Assessing the impact of sewage overflows on oyster harvest areas: Pambula Lake estuary technical summary

WRL TR 2023/27, May 2025

By Y Doherty, M Mason, A J Harrison and B M Miller

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Project details

Report title	Assessing the impact of sewage overflows on oyster harvest areas: Pambula Lake estuary technical summary
Authors(s)	Y Doherty, M Mason, A J Harrison and B M Miller
Report no.	2023/27
Report status	Final
Date of issue	May 2025
WRL project no.	2021101
Project manager	A J Harrison
Client	NSW Food Authority
Funding acknowledgement	This study was funded through a Department of Regional NSW Storm and Flood Industry Recovery Program (SFIRP) – Sector Recovery and Resilience Grant with support from local councils and wastewater authorities

Document status

Version	Reviewed by	Approved by	Date issued
Draft	BMM	FF	12/03/25
Final	BMM	FF	26/05/25

This report should be cited as: Doherty, Y, Mason, M, Harrison, AJ and Miller, BM 2025, Assessing the impact of sewage overflows on oyster harvest areas: Pambula Lake estuary technical summary, WRL Technical Report 2023/27, UNSW Water Research Laboratory.

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This project has been funded under the Storm and Flood Industry Recovery program, jointly funded by the Australian and NSW governments. Although funding for this project has been provided by both Australian and NSW governments, the material contained herein does not necessarily represent the views of either government.

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1 Introduction

1.1 Project overview

The Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at UNSW Sydney was engaged to undertake an extensive study titled “Assessing the impact of sewage overflows on oyster harvest areas in NSW”. This study was funded through a Department of Regional NSW Storm and Flood Industry Recovery Program (SFIRP) – Sector Recovery and Resilience grant with support from local councils and wastewater authorities.

The study seeks to understand the fate of contaminants and the potential exposure of oyster leases following overflow events under different environmental conditions including tides, wind and catchment runoff. The results of this study provide decision makers with quantitative data to assess exposure risk to specific harvest areas on an individual sewer overflow event basis. These outcomes allow for increased confidence in ensuring consumer safety, and more targeted harvest area closures to reduce the economic impact of widespread closures on local industry.

Sewage overflows into estuaries occur under a range of conditions, often due to malfunctioning or overwhelmed infrastructure. As a result, the environmental conditions in the estuary at the time of an overflow can vary. While experimental data (such as large scale dye release experiments) can be useful to understand contaminant transport in a single set of conditions (or a small number of conditions), it is impractical to collect such data for the broad range of conditions possible across multiple sewage overflow locations. Therefore, the approach of this study is to combine desktop numerical modelling and site-specific field investigations as a cost-effective means to gain sufficient understanding of contaminant transport.

For a detailed background to the study, refer to the User Guide (WRL TR2024/26).

1.2 Report context

This report is focussed on the Pambula Lake estuary. It provides technical details of the available data, data collection undertaken, model development and the capabilities of the predictive model.

This report provides specific details for Pambula Lake and should be read in parallel with User Guide WRL TR2024/26 and Technical Summary Report WRL TR2023/32 (Table 1-1). The other reports for each specific estuary are listed in Table 1-2.

Table 1-1 Summary of project reference documents

Report number	Intention
WRL TR2024/26	Project overview and user guide
WRL TR2023/32	Technical summary of fieldwork and modelling methods

Table 1-2 Summary of estuary specific reports

Estuary	Technical summary
Tweed River	WRL TR2023/18
Nambucca River	WRL TR2023/19
Hastings River	WRL TR2025/05
Camden Haven River	WRL TR2023/20
Wallis Lake	WRL TR2023/21
Port Stephens	WRL TR2023/22
Clyde River	WRL TR2023/24
Shoalhaven/Crookhaven Rivers	WRL TR2023/23
Wagonga Inlet	WRL TR2023/25
Merimbula Lake	WRL TR2023/26
Pambula Lake	WRL TR2023/27 (this report)

1.3 Pambula Lake site description

Pambula Lake is a coastal estuary on the far south coast of NSW, Australia, located 365 km south of Sydney and 10 km north of Eden. Towns in the area include Pambula, Merimbula, Tathra and Bega.

The Pambula Lake estuary system is comprised of a lake (up to 5 m deep) connected to the ocean via a 4 km inlet channel and an untrained entrance. The estuary upstream of Pambula Lake is comprised of two rivers: the Pambula River and a large tributary, the Yowaka River. Adjacent to the Pambula River is Panboola Wetlands, a large intertidal area. The estuary catchment area is 275 km^2, the waterway area is 2.9 km^2 and the tidal prism on a spring tide in 2003 was 3.5 x 10^6 m^3 (MHL, 2003). The lake entrance has no history of closure; however, the entrance bar is a dynamic feature with cyclical variation in entrance channel depth and sand bar morphology. The estuary has one oyster harvest area: Pambula Lake. Harvest areas and key locations are shown in Figure 1-1.

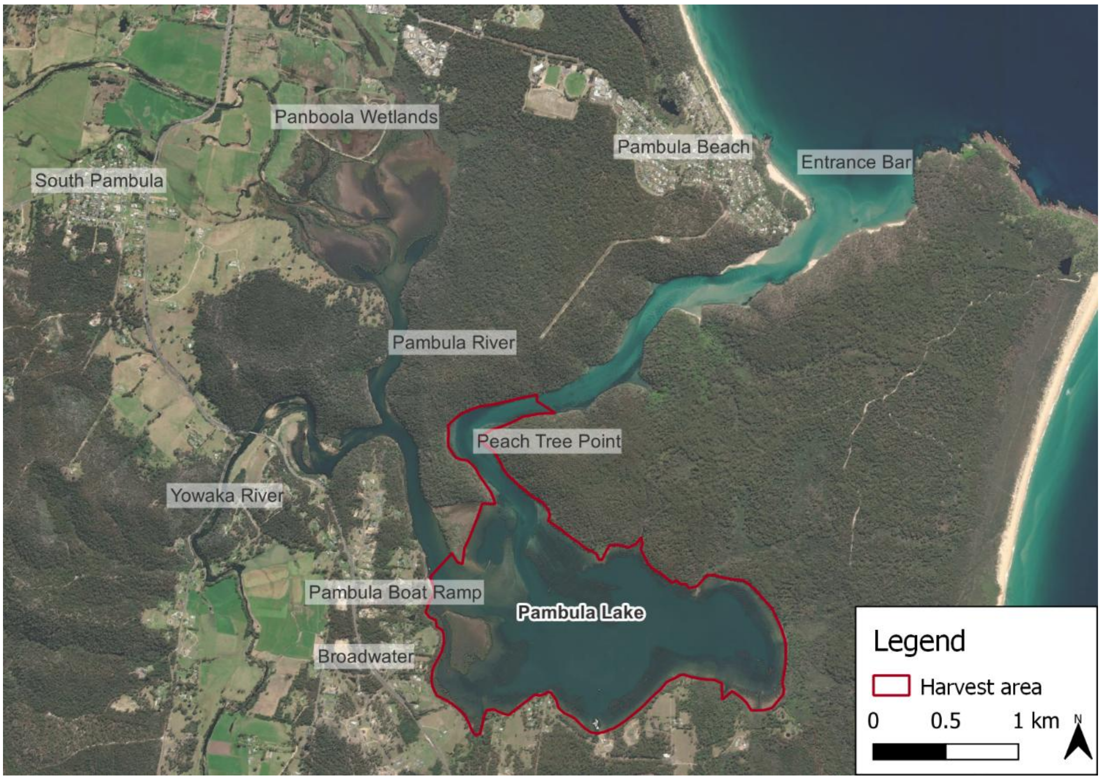

Figure 1-1 Oyster harvest areas in Pambula Lake estuary

1.4 About this report

This report includes the following sections:

- **Section 2: Data collation** – summarising the relevant existing data available to assist in calibration of the numerical model, including information on historical sewage overflow locations.
- **Section 3: Field data collection** – summarising the outcomes of a field data collection campaign on the estuary.
- **Section 4: Model development** – outlining the development of the numerical model of the Pambula Lake estuary.
- **Section 5: Scenario modelling** – describing the suite of scenarios run for the estuary.

The following appendices are included which provide additional detail:

- **Appendix A: Field data collection**
- **Appendix B: Model calibration**

2 Data collation

2.1 Preamble

Table 2-1 summarises the preexisting available data relevant for development of the numerical hydrodynamic and water quality model.

Table 2-1 Summary of data collated for this project

Data type	Primary sources	Comments	Report section
Long term water level data	MHL (2023a) MHL (2023b)	Long term water level data available at one location in Pambula Lake and at one nearby ocean tide gauge.	2.2
Water level data	NSW Food Authority (2023)	Single water level sensor in Pambula Lake.	2.2
Tidal flow and water level	MHL (2003)	Tidal flow gauging at three locations and temporary water level gauging at four locations in September and November 2003.	2.2
Catchment discharge	WaterNSW (2023)	One long term catchment flow monitoring location.	2.3
Sewage overflows	NSW Food Authority	Data provided on overflows reported to EPA and NSW Food Authority including closure action pursued, spill duration and volume.	2.4
Bathymetry	DPIE (2018) OEH (2003) Montano et al. (2024) NSW Spatial Services (2013) NAVONICS (2023) NearMap (2024)	Bathymetry primarily sourced from 2018 marine LiDAR survey with supplementary data from 2003 single beam survey, 2023 WRL survey of Panboola Wetland, 2013 Digital Elevation Model (DEM), NAVONICS SonarChart and NearMap aerials.	2.5

2.2 Water level and tidal flow gauging

Manly Hydraulics Laboratory (MHL) maintain one permanent water level gauge on Pambula Lake, and one nearby ocean tide gauge at Eden. Further water level and flow gauging has occurred during two MHL short-term data collection campaigns in 1979 and 2003 (MHL, 1982; MHL, 2003). Due to potential hydrodynamic changes to the system over the last 40+ years, only the 2003 study was considered for model calibration purposes for this study. NSW Food Authority maintain an additional water level sensor in Pambula Lake which is used by the oyster growers. These gauging and water level sensor locations are shown in Figure 2-1 and tabulated in Table 2-2 and Table 2-3. Water level and flow gauging locations from the 2023 field campaign (refer to Section 3) are also included in these.

Table 2-2 Summary of water level gauges in Pambula Lake and relevant ocean tide gauge

Water level gauge	Location label	Station number	Provider	Date range	MHL report number
Eden	-	220470	MHL	1970 – present	–
Pambula River Entrance	1	–	MHL	22/09/2003 – 28/11/2003	MHL1290
Pambula Lake South-East	2	–	MHL	22/09/2003 – 28/11/2003	MHL1290
Pambula Lake North-West	3	220415	MHL	1991 – present	–
Upper Yowaka River	4	–	MHL	22/09/2003 – 28/11/2003	MHL1290
Upper Pambula River	5	–	MHL	22/09/2003 – 28/11/2003	MHL1290
Pambula Lake (ICT)*	6	–	NSW Food Authority	2022 – present	–

* This sensor was initially deployed as part of the 2017-2020 Food Agility CRC project: Oyster industry transformation – Building sustainability and profitability in the Australian Oyster Industry.

Table 2-3 Summary of tidal flow gauging locations in Pambula Lake estuary

Tidal flow gauge	Location label	Date	Study
Pambula River Downstream	A	25/10/2003	MHL1299
Pambula River Upstream	B	25/10/2003	MHL1299
Yowaka River	C	25/10/2003	MHL1299

Figure 2-1 Water level and tidal flow gauging locations

2.3 Catchment inflows

Gauged catchment inflows were available from WaterNSW. When these were not at the tidal limit (the model boundary), the flows were scaled up proportional to the additional catchment area using the method in WRL TR2023/32 Section 2.4. There are two model boundary inflows into the Pambula estuary and continuous flow gauging of discharge and water levels are available from WaterNSW (2023) at one relevant location: Pambula River at Lochiel (1966 to the present). Table 2-4 lists the model boundaries, the gauge used and the relevant scaling factor applied. Figure 2-2 shows the locations along with the catchment area flowing into each tidal boundary (solid line polygon) along with the associated portion of that catchment that is upstream of the gauge (hatched).

Table 2-4 Summary of scaling factors for model catchment boundaries

Model boundary	Base WaterNSW gauge	Scaling factor
Pambula River	220003	1.04
Pipeclay Creek*	220003	1.27

*This catchment was ungauged, so the gauge in the nearby Pambula River catchment was scaled and used.

Flowrates exceeded at various percentiles for each WaterNSW gauge are shown in Table 2-5.

Table 2-5 WaterNSW gauge flow percentiles

Percentile	Pambula River at Lochiel (220003) ML/d *(m^3/s)*
5th	0.0 *(0.0)*
20th	0.69 *(0.008)*
50th (median)	6.8 *(0.079)*
80th	29 *(0.34)*
95th	332 *(3.8)*

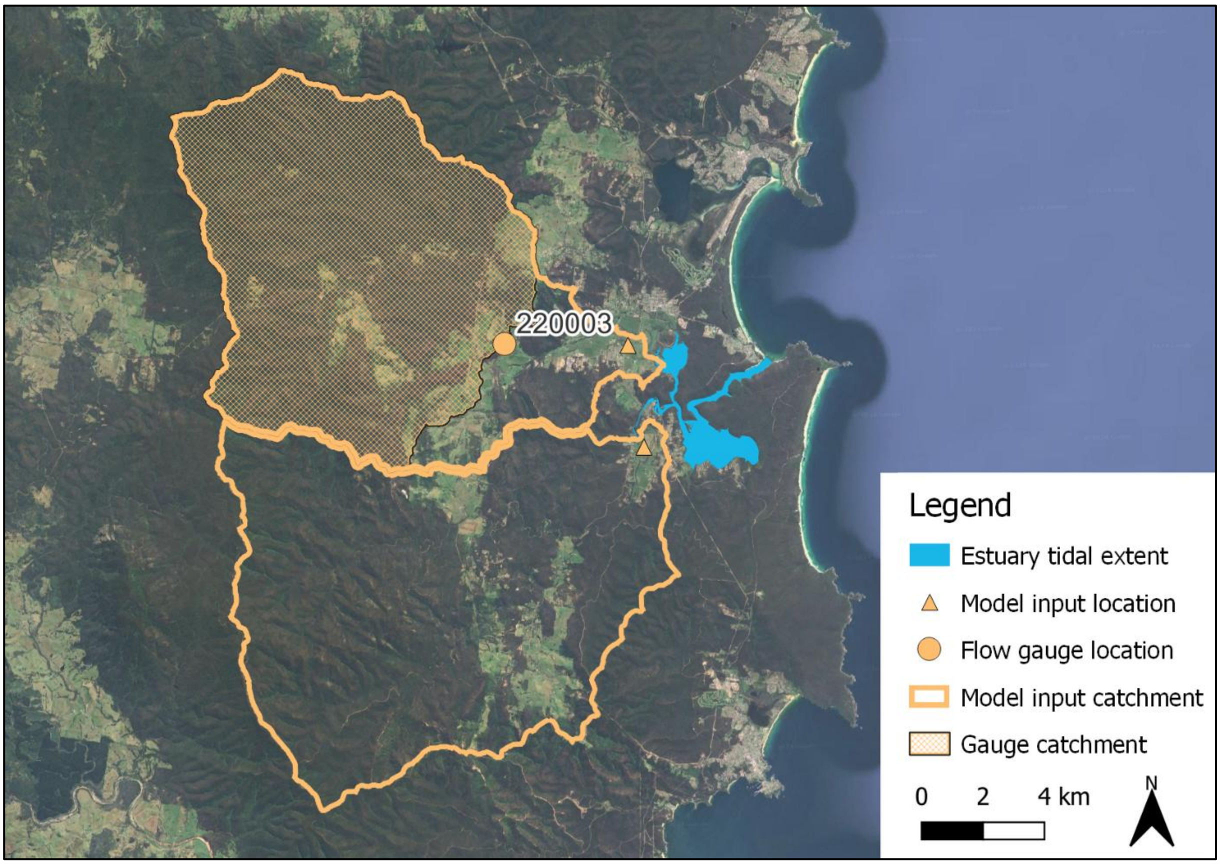

Figure 2-2 Catchment flow gauging stations*

*Hatched areas correspond to upstream catchments of WaterNSW gauges. Outline areas correspond to model input catchment areas.

2.4 Sewage overflow data

Bega Valley Shire Council (BVSC) is the agency responsible for wastewater treatment and sewage management in the catchment surrounding the Pambula estuary. The sewerage system is comprised of a reticulation network of pipes and sewage pumping stations (SPS), in addition to the Merimbula wastewater treatment plant (WWTP). When sewage overflows occur, BVSC is required to notify NSW Food Authority so that appropriate decisions can be made on whether harvest area closures are necessary. Information on sewage overflows between 2016 and 2023 has been provided by the NSW Food Authority and reported overflow locations are shown in Figure 2-3. More information on sewage overflows and why they occur is provided in WRL TR2023/32 Section 2.5.

Figure 2-3 Locations of reported sewage overflows in Pambula Lake estuary

2.5 Bathymetry

Two existing bathymetry datasets were sourced for this project:

- Coastal marine LiDAR collected by the former NSW Department of Planning, Industry and Environment (now DCCEEW) in 2018. In the Pambula Lake estuary region, this survey covers areas within 1.5 km of the coast and corresponds to the estuary entrance and most of the inlet channel (shown in Figure 2-4) at a resolution of 5 m. This is the most recent and detailed survey and was used as the preferred bathymetry source for all regions of the mesh covered by the survey extent.
- Single beam bathymetry data collected in 2003. This dataset was collated and provided by the NSW Office of Environment and Heritage (OEH, now DCCEEW) and is available on the Australian Ocean Data Network (AODN) portal. This data was collected as a series of transects which cover the estuary with 25 to 50 m spacing (refer to Figure 2-5). This dataset was used in regions not covered by the marine LiDAR.

For areas where the 2003 single beam survey overlapped with the 2018 marine LiDAR extent, the difference in depth was investigated (refer to Figure 2-6). This is a dynamic region between wave driven sediment deposition and tidal current driven channel scour. Between the two surveys, significant changes to entrance bar morphology were observed with a deepening of the primary channel and a corresponding deposition of sediment as sand bars and shoals. Based on aerial imagery, it is apparent that the entrance sand bars and shoals are mobile but appear to be in a state of dynamic equilibrium with no obvious long-term erosive or accretive trends.

