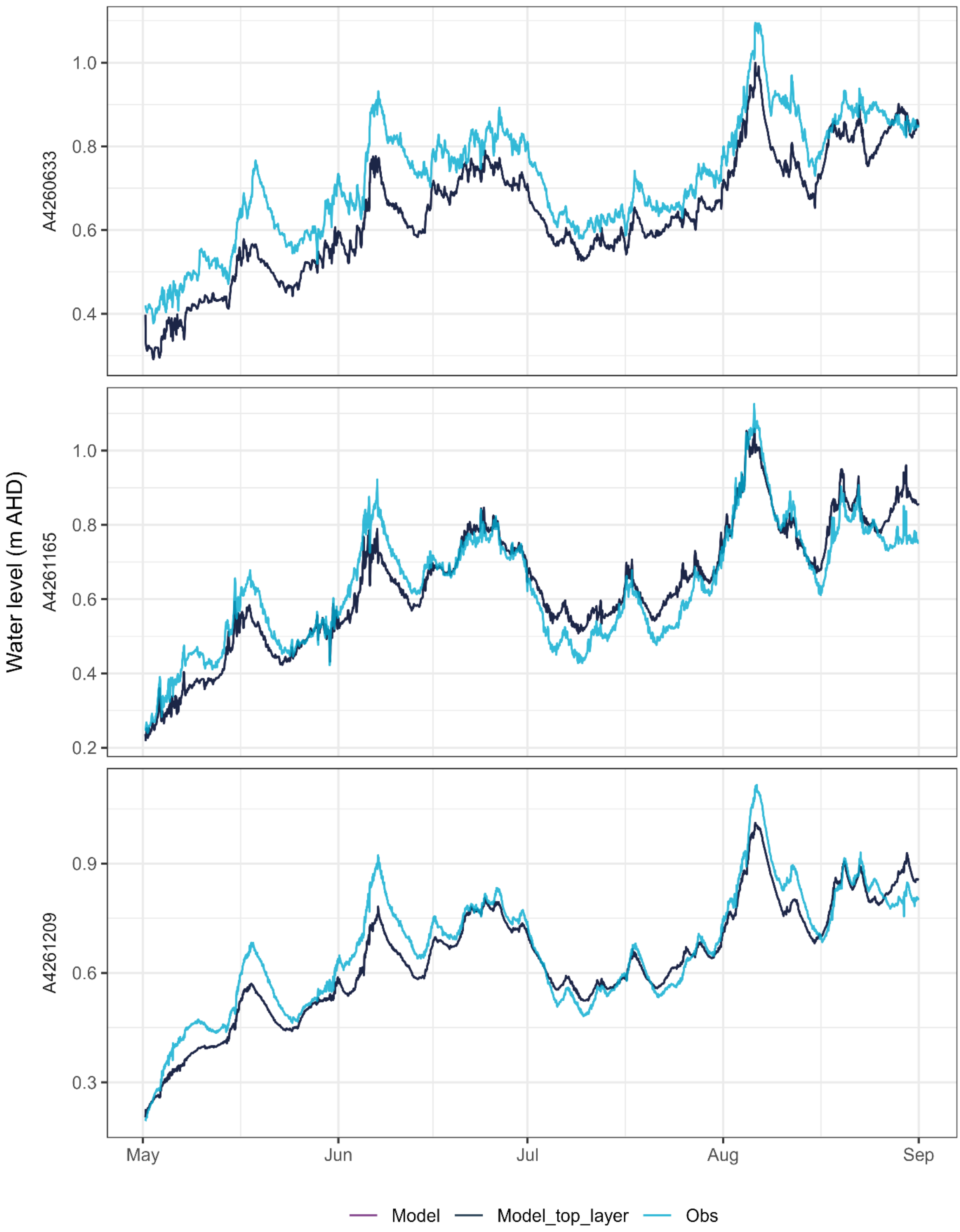


Figure A14. Modelled and observed Coorong South Lagoon water level

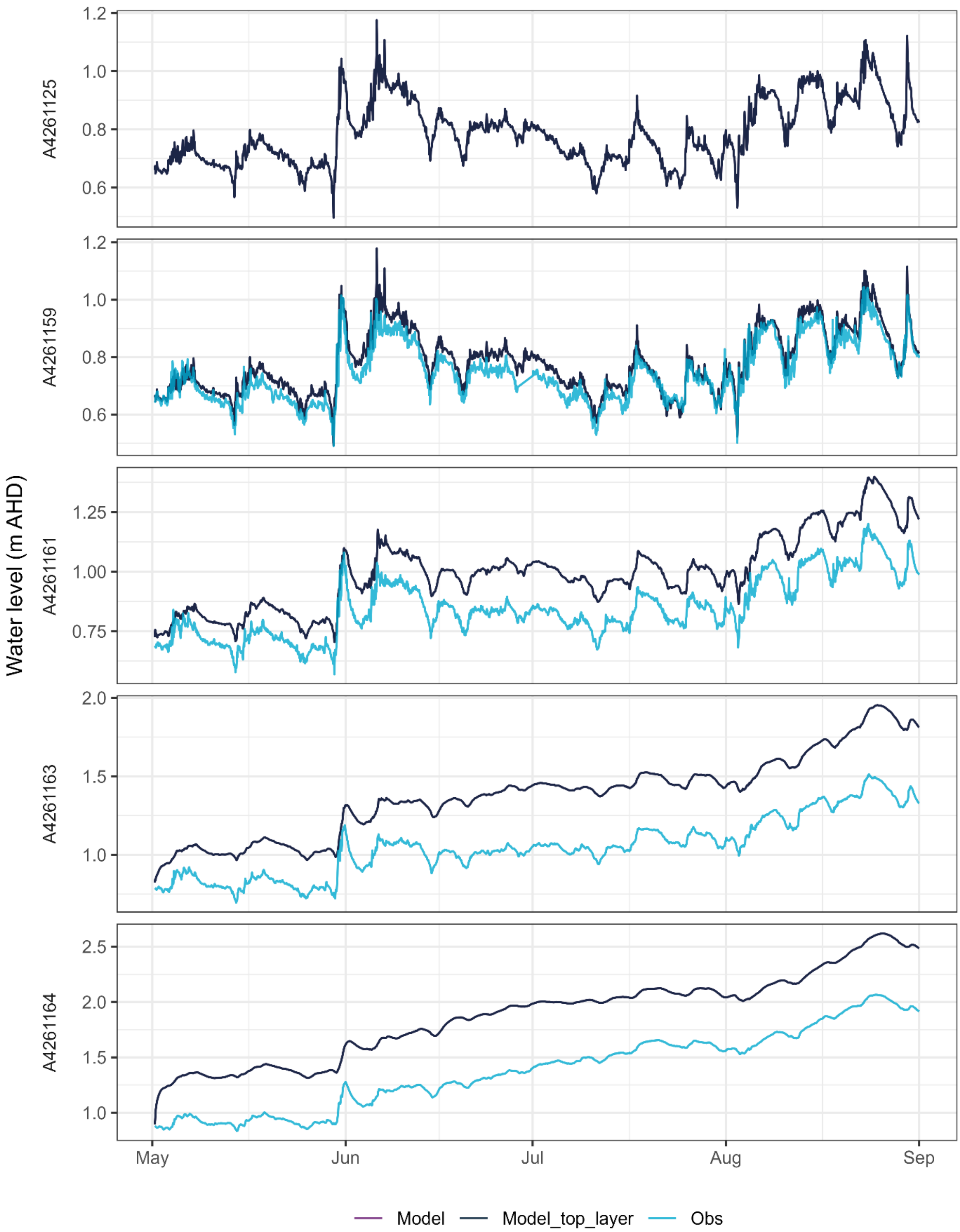


Figure A15. Modelled and observed River Murray water level

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