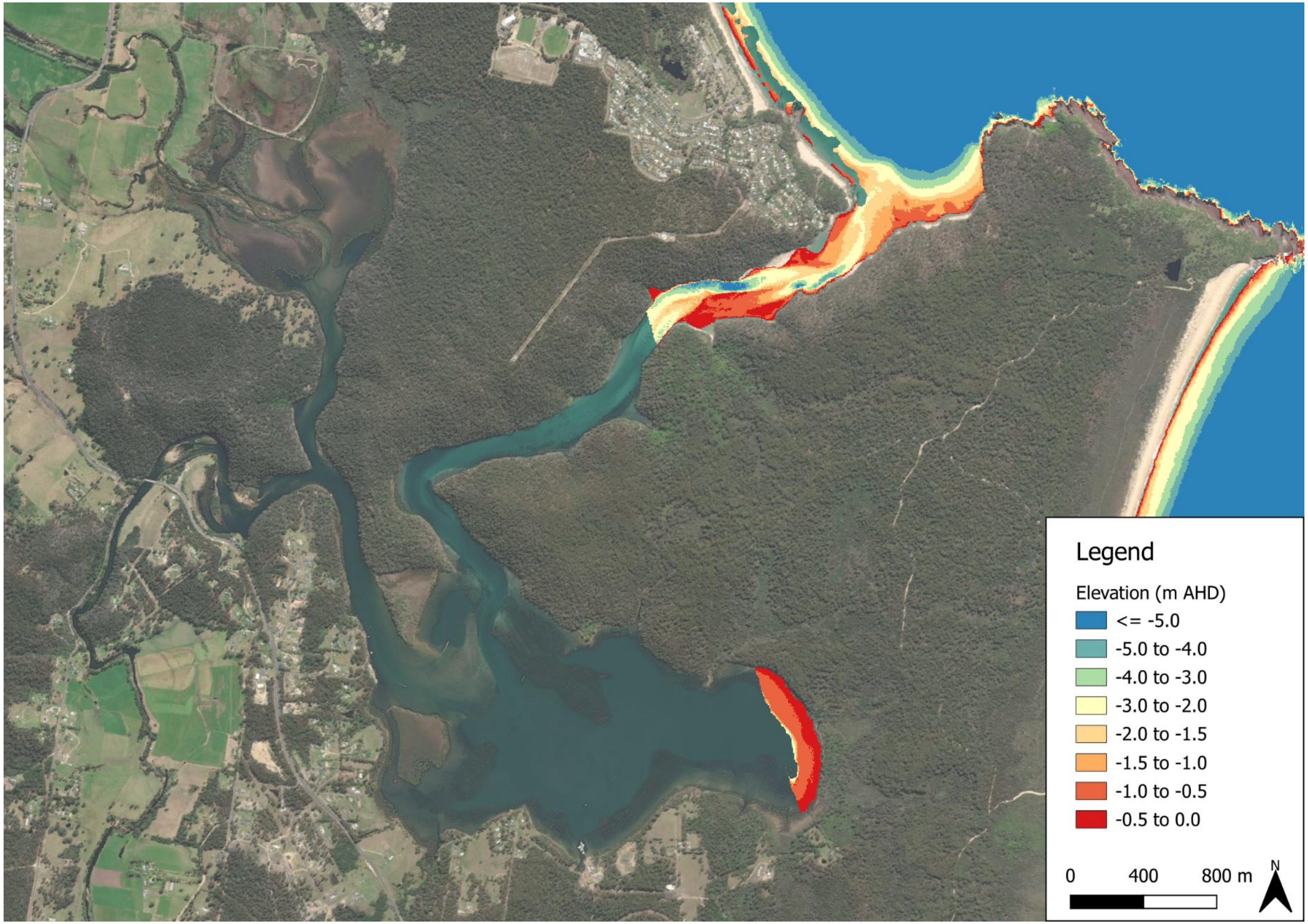

Figure 2-4 Coverage of 2018 LiDAR survey

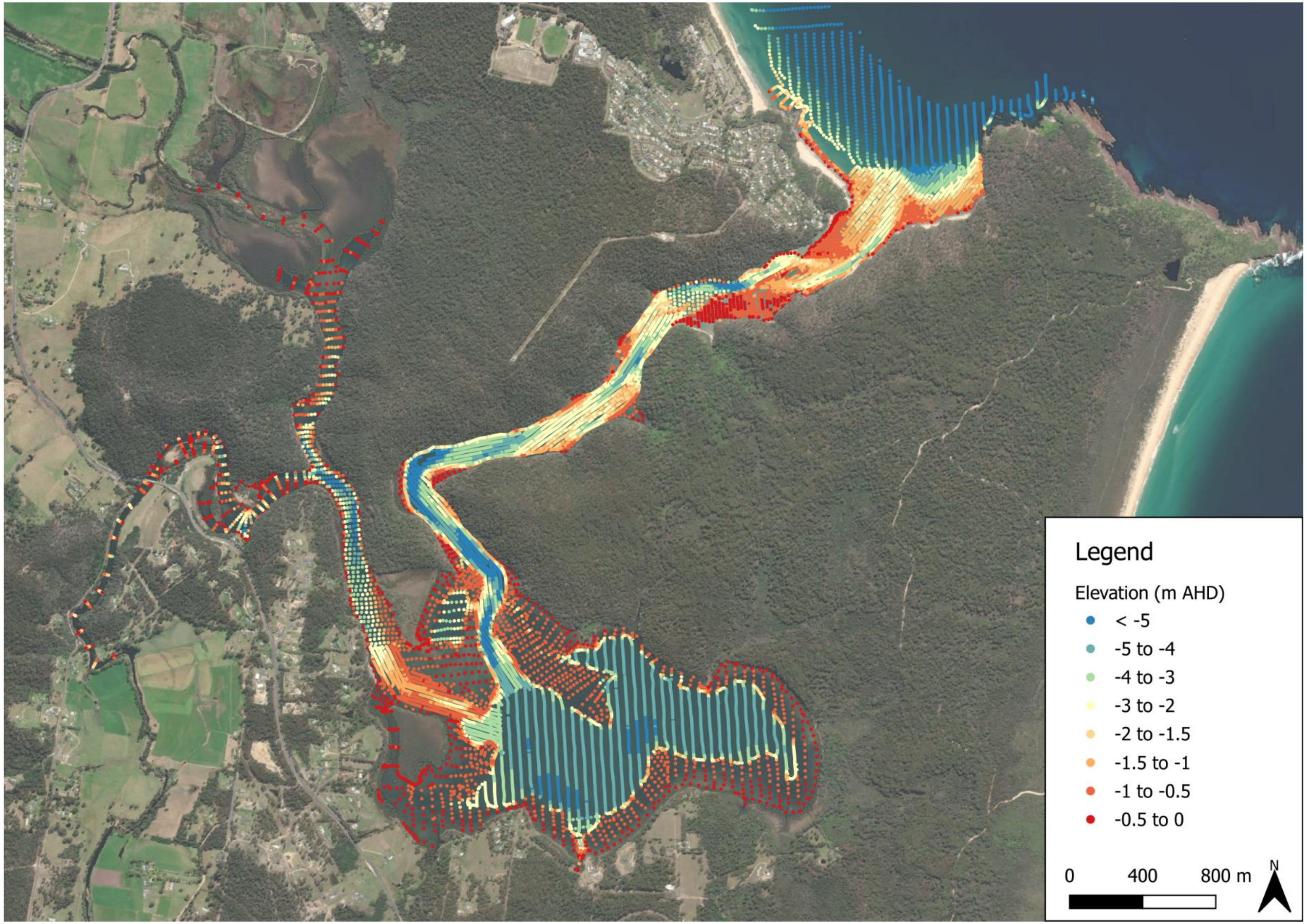

Figure 2-5 Coverage of 2003 single beam survey

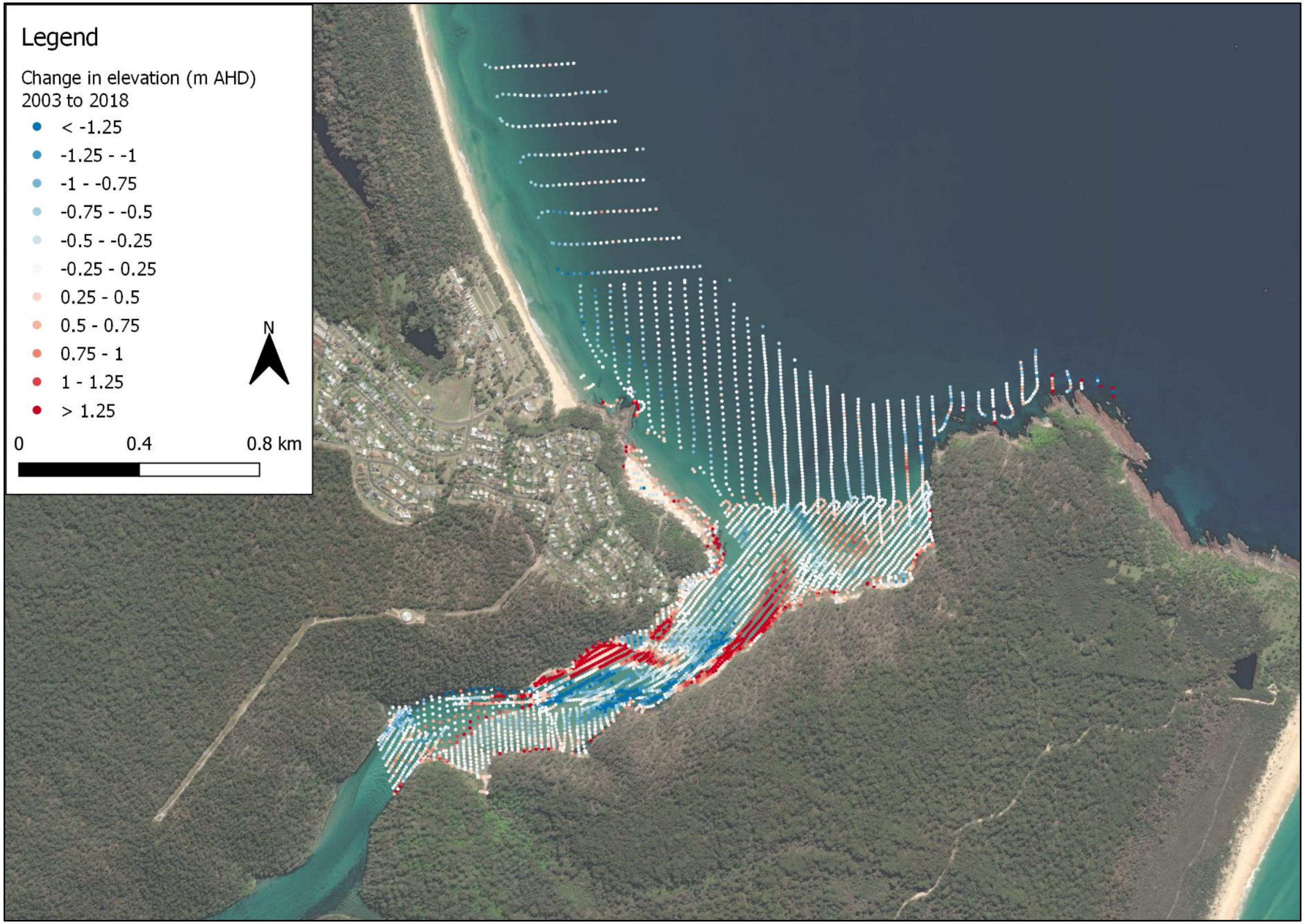

Figure 2-6 Bathymetry change between 2003 survey and 2018 marine LiDAR. Blue represents erosion and red represents accretion

Additional bathymetric, topographic, and aerial data utilised include:

- 1 x 1 m DEM LiDAR data, collected in 2013 and available from NSW Spatial Services, was used for shallow areas inland of the extent of the 2018 LiDAR survey, provided they were above water level during the 2012 survey.
- RTK GPS survey data collected by WRL at Panboola Wetland in 2023, as detailed in Montano et al. (2024) was used for qualitative verification of model bathymetry in the wetland region.
- NAVONICS SonarChart^{TM} was utilised for qualitative verification of model bathymetry. This was primarily used to assess whether model bathymetry was capturing the location and geometry of complex features not fully captured by single depth soundings such as shallow reefs, abrupt drop-offs, and river confluences.
- High resolution NearMap imagery was used to qualitatively provide information on important bathymetric features such as changes to shoal geometry over time.

3 Field data collection

3.1 Preamble

A data collection campaign was completed on 5 July 2023. Field data collection included:

- Monitoring of current velocities and volumetric flow using an ADCP
- Monitoring of dispersion and advection using Rhodamine WT dye
- Monitoring of surface current speed and flow paths using GPS drifter drogues
- Collation of data from MHL water level monitoring sites

3.2 Weather and tides

Data collection on Pambula Lake was undertaken on both ebb and flood tides. Tides during field investigations were relatively small, ranging between approximately -0.44 to 0.18 m AHD recorded at Eden. The observed water levels at Eden, alongside the timing of key fieldwork components is shown in Figure 3-1. Predicted and observed tides at the Eden ocean tide station are shown in Figure 3-2. The residual between observed and predicted tides were near zero for this period.

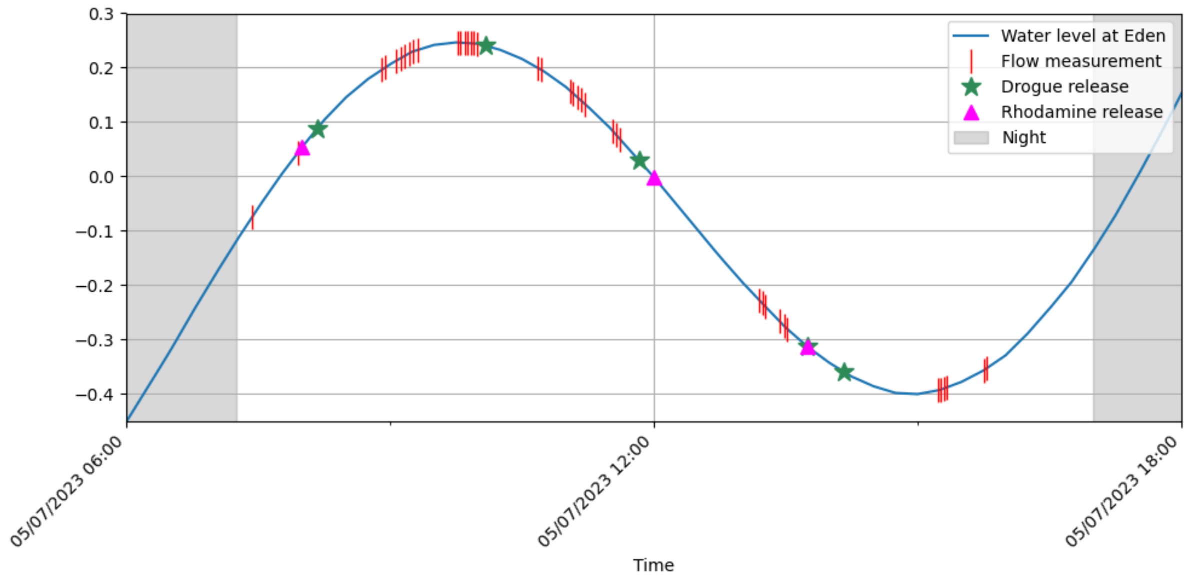

Figure 3-1 Ocean tide at Eden with timing of key data collection events

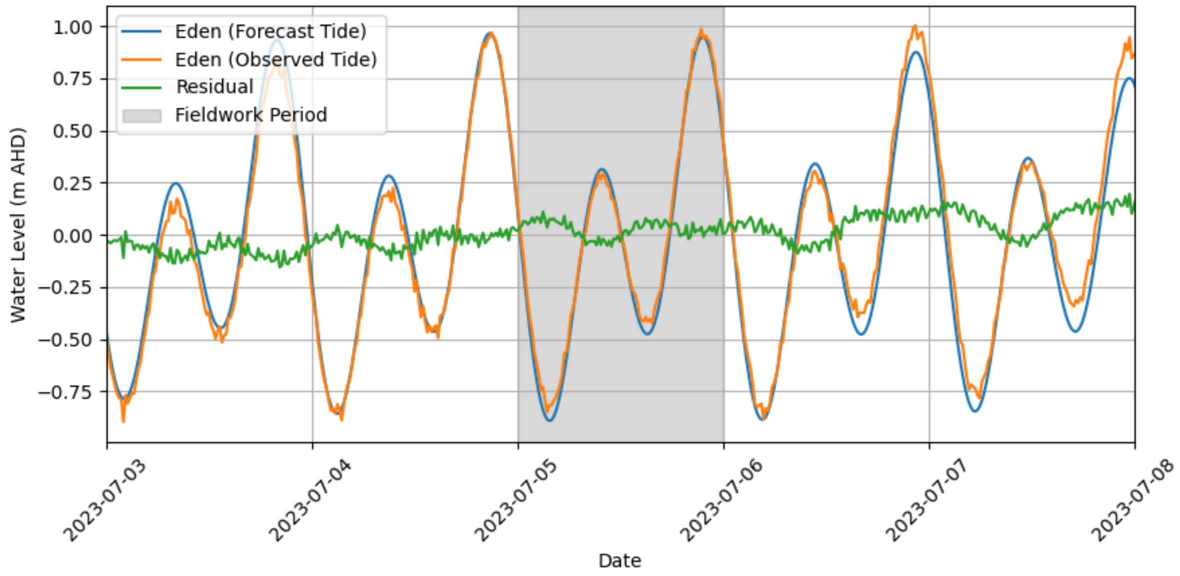

Figure 3-2 Forecasted and observed tides at Eden

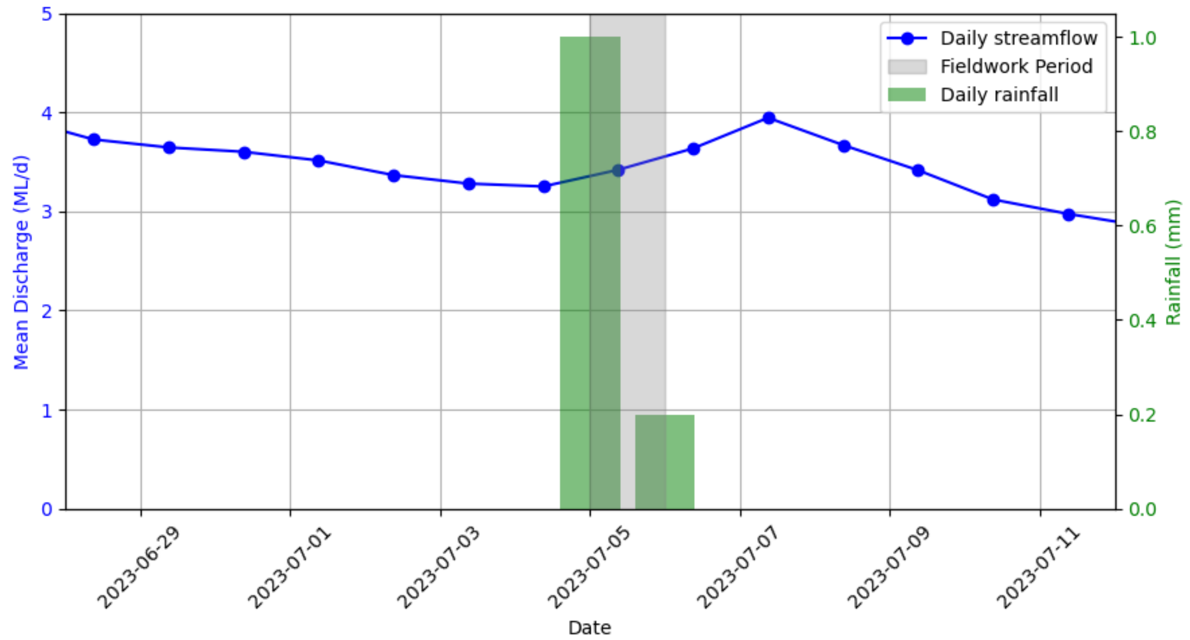

Figure 3-3 Rainfall recorded at Merimbula Airport and streamflow recorded at Pambula River at Lochiel for the period surrounding fieldwork

No rain was observed in the field, although a small amount of rainfall was recorded at Merimbula Airport (BoM station number 069147), as can be seen in Figure 3-3, (BoM, 2023). As can also be seen in Figure 3-3, freshwater inflows from the upstream catchments were low. Flows were below median flows at the nearby WaterNSW gauges on Pambula River, discussed in Section 2.3. Negligible wind was observed at Merimbula Airport.

3.3 Tidal flow gauging

Flow was measured using a boat mounted SonTek RiverSurveyor M9 ADCP at four locations across a range of ebb and flood tidal stages. More information on methods used for tidal gauging can be found in WRL TR2023/32 Section 4.2. Flow measurements in Pambula Lake are summarised in Table 3-1, with locations shown in Figure 3-4. For a table of tidal gauging measurements refer to Appendix A2, and for plots of tidal flows refer to Appendix A3 and A4.

Table 3-1 Summary of 2023 fieldwork tidal flow gauging locations

Location	Location label*	Number of transects
Pambula Entrance	D	1
Pambula Lake Downstream	E	20
Pambula Lake Upstream	F	16
Upper Pambula River	G	2

* Location labels correspond to locations shown in Figure 2-1.

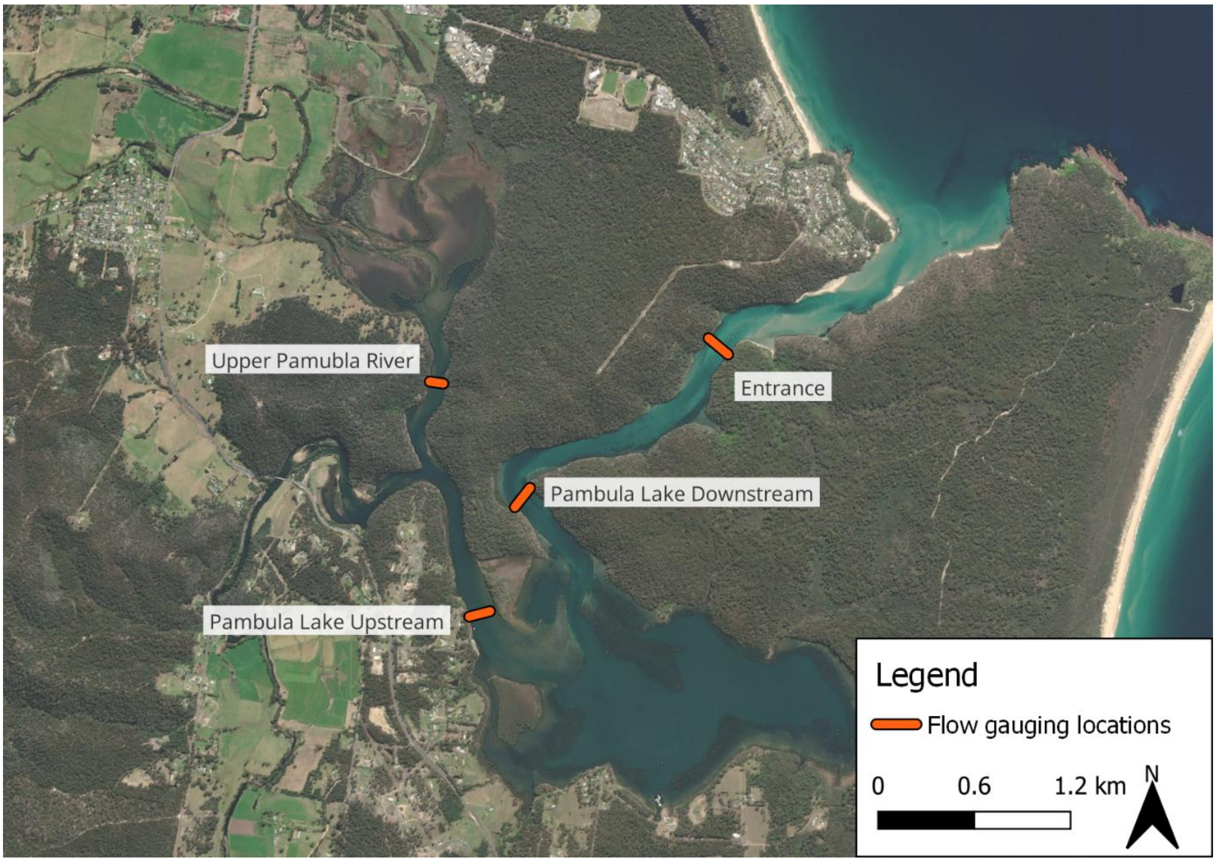

Figure 3-4 Tidal flow gauging locations from 2023 fieldwork

In addition to measuring total flow, ADCP data collected along each transect was used to understand flow and velocity distributions across the channel. Refer to Appendix A3 for figures of ebb and flood channel velocity distribution for all gauging transects.

Vertical velocity distribution for incoming and outgoing flows was also assessed for each gauging transect, which is useful for assessing the validity of assumptions associated with using a two-dimensional depth averaged model. For all locations and transects, observations approximated depth averaged flow. Velocity depth profiles for each gauging location are presented in Appendix A4.

3.4 Bathymetry and elevation surveys

During the ADCP data collection campaign, an RTK-GPS unit collected vertical position data to an accuracy of 10 cm. By pairing depth soundings and elevation data, bathymetry was captured for all flow gauging locations (refer to WRL TR2023/32 Section 4.3 for details on methods used for bathymetric surveys). Additional bathymetry was collected along the main inlet channel from the entrance to Pambula Lake. Bathymetry data for all locations is shown in Figure 3-5, and the change between the 2018 LiDAR data and field captured bathymetry is shown in Figure 3-6. No major changes in bathymetry were observed for the overlapping area between 2018 and 2023.

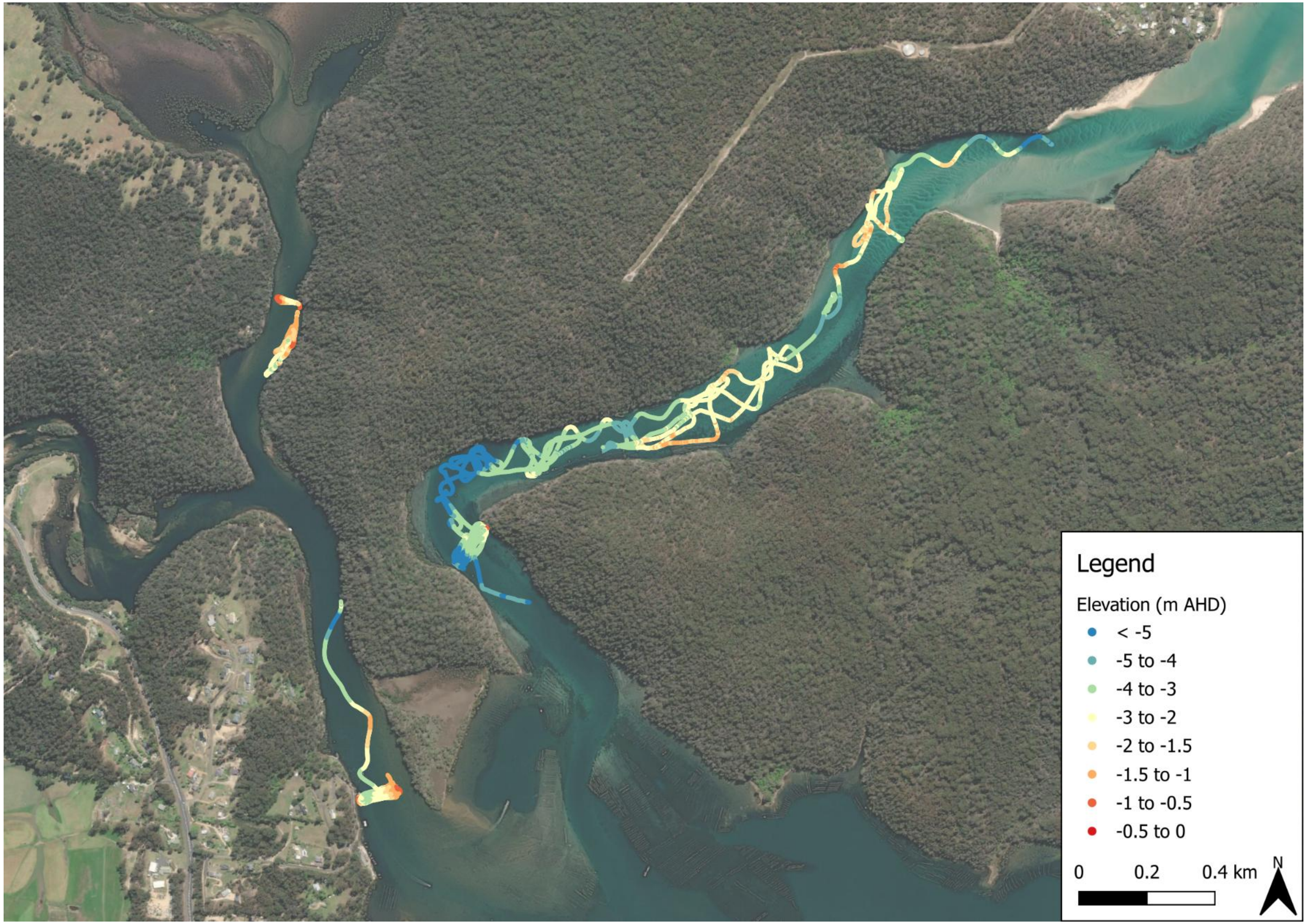

Figure 3-5 Bathymetry collected during 2023 fieldwork

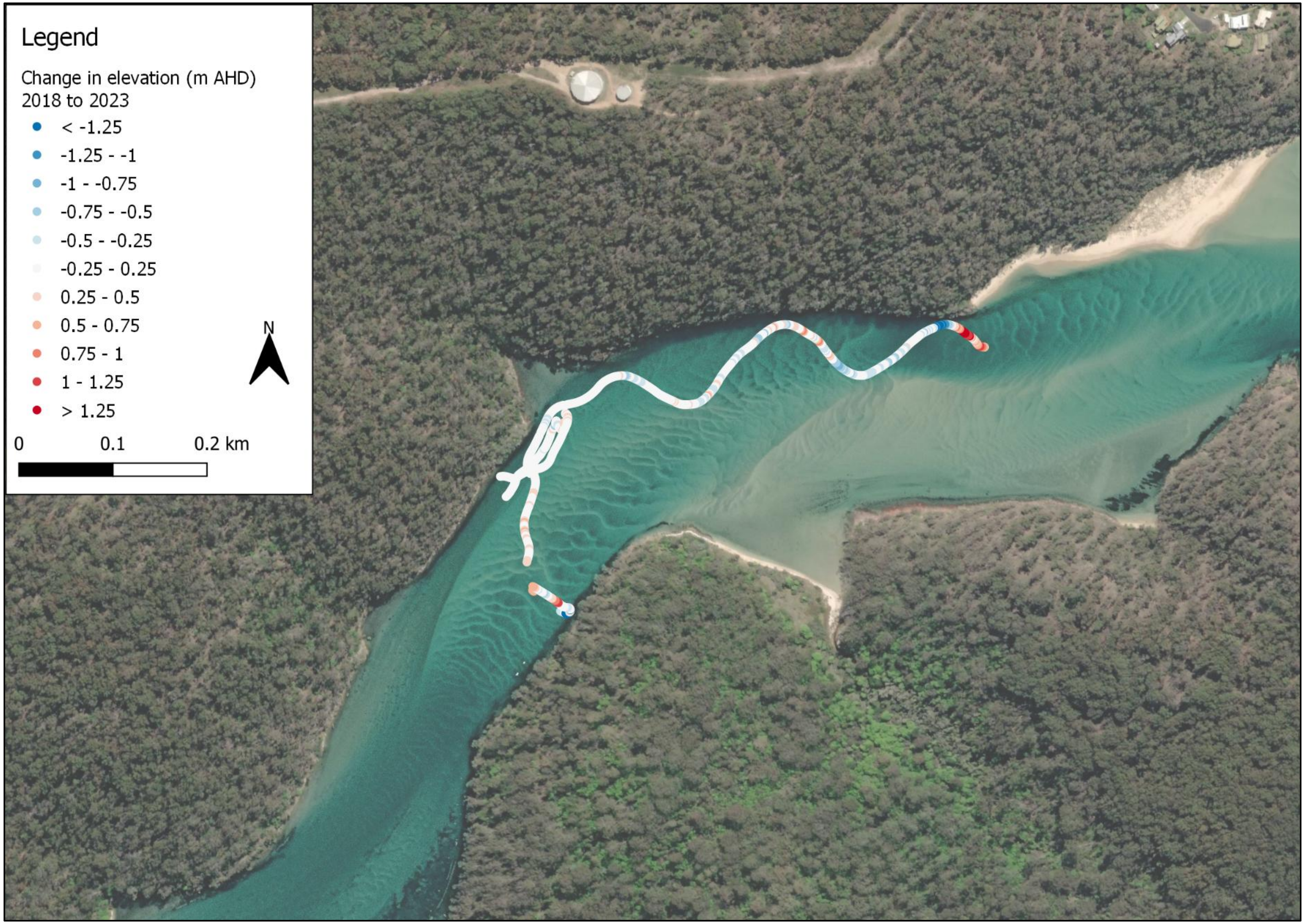

Figure 3-6 Difference between 2018 LiDAR and 2023 fieldwork bathymetry. Red corresponds to accretion and blue to erosion

3.5 Rhodamine WT dye releases

To simulate pollutant advection and dispersion in the Pambula Lake estuary, three Rhodamine WT dye releases were performed on during the field campaign (refer to WRL TR2023/32 Section 4.4 for methods). These are summarised in Table 3-2, with locations shown in Figure 3-7. The initial release concentration was 200,000,000 ppb in all instances.

Table 3-2 Summary of dye releases

No.	Date	Time released	Tracked until	Volume of dye released (mL)	Location	Tide
1	05/07/2023	8.06am	9.28am	500	Pambula Entrance	Flood
2	05/07/2023	11.52am	1.04pm	250	Upper Pambula River	Ebb
3	05/07/2023	1.42pm	2.58pm	500	Downstream of Pambula Lake	Ebb

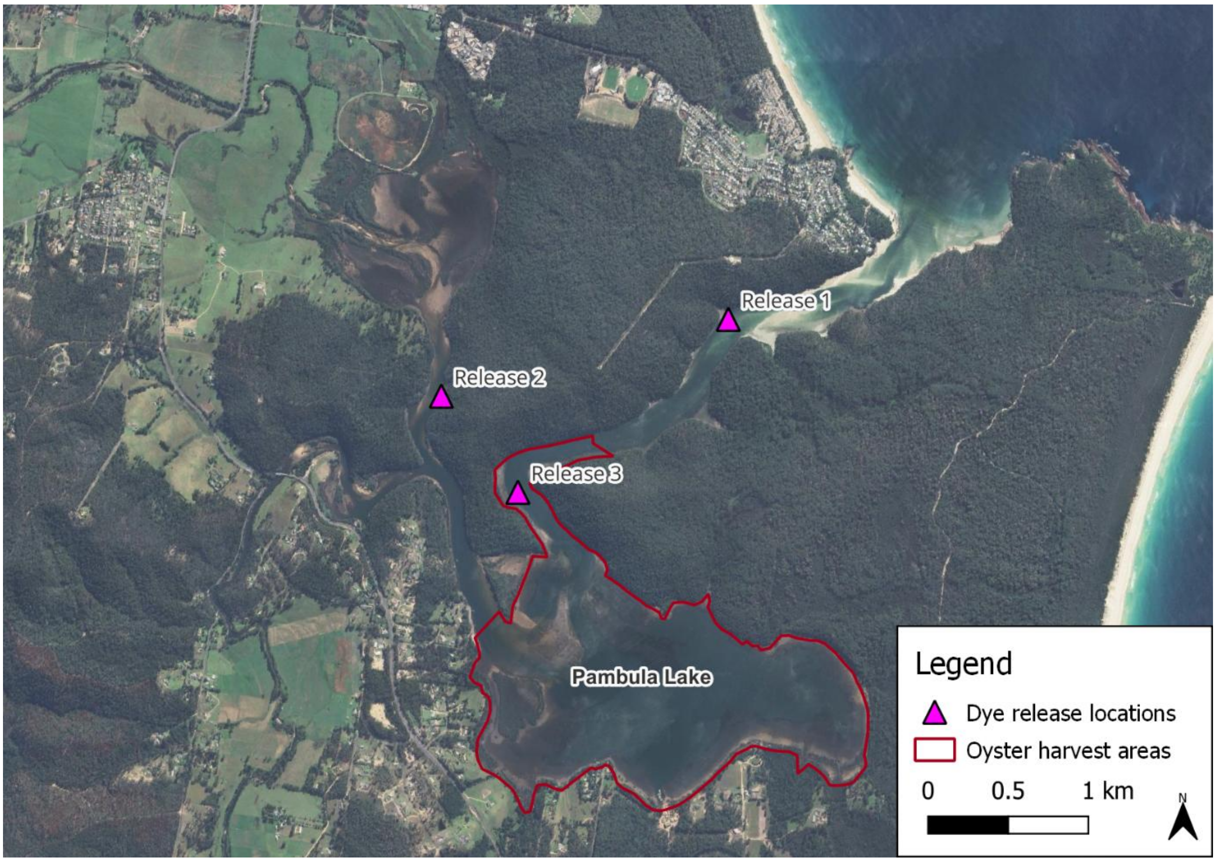

Figure 3-7 Rhodamine WT dye release locations

3.5.1 Release 1 – Pambula Entrance

Dye release 1 was released on the northern bank of the main channel 1.5 km upstream of the estuary entrance (see Figure 3-7 and Figure 3-10). This release was completed to understand transport rates in the entrance channel and to determine pollutant dispersion rates. The release occurred on an incoming tide, approximately 1 hour before peak inflow at the Pambula Lake Downstream transect. Dye was released around 8.00am and tracked for 1 hour 20 minutes. Figure 3-9 shows the observed dye concentrations over the period of monitoring, with the maximum plume concentration along select transects highlighted.

Figure 3-8 Dye release 1 after 5 minutes

Steady mixing and dispersion were observed immediately after the dye release due to the high current velocities. Significant longitudinal spreading was observed, and after 20 minutes the plume measured 40 x 150 m. The plume stayed in the deepest part of the channel and generally hugged the northern bank. As the plume rounded the bend at Tea Tree Point, significant dilution was observed as the channel depth increased from 4 m to greater than 10 m. The plume was difficult to visually distinguish, so consecutive transects were made further upstream across the width of the channel to capture the plume width and peak as it flowed past.

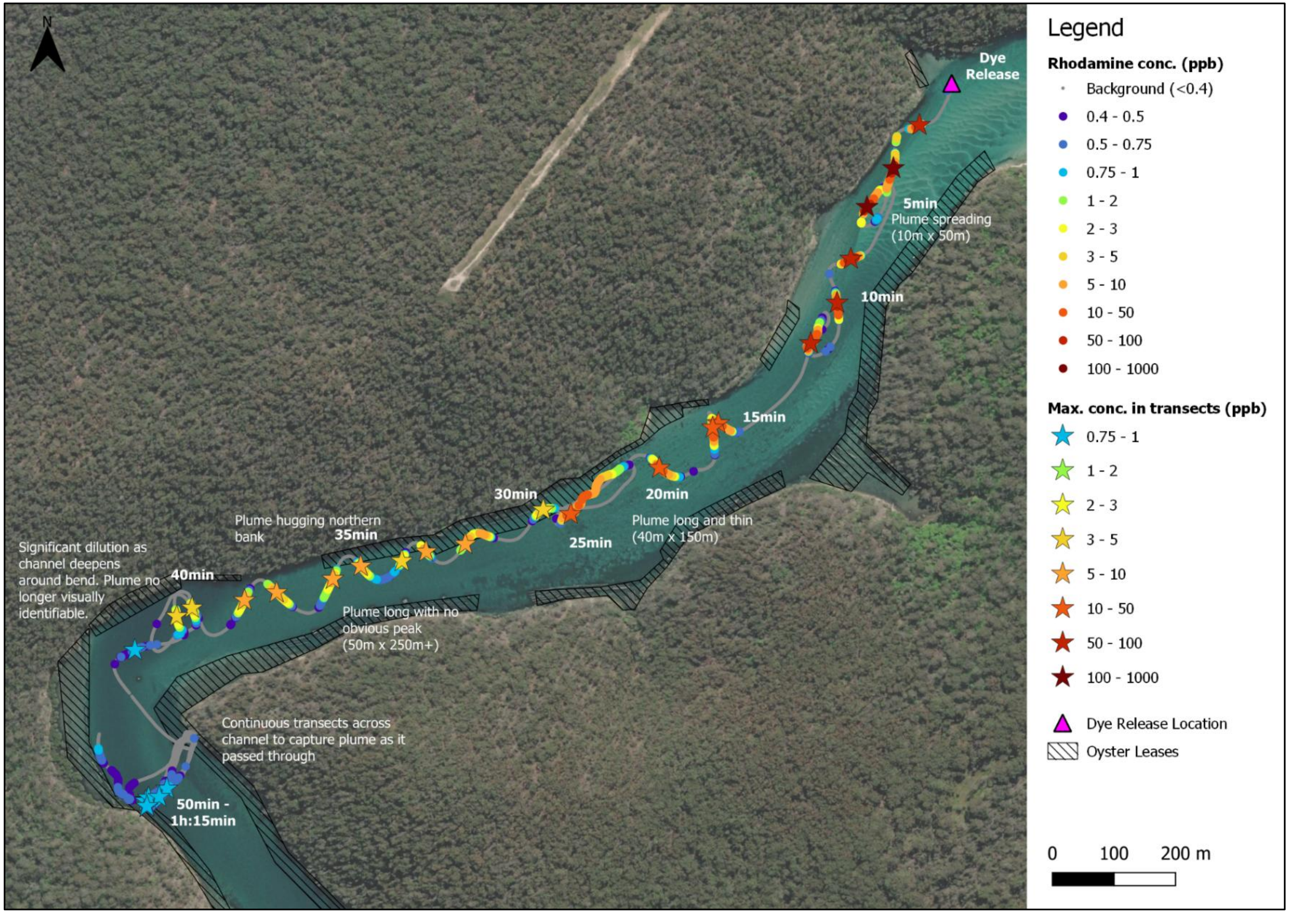

Figure 3-9 Dye release 1 at Pambula Entrance. All observed concentrations (circles) and maximum concentration observed in select transects (stars)

3.5.2 Release 2 – Upper Pambula River

Dye release 2 was conducted in the deepest part of the channel in Upper Pambula River, approximately 500 m upstream of the confluence with Yowaka River (see Figure 3-7 and Figure 3-10). The aim of this release was to observe plume velocity and dispersion in the slow moving Upper Pambula River. For this release, 250 mL of dye was released instead of the usual 500 mL due to low anticipated dispersion and advection. The release was timed to coincide with the anticipated peak outflow at the location and was tracked for 1 hour 5 minutes from 11.50am. Figure 3-11 shows the observed dye concentrations over the period of monitoring, with the maximum plume concentration along select transects highlighted.

Figure 3-10 Dye release 2 after 10 minutes

Immediately after release, very little plume movement was observed. After 5 minutes, the plume visually covered the depth of the water column but was still within a 5 m radius of the release location. After 20 minutes, the leading edge of the plume had travelled 40 m and was hugging the eastern bank, however, the tail of the plume appeared to remain on the bed at the release location. Depth profiles confirmed that dye was present over the entire water column, however, visual observations showed the depth of maximum concentration varied along the length of the plume and was not at the surface. To better capture the maximum plume concentration, the C3 fluorometer was taken out of its fixed depth housing for the rest of the dye tracking. This allowed for manual adjustments to the sensor depth to measure concentration at the visual peak plume depth. After 45 minutes, the leading edge of the plume reached a bend in the river and dispersion increased as it entered deeper water in the centre of the channel. The plume was tracked for another 20 minutes. Dye was still measurable close to the release location when tracking was stopped.

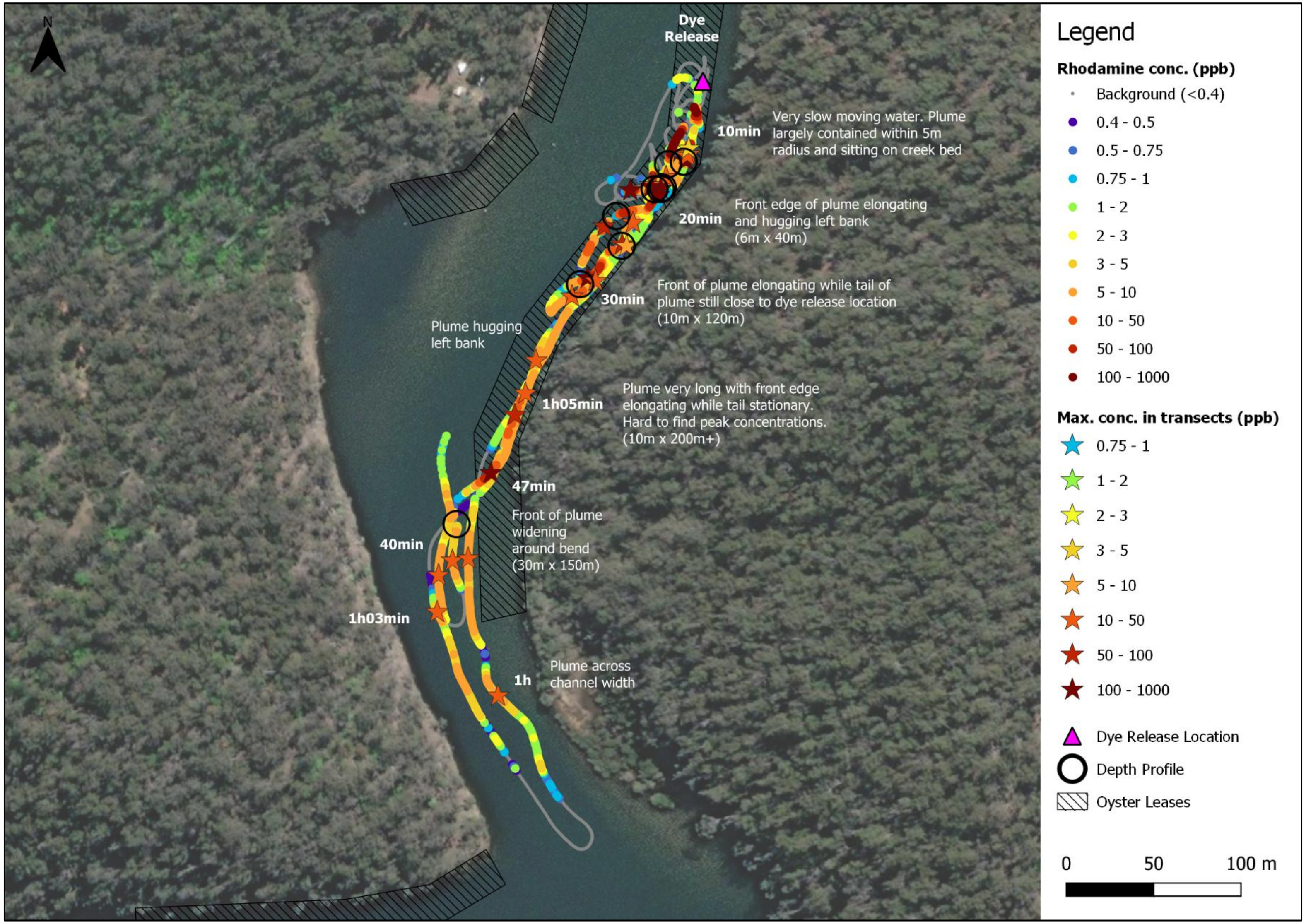

Figure 3-11 Dye release 2 at Upper Pambula River. All observed concentrations (circles) and maximum concentration observed in select transects (stars)

3.5.3 Release 3 – Downstream of Pambula Lake

Dye release 3 was completed mid-channel at Tea Tree Point approximately 1 km downstream of Pambula Lake (see Figure 3-7 and Figure 3-12). This release was completed to understand transport rates in the entrance channel and to determine pollutant dispersion rates. The release occurred on an outgoing tide, approximately 30 minutes after estimated peak outflow at the release location. Dye was released around 1.45pm and was tracked for 1 hour 15 minutes. Figure 3-13 shows the observed dye concentrations over the period of monitoring, with the maximum plume concentration along select transects highlighted.

Figure 3-12 Dye release 3 after 10 minutes

Dye was released in the deep scour region adjacent to Tea Tree Point. Due to low current velocities, slow three-dimensional dispersion was visually evident. Depth profiles after 10 minutes indicated the plume was reasonably well mixed to a depth of 7 m (in water depth of 10 to 12 m). The plume at this time had a small footprint of approximately 20 x 20 m. As the plume rounded the bend after 20 minutes, rapid mixing and dilution were observed as the channel shallowed and velocity increased. Transects at 30 minutes indicated the plume covered the channel width. After 45 minutes, the plume was visually diluted and hard to visually distinguish. Plume tracking was continued for another 30 minutes.

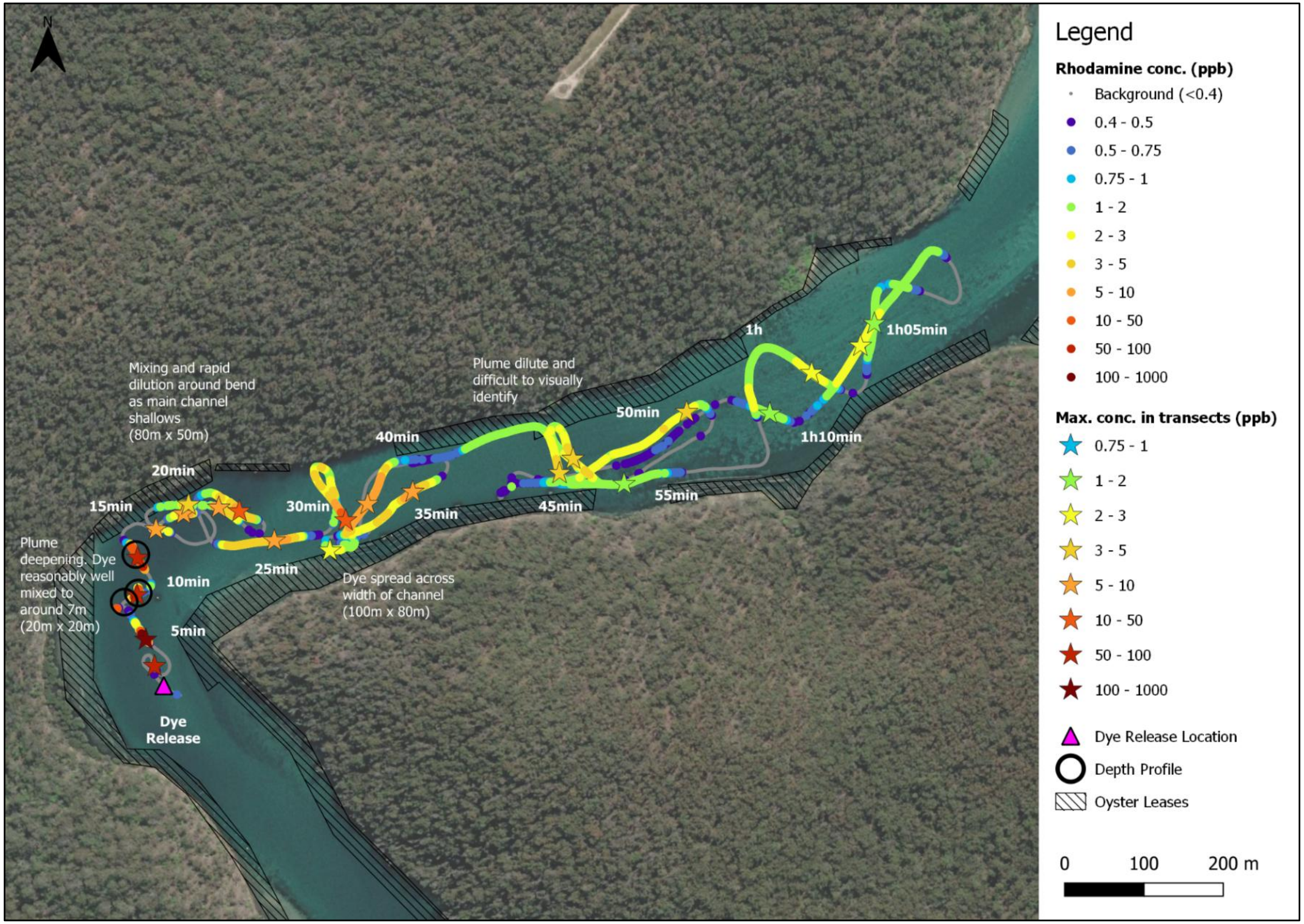

Figure 3-13 Dye release 3 downstream of Pambula Lake. All observed concentrations (circles) and maximum concentration observed in select transects (stars)

3.5.4 Field derived dispersion values

Field dye experiments were used to obtain estimates of plume spreading dispersion rates in the Pambula Lake estuary, using the methods described in WRL TR2023/32 Section 7.3. During each dye release, transects were taken across the plume to capture the plume width and peak concentration at a point in time. From the set of all transects, a subset of representative peak concentrations was compared to theoretical estimates of maximum plume concentrations over time. This is shown in Figure 3-14. To allow easy comparison, concentrations for all dye releases were scaled to match an initial release volume of 500 mL before plotting.

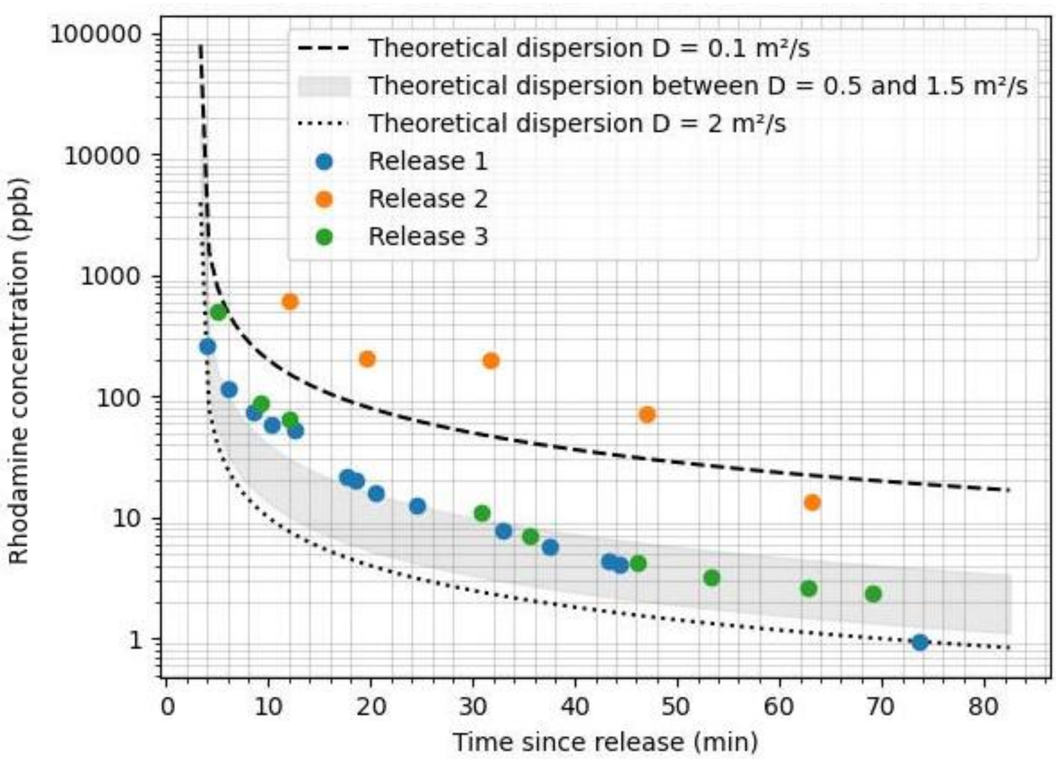

Figure 3-14 Peak concentration of transects plotted against theoretical dispersion

Measurements of field dispersion across the state for this project showed dispersion was spatially and temporally variable, typically between D = 0.1 and 2 m^2/s, with the most common range being 0.5 to 1.5 m^2/s. When comparing the observed peak observations to theoretical dispersion in Pambula, release 1 and 3 fall within D = 0.5 to 1.5 m^2/s. The dispersion rates for release 2 were much lower, as this release occurred near slack tide in the slow moving Pambula River, upstream of the lake.

3.6 GPS drifter drogue releases

To monitor surface current speeds and flow paths in the Pambula estuary, GPS drifter drogues were deployed at strategic locations throughout the field campaign (refer to WRL TR2023/32 Section 4.5 for further information on drifter drogues). Drogues were released during all dye releases to aid plume tracking, with two additional drogue releases completed at various stages of the tide cycle (refer to Table 3-3). The GPS tracks for the drogue releases are shown in Appendix A1. A brief discussion of the observations is provided in this section.

Table 3-3 Summary of drogue releases

No.	Date	Time	Tide	Duration (h)	Location	Comments
1	05/07/2023	8.09am	Flood	1:22	Pambula Entrance	Released with dye drop 1
2	05/07/2023	10.05am	Slack	1:36	Pambula Lake Upstream	
3	05/07/2023	11.52am	Ebb	1:14	Upper Pambula River	Released with dye drop 2
4	05/07/2023	1.45pm	Ebb	1:35	Downstream of Pambula Lake	Released with dye drop 3

Drogue releases 1, 3 and 4 coincided with dye experiments outlined in Section 3.5. During the releases it was noted that the drogues were a reasonable proxy for the advection and longitudinal dispersion of dye in the river. Where drogues were released as a group, the drogues spread longitudinally along the river with the distance between the leading and trailing drogue a similar distance to the length of the dye plume at the corresponding location. Drogue release 2 was completed around slack tide in the slow moving Pambula River and little to no drogue movement was observed.

4 Model development

4.1 Preamble

The model used for this project consists of both a hydrodynamic and a water quality model. Initially, a hydrodynamic pilot model was developed which identified data gaps to be targeted during field data collection. After incorporating new data from the field, the hydrodynamic model was iteratively refined through calibration based on the MHL data collection campaign in 2003 and field data collected for this project in 2023. The hydrodynamic model was then used as an input for the water quality model. This model was informed by dye release experiments and was then used to run sewage overflow scenarios. A schematic of this process can be seen in Figure 4-1. For a detailed overview of the model development used for the broader project, refer to WRL TR2023/32 Sections 6 and 7.

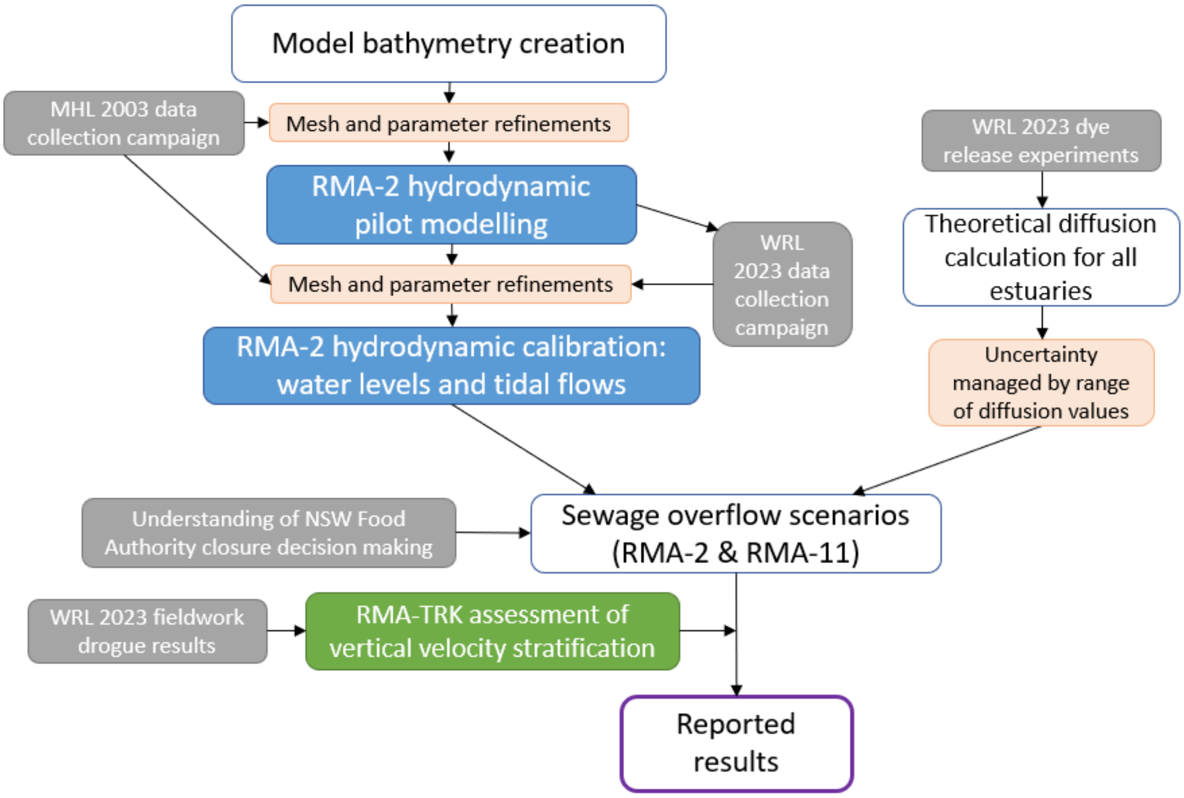

Figure 4-1 Overview of modelling approach

4.2 Model mesh development

The model domain extends from approximately 750 m offshore of the ocean entrance of Pambula Lake estuary, to the tidal limits of the estuary and its major tributaries (refer to Figure 4-2). The model mesh consists of over 11,100 nodes and 4,500 two dimensional elements varying in size from 120 m^2 to over 9,500 m^2. Mesh resolution is highest in sharp channel bends, with lower resolution along straight channels. A two-dimensional, depth averaged model mesh was chosen for Pambula, where advective transport in the areas of interest (the channels) is largely driven by tidal and riverine flow, and near-depth averaged vertical velocity profiles were observed. Wind would contribute to transport in the lake itself, which has been accounted for with an increased diffusion coefficient (see Section 4.7.1). A discussion on the impact of model dimensionality is provided in WRL TR2023/32 Section 6.2.2.

Mesh resolution is highest in the main entrance channel, around the bridge and around overflows, with lower resolution in the lake system. Refer to WRL TR2023/32 Section 6.2.3 for a discussion of model resolution.

4.3 Model bathymetry

Model bathymetry was based on the sources discussed in Section 2.5 and primarily utilised the 2018 DPIE (now DCCEEW) coastal marine LiDAR topo-bathy survey for the lower estuary. For regions outside of the LiDAR extent, the OEH 2003 single beam survey was used. NAVONICS (2023) SonarChart™ and NearMap imagery were used to inform sand bar bathymetry and channel edge locations in areas where no additional data was available. The NSW Spatial Services 1 m resolution DEM (2012) was used for shallow intertidal regions. The scour region at Peach Tree Point reaches depths greater than -10 m AHD, however the majority of estuary channels are around -4 to -2 m AHD, with the lake around -5 m AHD. The model bathymetry and nodal bed elevations are shown in Figure 4-3.

Estuaries are dynamic systems and bathymetric changes through time will alter water levels, velocities, and tidal flows for the same set of boundary conditions. The Pambula estuary has a dynamic and untrained river entrance, although with no history of closure. While change to bathymetry at the entrance in the river downstream of the lake (e.g. movement of sand shoals, or deepening of the channel) is evident, a single bathymetry was developed for this model and used for all model runs. This was shown to result in reasonable model calibration for water levels and flow in multiple periods, discussed further in Section 4.6.

4.4 Model boundaries

The model includes two upstream catchment flow boundaries, shown in Figure 4-2 and discussed in Section 2.3. A tidal elevation boundary was included in the model offshore of the Pambula River entrance (refer to Figure 4-2). This modelled water level boundary was based on observed tidal elevation data collected by MHL at Eden (station number 220470). This data was then smoothed to remove signal noise to increase model stability. For modelling water quality scenarios, all boundaries (upstream and ocean) were set to a constant constituent concentration of zero (e.g. no pollutant inflows from these boundaries).

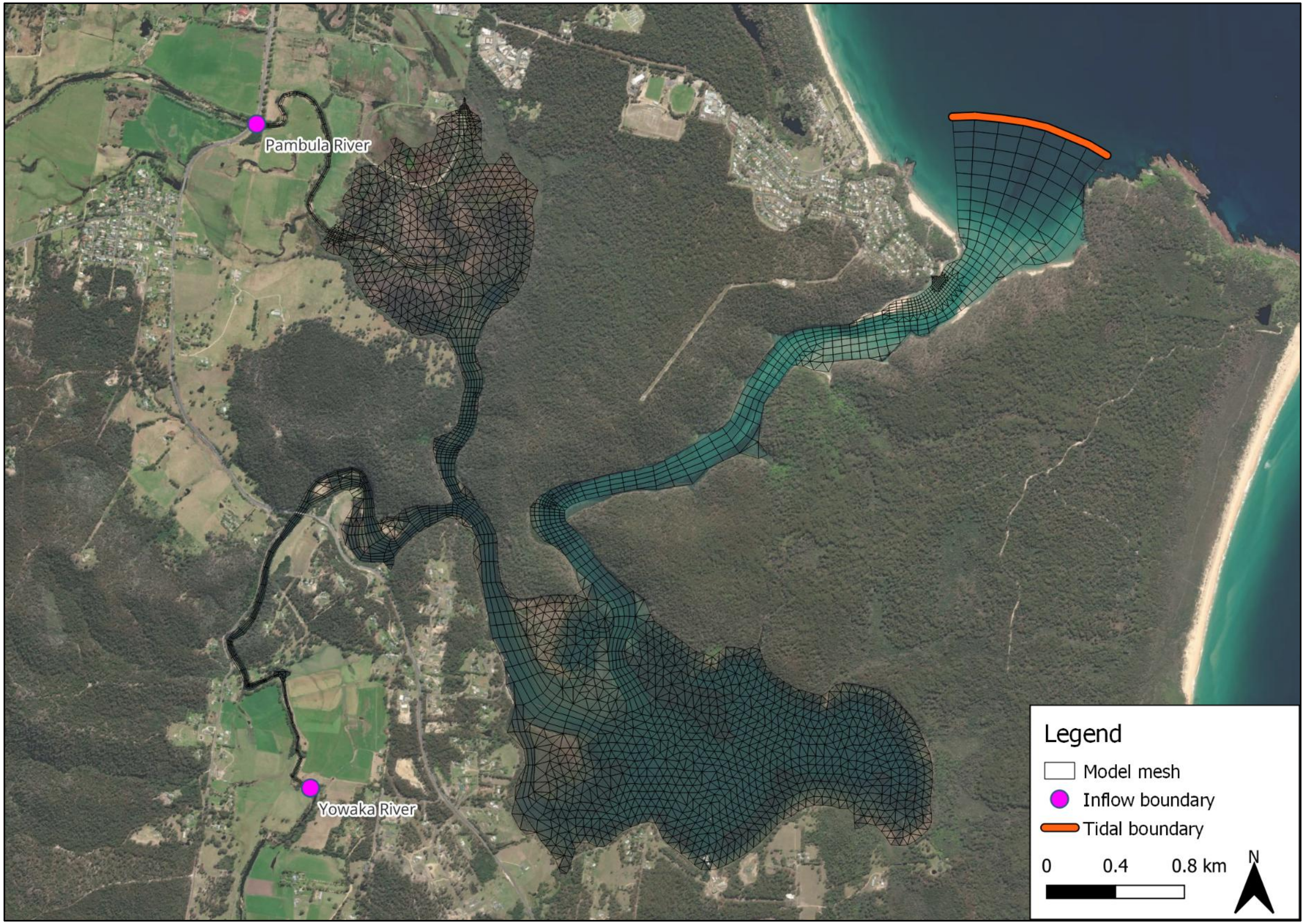

Figure 4-2 RMA model mesh showing boundary condition locations

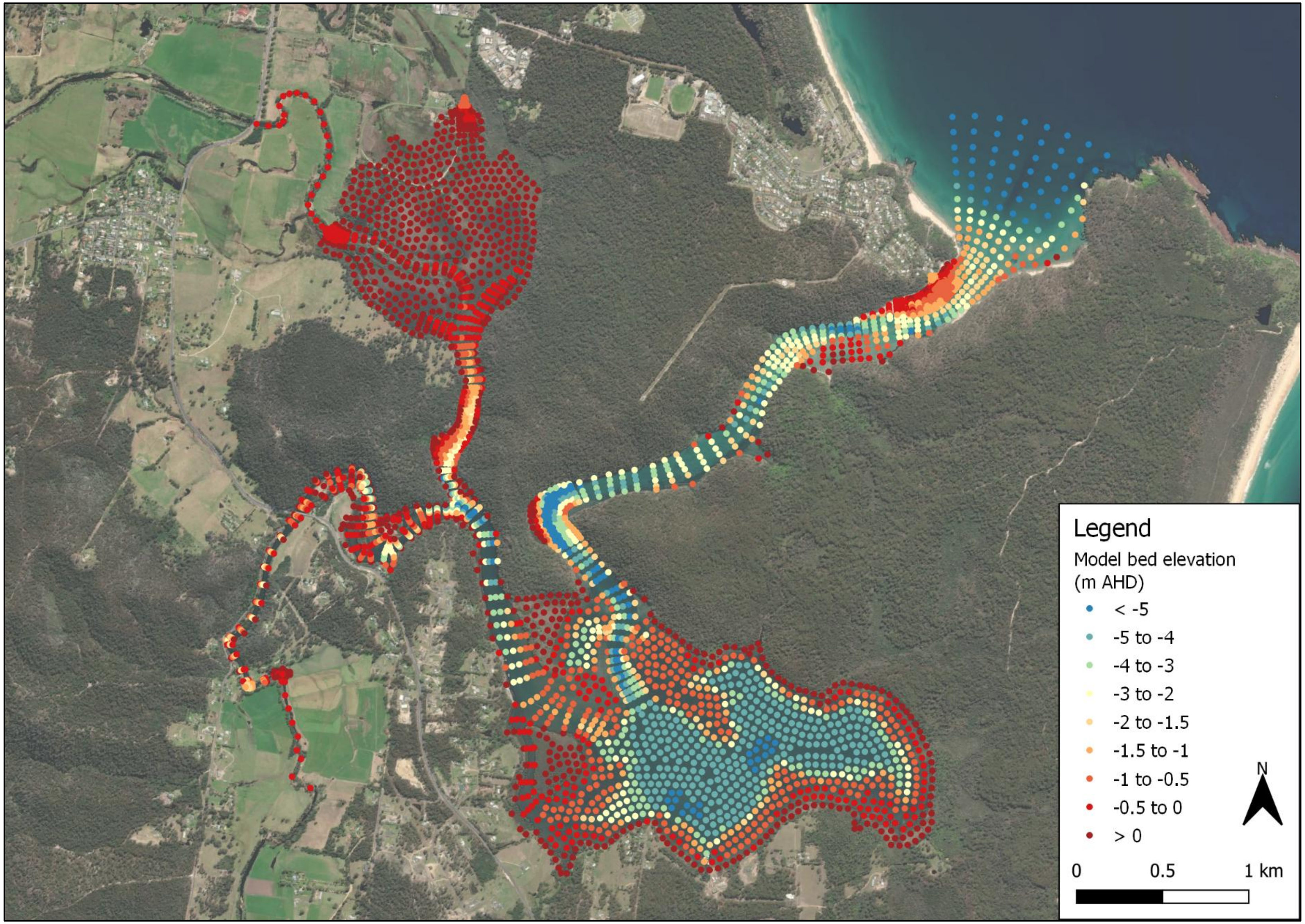

Figure 4-3 RMA model bathymetry

4.5 Pilot model

Initially, a hydrodynamic pilot model was developed using the existing data described in Section 2. For more details on pilot modelling and its purpose refer to WRL TR2023/32 Section 3. This initial modelling was used to identify data gaps to be targeted during fieldwork. The primary gaps identified were modern flow data and channel bathymetry data.

4.6 Hydrodynamic calibration

It is important for a hydrodynamic model to be able to replicate water levels, velocities, and flow throughout the model domain. One appropriate preexisting set of hydrodynamic data was available, collected by MHL in 2003 and described in Section 2.2. This was supplemented by data from the 2023 fieldwork period, which targeted key stages of the tide but was not a full tidal flow gauging (refer to Section 3). Additional water level data was available from a long-term water level gauge managed by MHL, and a recently installed water level logger managed by NSW Food Authority (see Section 2.2). For each period, a minimum 3 day model warmup period was run.

4.6.1 September 2003 calibration period

During the 2003 MHL data collection campaign in Pambula Lake estuary, tidal flow data was collected at three transects and water level data at five locations (refer to Section 2.2). The pilot model was calibrated to flow and water level for this period. Measured tide levels were applied at the ocean boundary and scaled catchment inflows were applied at the two upstream model inflow boundaries. Plots of all observed water level and flow compared with model results are shown in Appendix B1.1 and B1.2, while select results are shown below.

A good model match was achieved for water levels downstream of Pambula boat ramp, although the measured water levels at Pambula Lake South East stop falling at -0.4 m AHD, likely indicating that the water level logger has gone dry (see Figure 4-4) rather than being representative of the true water level conditions. However, peaks are captured well. There is a small offset in water levels between measured and modelled results on 19, 20 and 21 October. This offset is likely due to a local low pressure system which affected the Pambula area, but not Eden (where the driving tides are sourced), as the model represents water levels of other periods with mixed semi-diurnal tides well.

A reasonable model flow and flow curve shape was achieved for model tidal flows into the system near the entrance (Figure 4-5). Peak outflow and slack timing were matched well, although the peak magnitude of incoming flows were underestimated by the model. A good match was achieved for Yowaka River flows (Figure 4-6), however, flows in Pambula River Upstream were significantly underestimated (Figure 4-7). Flows past this location are small compared to flow into the entrance, nevertheless, may affect transport from the two upstream sewage overflow locations. However, model performance in the Upper Pambula River simulating the 2023 field campaign was improved.

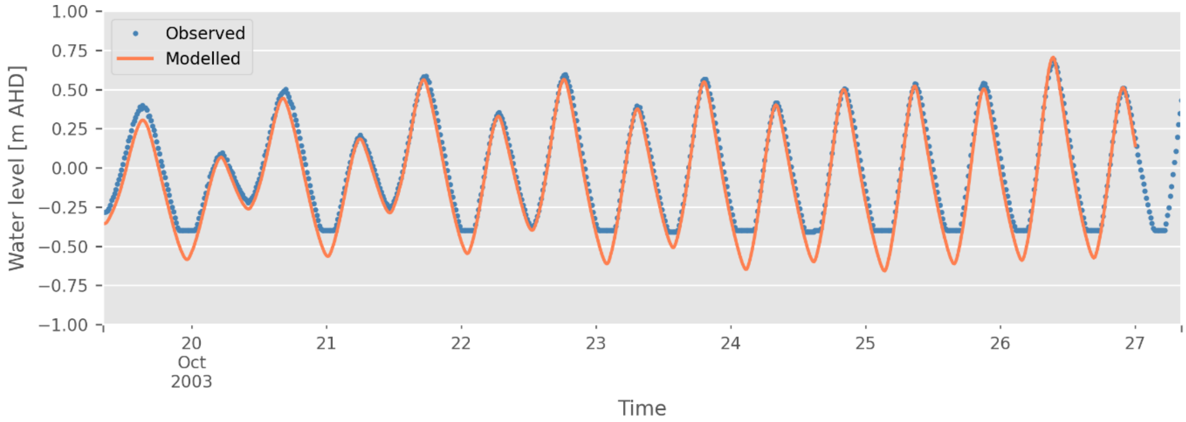

Figure 4-4 2003 water level calibration – Location 2 – Pambula Lake South-East

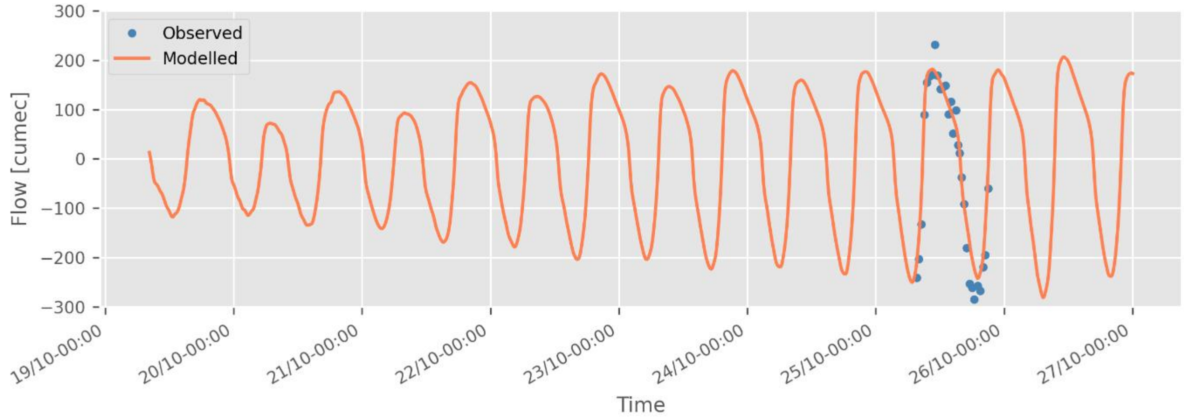

Figure 4-5 2003 tidal flow calibration – Location A – Pambula River Downstream

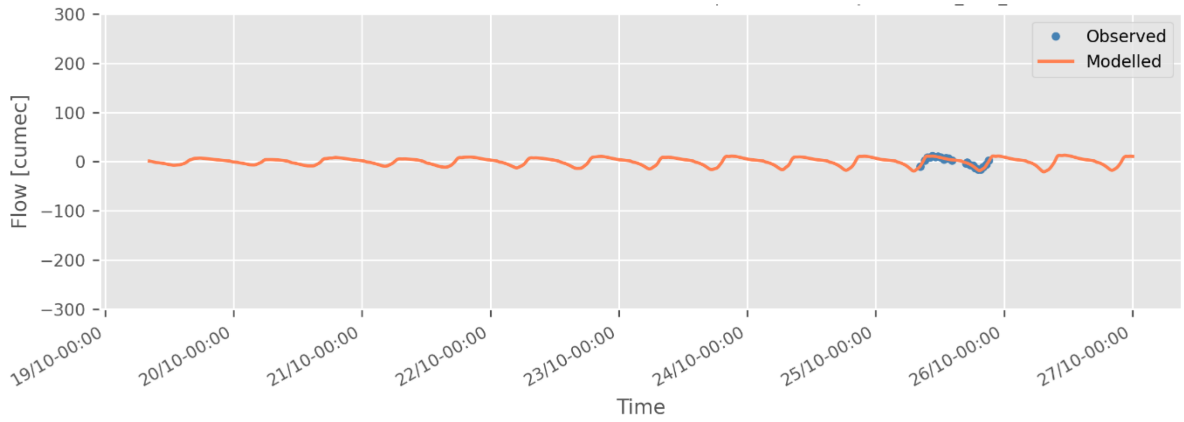

Figure 4-6 2003 tidal flow calibration – Location C – Yowaka River

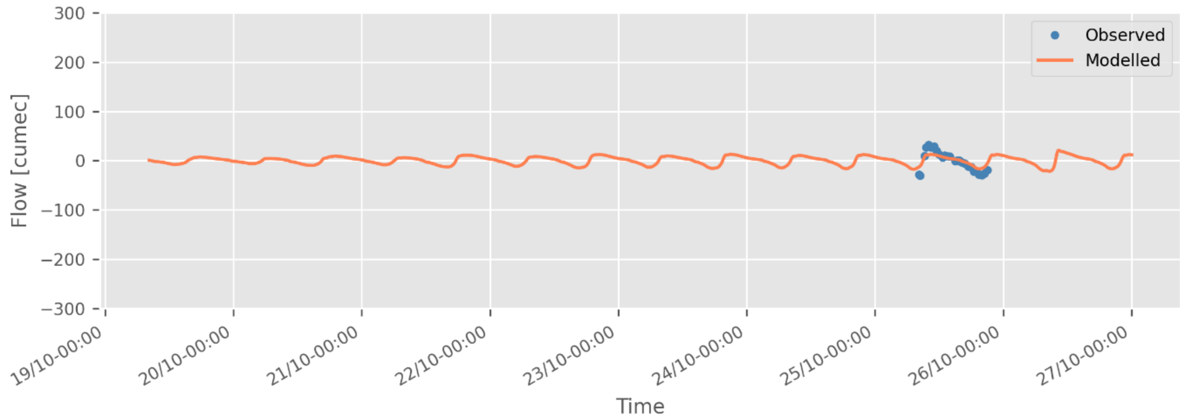

Figure 4-7 2003 tidal flow calibration – Location B – Pambula River Upstream

4.6.2 July 2023 field data calibration period

The 2023 field campaign involved the collection of tidal flow data at four transects, and water level data at two locations (refer to Section 3). Measured tide levels were applied at the ocean boundary and scaled measured catchment inflows were applied at the two upstream model inflow boundaries. Model results were then compared with the observed data, using the same model parameters used for the 2003 model run. Plots of all observed water level and flow compared with model results are shown in Appendix B1.3 and B1.4, while select results are shown below.

Water level and flow results from the 2023 calibration show improved fit compared to the results from the 2003 calibration periods for all locations (see Figure 4-8 for an example). Modelled flow in the Upper Pambula River shows an improved match compared to the 2003 calibration period (Figure 4-9 and Figure 4-10), although the incoming flow is still slightly underestimated, and gauging occurred on a tide with a small tidal range, meaning the models capacity to simulate larger tides is uncertain. Water levels at the Pambula Lake ICT water level logger are simulated well by the model on 6 July, however underestimated at other times (see Figure 4-11). However, the data appears noisy and these offsets may be errors in the measured data. Given the appropriate fit to flows and water level data (including the MHL water level logger in the lake in 2023) during the two calibration periods, the model was considered fit for purpose.

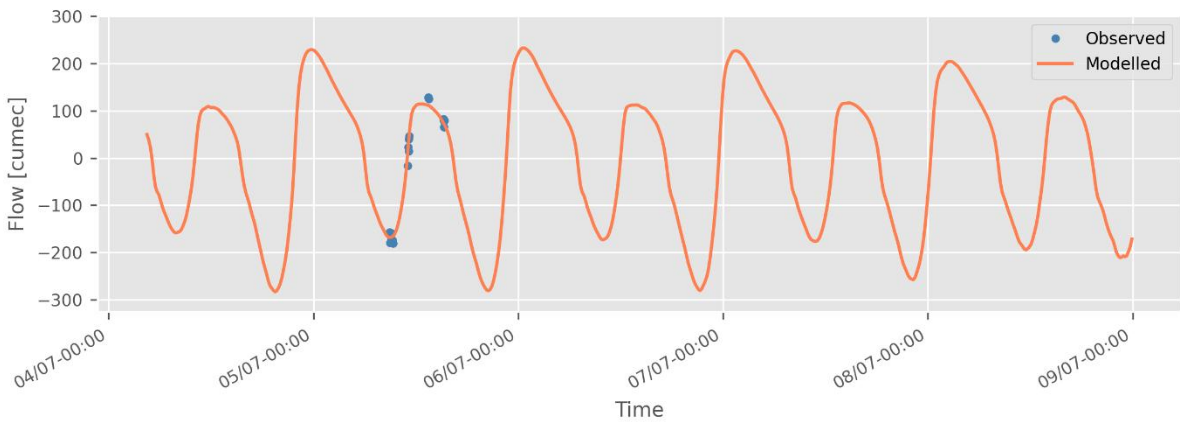

Figure 4-8 2003 tidal flow calibration – Location E – Pambula Lake Downstream

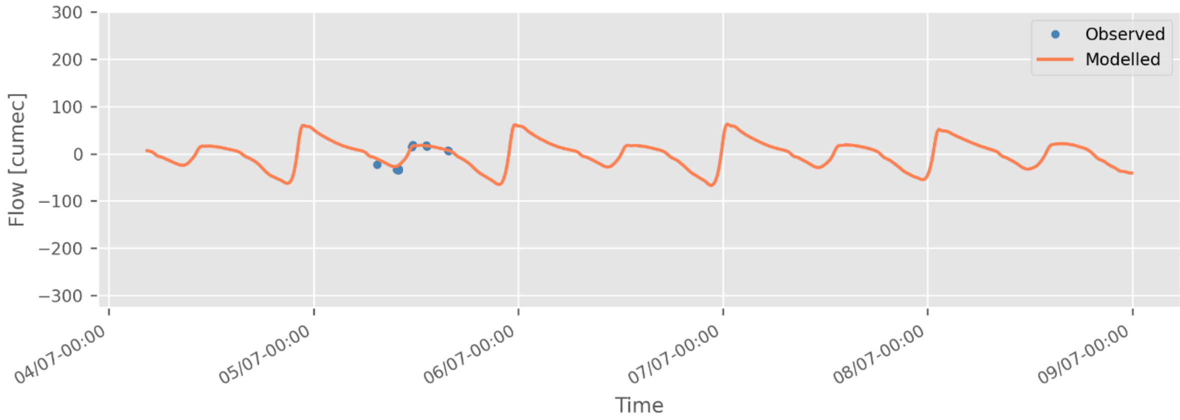

Figure 4-9 2003 tidal flow calibration – Location F – Pambula Lake Upstream

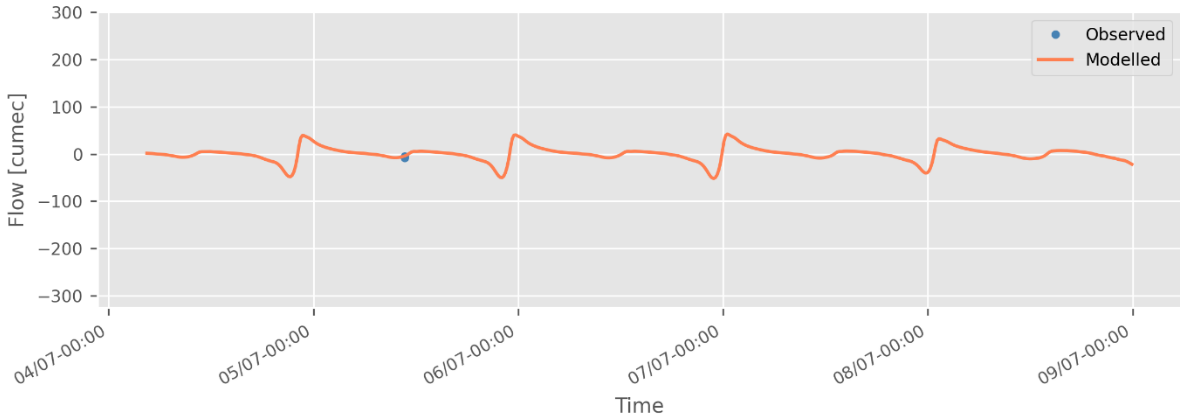

Figure 4-10 2003 tidal flow calibration – Location G – Upper Pambula River

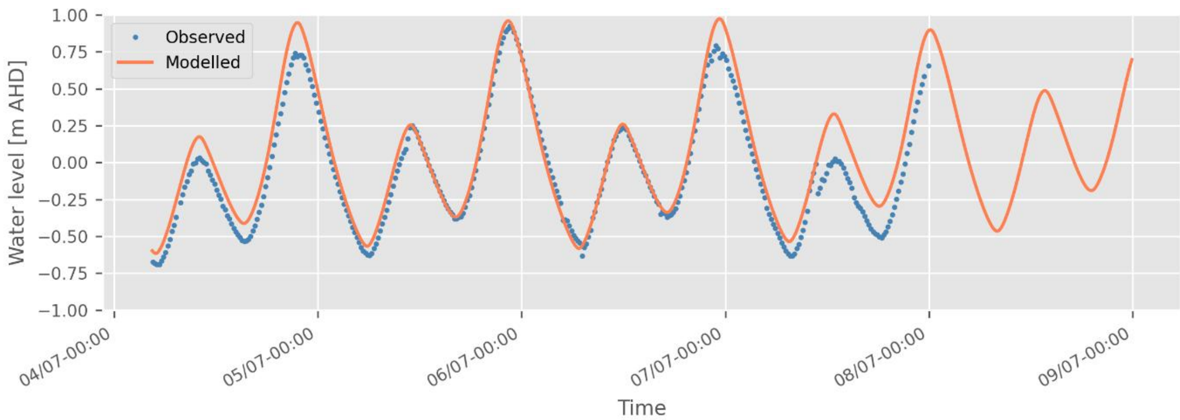

Figure 4-11 2003 water level calibration – Location 6 – Pambula Lake (ICT)

4.6.3 Roughness coefficients

Table 4-1 lists the roughness coefficients (Manning's n) which control the frictional losses in the final calibrated model. Most areas have a coefficient between 0.02 and 0.03, which is typical for large sandy channels.

Table 4-1 Mannings n roughness coefficients of the final model

Location	Manning's n roughness coefficient
Pambula River entrance to 2 km upstream (shoaled area)	0.030
Pambula River from 2 km upstream of entrance to Yowaka River junction	0.020
Lake	0.020
Intertidal areas	0.050
Yowaka River and Pambula Rive upstream of Yowaka River junction	0.025

4.7 Water quality model

4.7.1 Modelling of dispersion in RMA-11

Dye dispersion experiments, discussed in Section 3.5, provided valuable information on dispersion and its simulation in modelling. In particular, they provided evidence for a sensible range of dispersion coefficients to use in the modelling. However, it was concluded that they could not be used to produce estuary specific values for dispersion. Hence, a range of dispersion values derived from the field experiments was used across all the estuaries. Models were run with two dispersion coefficients, 0.5 and 1.5 m^2/s in the channels, and the scenario results presented are a combination of the two to manage the uncertainty in dispersion. For further details on how these dispersion values were determined, sensitivity testing, and how model results were combined refer to WRL TR2023/32 Section 7.3, 7.4 and 8.2.3.

A single dispersion coefficient of 4 m^2/s was used in the lake to capture potential dispersion from wind driven mixing. The RMA-11 model utilised a 3 minute timestep, with results output every 30 minutes.

4.7.2 Tidal straining and vertical velocity distribution

As outlined in WRL TR2023/32 Section 7.5, tidal straining is a process leading to asymmetrical vertical velocity distributions in some estuaries. In instances of tidal straining, much higher velocities are observed at the surface than at the bed on the ebb tide, with much less velocity difference observed on the flood tide. Using the methods described in WRL TR2023/32 Section 7.5, RMA-TRK (Lagrangian model) was used to compare the travel times from field observations with drifter drogues (see Section 3.6) with modelled transport. Table 4-2 shows the difference in drogue velocity and velocity of particles released in the model at the same location and time, plus the ratio between the two.

In the Pambula system, ratios were close to one, indicating that vertical velocity profiles in the system were close to depth averaged (consistent with observations from the tidal flow gauging). Drogue release 3 has a higher ratio (1.54), however, this release was conducted in the slow moving upper Pambula River, and was near the bank, thus small changes in distance travelled resulted in big differences in velocity. Therefore, this measurement should not be considered with as much weight as the other two. Hence, no timing adjustments were required for this system.

Table 4-2 Summary of RMA-11 velocity factors calculated from GPS drifter drogues

Drogue release	Location	Tide	Average drogue velocity (km/h)	Average model particle velocity (km/h)	Average ratio (velocity factor)
1	Pambula Entrance	Flood	2.17	1.83	1.18
3	Upper Pambula River	Ebb	0.30	0.19	1.54
4	Pambula Lake Downstream	Ebb	1.02	1.06	0.96

4.8 Limitations for future model uses

This model has been constructed and calibrated to be fit for the purpose of modelling sewage overflow transport from the modelled locations to oyster harvest areas. The model may be adapted for other uses, however the limitations must be considered. A general discussion on the limitations of applying these models to other use cases can be found in WRL TR2023/32 Section 6.6.

Limitations specific to the Pambula Lake model include:

- The lake transport processes are likely to be driven by wind, not captured in this model. Uncertainty about the lake transport processes is dealt with in the model by having a higher diffusion coefficient of 4 m^2/s in the lake. However, future modelling purposes may wish to simulate lake transport processes explicitly through the addition of wind as an input.
- Due to the limited amount of preexisting hydrodynamic data for this estuary, the 2023 field data was used as further calibration data rather than separate verification (validation) data as it was on some other estuaries. Thus, this model is not validated. This was deemed acceptable for this purpose, however, may not be for other use cases. This is discussed further in WRL TR2023/32 Section 6.4.
- The tidal flows in the upstream Pambula River are underestimated during some calibration periods. If this location is important for future modelling purposes, further calibration may be needed in this area.
- This estuary has a dynamic, untrained entrance which can change over time. This was not deemed to be necessary to simulate for this project, as a single bathymetry provided appropriate calibration over two periods, however, other use cases may require multiple bathymetries or updated bathymetry in the future.

5 Scenario modelling

5.1 Preamble

A detailed description for the methods of scenario modelling for this project can be found in WRL TR2023/32 Section 8. For Pambula, a total of 81 model scenario simulations were completed, including permutations of:

- Three overflow locations
- Four stages of the tide
- Three catchment inflow conditions
- Three overflow volumes and duration

Reporting focused on the minimum dilution observed in each harvest area (during the 21 day scenario) and the time taken for the plume to reach each harvest area at 5,000,000 times dilution. Refer to WRL TR2023/32 Section 8.3 for more information. In situations where multiple scenarios gave very similar results, these scenarios were grouped for ease of use, and the worst case results (minimum dilution and shortest travel time) were reported, as detailed in WRL TR2023/32 Section 8.3.6.

The results of all modelled scenarios have been compiled into a user-friendly HTML tool. A description of the tool and its use can be found in the User Guide (WRL TR2024/26).

5.2 Overflow locations

Three locations were used to simulate overflow locations into the Pambula estuary. These locations were based on historical overflow events (Section 2.4) and input from NSW Food Authority. These locations typically correspond to creek lines or infrastructure where sewage may be directed to following an overflow. The model only considers overflows from the moment they enter the estuary surface water system. Containment prior to reaching the estuary may still be effective. This is particularly important for overflows in the Pambula township, which have a significant distance to travel to the estuary. A judgement of whether the overflow reached the estuary should be made in consultation with local authorities to determine if the modelled scenarios need to be consulted. Moreover, in situations where there is a delay between the overflow occurrence and the time it reaches the estuary, this delay and related uncertainty needs to be considered when determining which stage of the tide scenario to use. If it is uncertain which scenario timing should be used, use the possible timing which results in the worst case scenario. Modelled overflow locations are shown in Figure 5-1.

At each overflow location, three different overflow conditions were considered:

1. 10 kL overflow over 1 hour (10 kL/hr)
2. 30 kL overflow over 3 hours (10 kL/hr)
3. 100 kL overflow over 10 hours (10 kL/hr)

The rate of discharge (10 kL/hr) was kept constant between each condition. This is equivalent to a rate of approximately 3 L/s. Intermediate results can be inferred for overflows of the same duration, but a different volume. See WRL TR2023/32 Section 8.3.3 for details on how to do this.

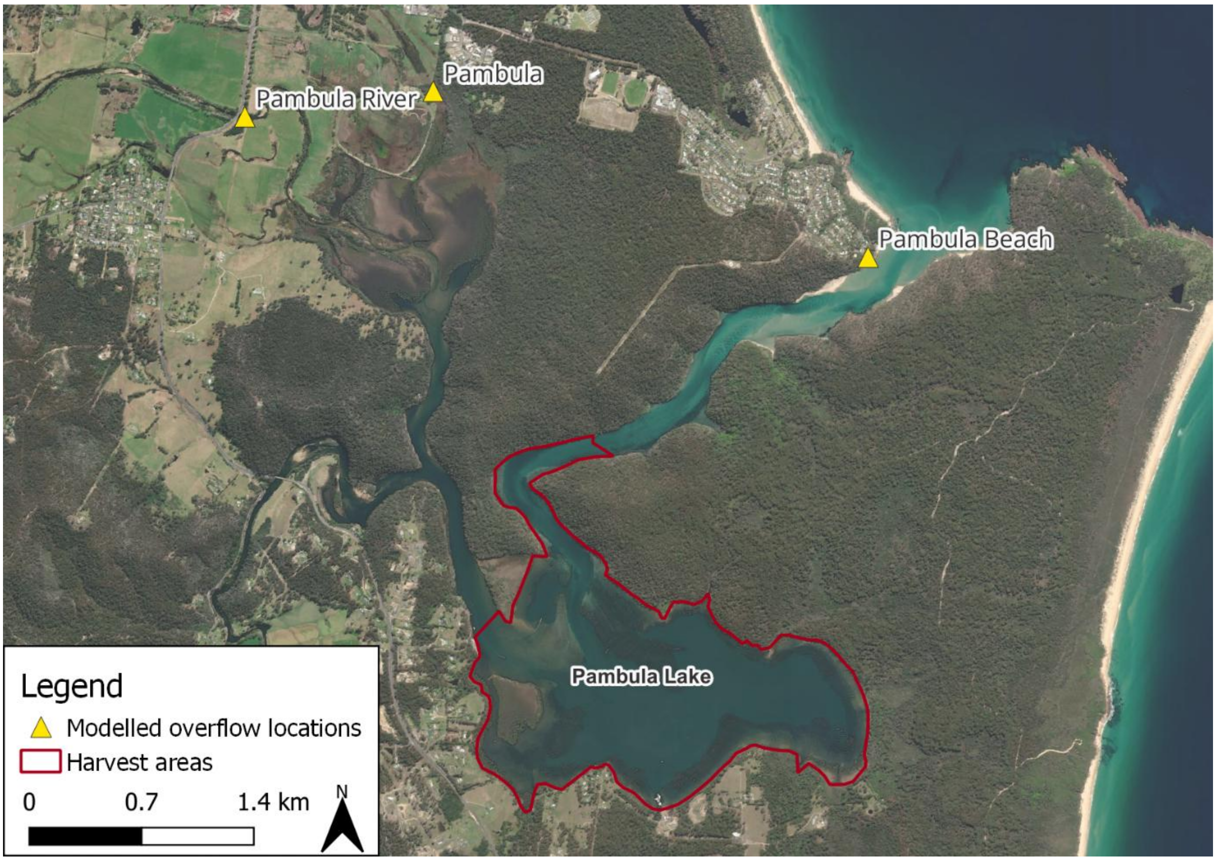

Figure 5-1 Modelled overflow locations in Pambula Lake

5.3 Environmental variables

Two environmental variables were tested for Pambula:

1. Stage of the tide (slack low tide, slack high tide, mid ebb tide and mid flood tide)
2. Magnitude of catchment inflows (median, 80^{th} percentile and 95^{th} percentile)

5.3.1 Stage of the tide

Stage of the tide for all locations is indexed to the MHL water level gauge at Pambula Lake, via the relationship described in Table 5-1.

Table 5-1: Model stage of tide timing relative to the MHL water level gauges

Overflow location	Results scenario	MHL water level gauge	Water level at start of spill
All locations	Slack low tide	Pambula Lake (220415)	Low tide
All locations	Mid flood tide	Pambula Lake (220415)	Half way between low and high tide
All locations	Slack high tide	Pambula Lake (220415)	High tide
All locations	Mid ebb tide	Pambula Lake (220415)	Half way between high and low tide

The stage of the tide affects plume transport for overflows from Pambula Beach, however all overflows from this location of at least 10 kL affect the harvest area at a high concentration. Figure 5-2 and Figure 5-3 show changes to the plume shape with overflows at high and low tides. Because plumes exiting the estuary enter the deep water of the bay offshore of Pambula Beach, which is protected by the headland to the east of the entrance, the majority of the overflow enters the system on the next incoming tide. Therefore, though this location is close to the entrance, the oyster harvest area is not necessarily protected from overflows on an outgoing tide.

Stage of the tide did not affect the two upstream overflow locations. For ease of use, results for overflows on different stages of the tide have been combined when management implications were the same. See WRL TR2023/32 Section 8.3.4 for more details on scenario grouping.

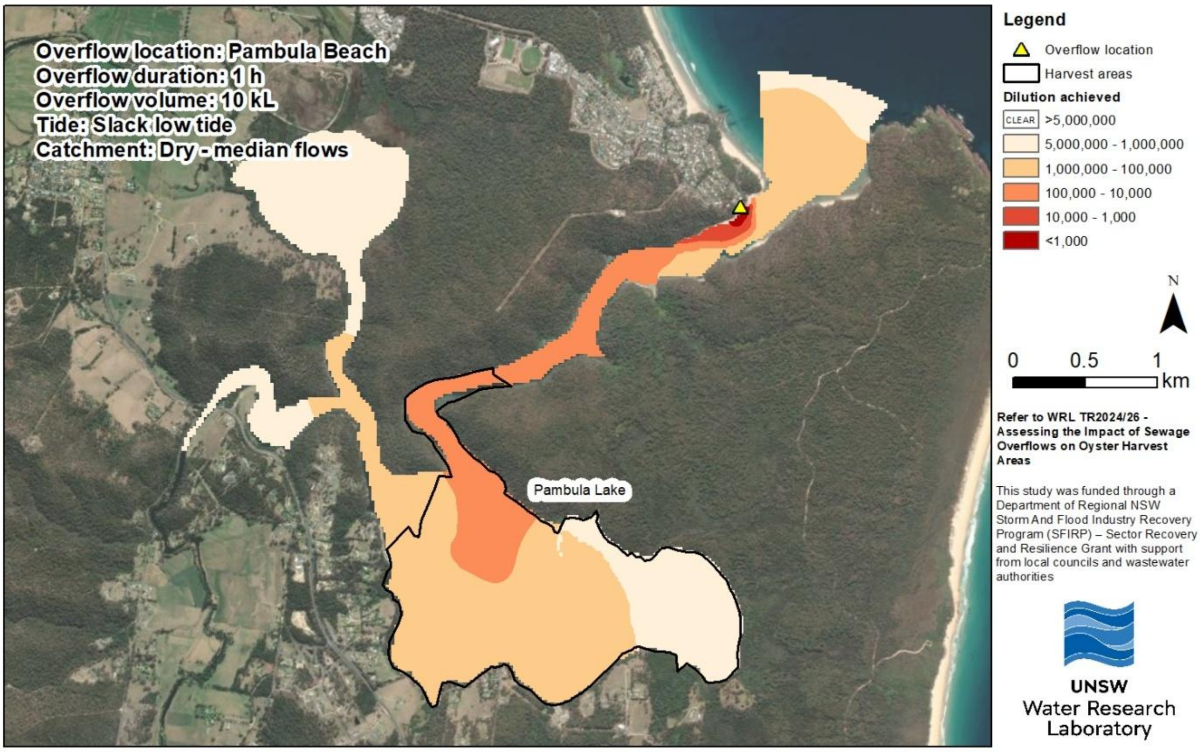

Figure 5-2 Example of a 1 hour overflow at Pambula Beach at slack low tide*

*Result figures present the minimum dilution (i.e. maximum concentration) observed at each point during the entire scenario period (21 days).

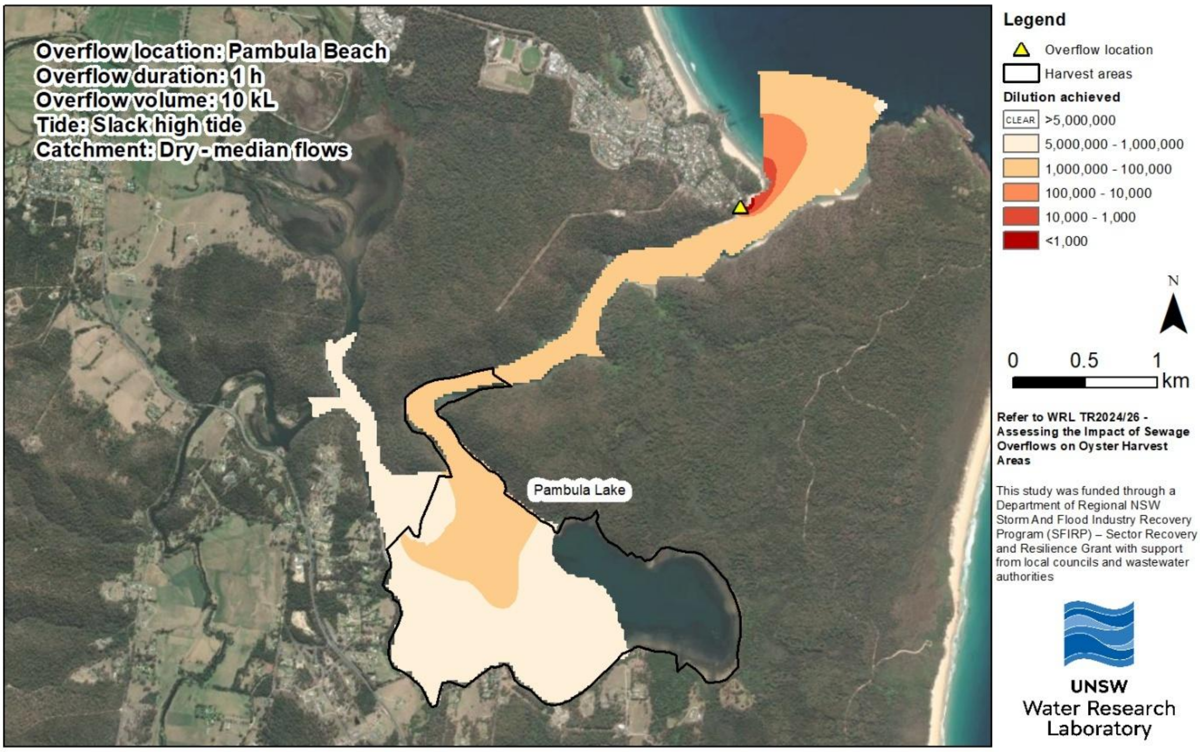

Figure 5-3 Example of a 1 hour overflow at Pambula Beach at slack high tide*

*Result figures present the minimum dilution (i.e. maximum concentration) observed at each point during the entire scenario period (21 days).

5.3.2 Catchment inflows

Catchment inflows affected overflow results from the two upstream overflow locations. Higher catchment inflows lead to faster transport downstream, and slightly higher concentrations reaching the harvest area (as can be seen in Figure 5-4 and Figure 5-5). However, due to the minimal opportunities for dilution in the small Pambula River before the harvest area is reached, even very small overflows from these two locations (1 kL) impact the harvest areas. Catchment inflows do not affect overflow from the Pambula Beach location, and results for different overflow locations have been grouped. See WRL TR2023/32 Section 8.3.4 for more details on scenario grouping.

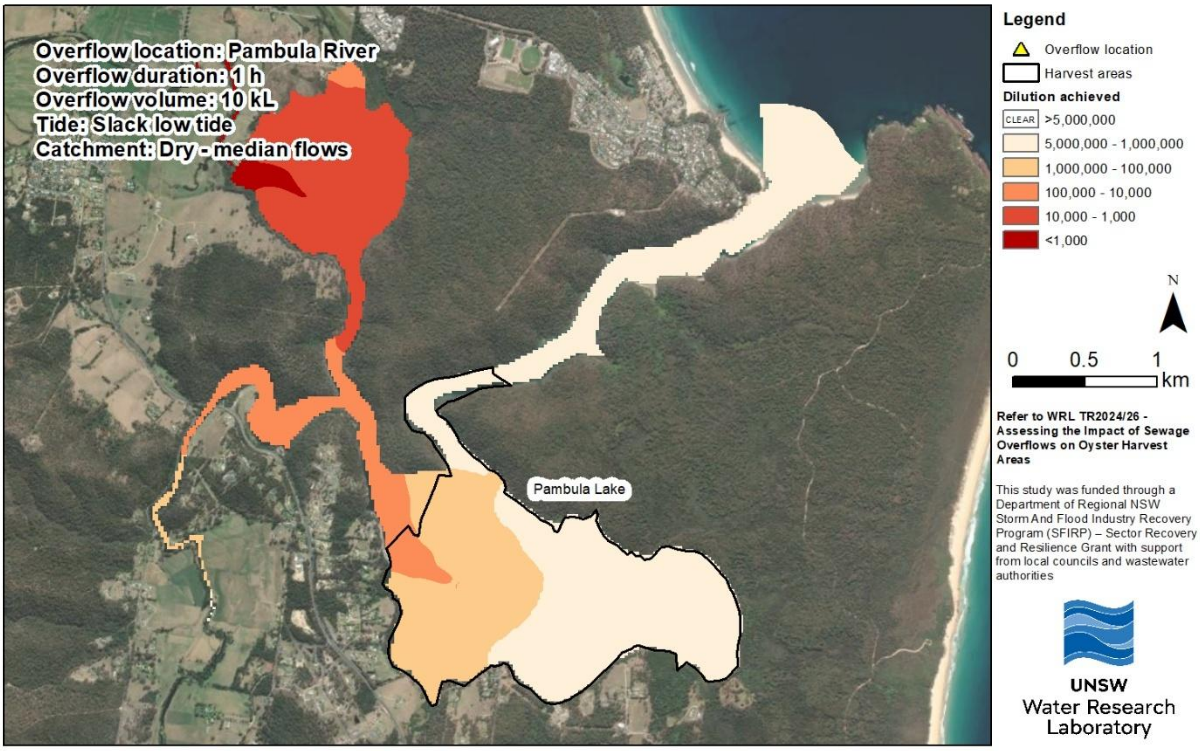

Figure 5-4 Example of a 1 hour overflow at Pambula River during median inflow conditions*

*Result figures present the minimum dilution (i.e. maximum concentration) observed at each point during the entire scenario period (21 days).

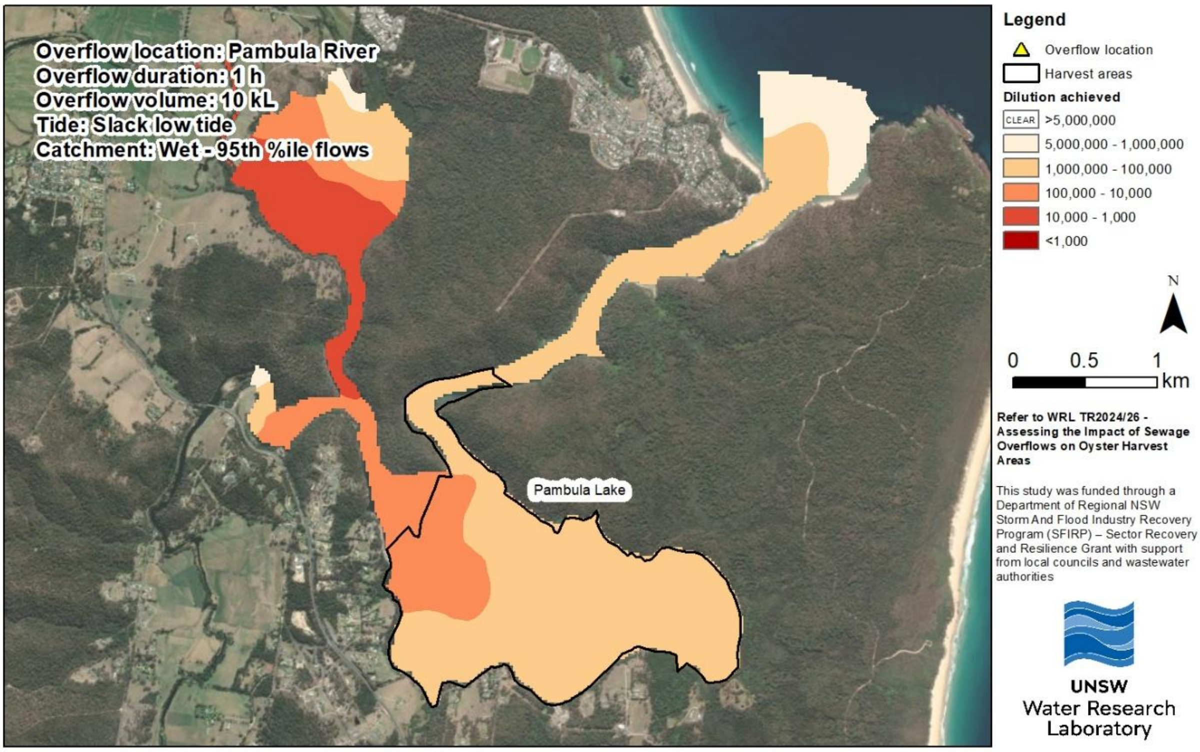

Figure 5-5 Example of a 1 hour overflow at Pambula Beach during 95th percentile inflow conditions*

*Result figures present the minimum dilution (i.e. maximum concentration) observed at each point during the entire scenario period (21 days).

6 Conclusion

This report is focussed on the Pambula Lake study and produced for the study “Assessing the impact of sewage overflows on oyster harvest areas in NSW”. The purpose of this report was to provide technical and estuary specific information on the process and data sources used to create the Pambula Lake model. Key information included in the report relates to the integration of existing data sources, the July 2023 field data collection campaign, data processing and model development.

This report should be read in conjunction with WRL TR2023/32 which provides details on the technical methods used across each of the 11 study estuaries (including Pambula) and discussions on modelling limitations including model parameter sensitivity and pollutant dispersion. Results of the scenario modelling is available in the accompanying tool, which is documented in the User Guide (WRL TR2024/26).

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Appendix A Field data collection

A1 Drifter drogue experiments

The below figures summarise the behaviour of the four drifter drogue experiments. For more information on these deployments, refer to Section 3.5.4.

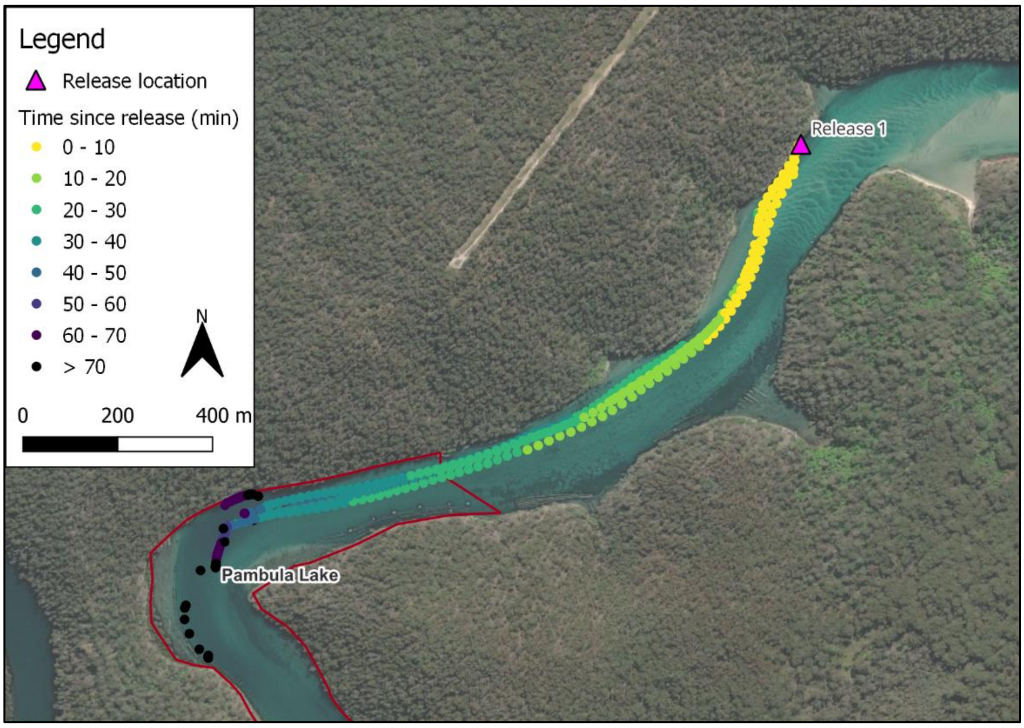

Figure A-1 GPS drifter drogue release 1 – Pambula Entrance – incoming tide

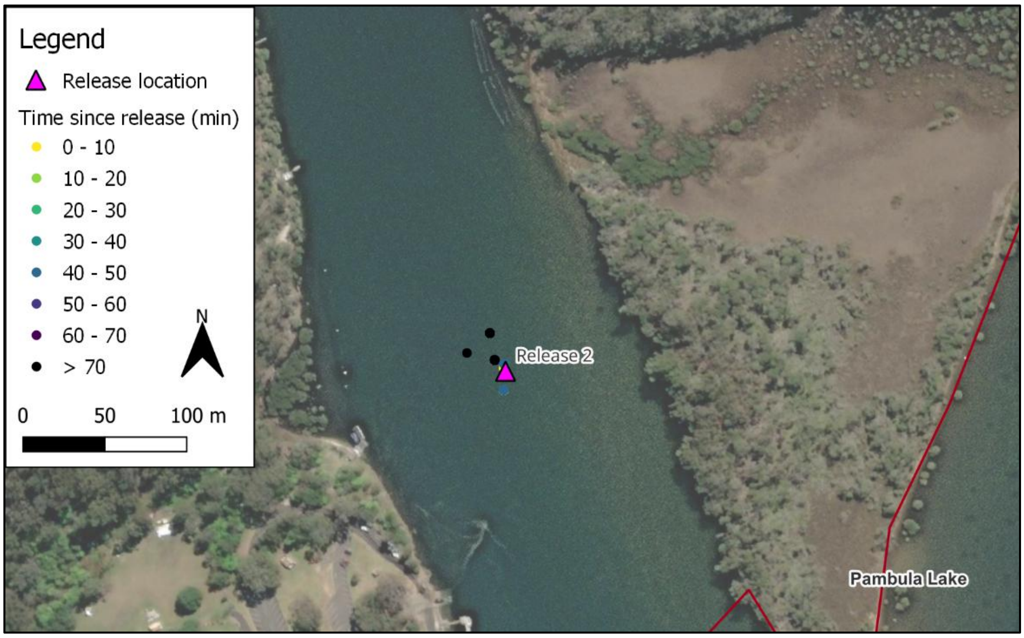

Figure A-2 GPS drifter drogue release 2 – Pambula Lake Upstream – incoming tide

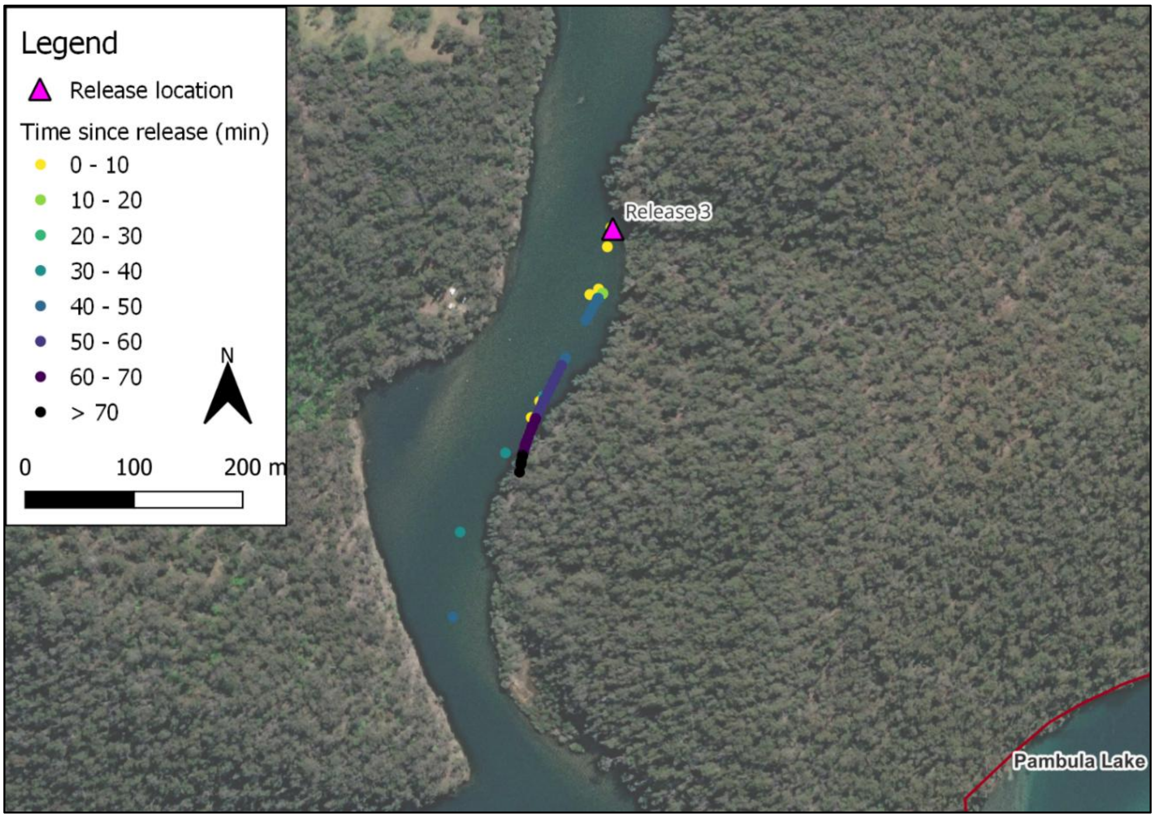

Figure A-3 GPS drifter drogue release 3 – Upper Pambula River – outgoing tide

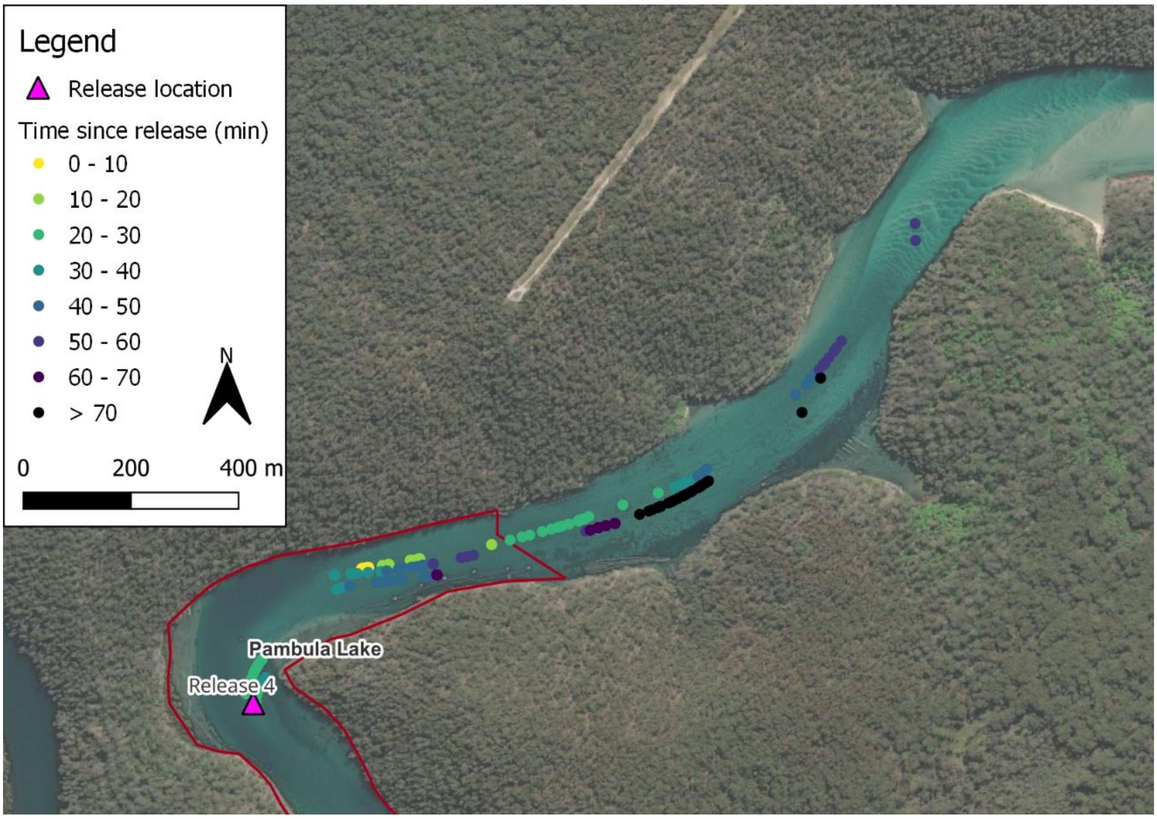

Figure A-4 GPS drifter drogue release 4 – Pambula Lake Downstream – outgoing tide

A2 Tidal flow gauging

The below figures summarise tidal flow gauging results from the 2023 field campaign. For more information, refer to Section 3.3.

Table A-1 Pambula Entrance 2023 tidal flow gauging

No.	Date	Time	Flow (m^3/s) *
1	05/07/2023	7:57:46	-167

* Flow sign relative to upstream river flow direction. Outgoing ebb flows are positive, while incoming flood flows are negative.

Table A-2 Pambula Lake Downstream 2023 tidal flow gauging

No.	Date	Time	Flow (m^3/s) *
1	05/07/2023	8:54:47	-157
2	05/07/2023	8:57:51	-179
3	05/07/2023	9:04:24	-174
4	05/07/2023	9:07:23	-178
5	05/07/2023	9:10:49	-159
6	05/07/2023	9:13:33	-179
7	05/07/2023	9:16:25	-174
8	05/07/2023	9:19:17	-181
9	05/07/2023	11:03:03	-16
10	05/07/2023	11:05:32	23
11	05/07/2023	11:08:29	15
12	05/07/2023	11:10:52	40
13	05/07/2023	11:13:33	46
14	05/07/2023	13:26:36	129
15	05/07/2023	13:29:22	127
16	05/07/2023	13:31:45	125
17	05/07/2023	15:14:16	83
18	05/07/2023	15:16:43	66

No.	Date	Time	Flow (m^3/s) *
19	05/07/2023	15:18:34	78
20	05/07/2023	15:20:48	79

* Flow sign relative to upstream river flow direction. Outgoing ebb flows are positive, while incoming flood flows are negative.

Table A-3 Pambula Lake Upstream 2023 tidal flow gauging

No.	Date	Time	Flow (m^3/s) *
1	05/07/2023	7:26:36	-23
2	05/07/2023	9:46:13	-33
3	05/07/2023	9:48:32	-34
4	05/07/2023	9:51:06	-34
5	05/07/2023	9:53:23	-35
6	5/07/2023	9:55:31	-32
7	05/07/2023	9:57:30	-35
8	05/07/2023	9:59:48	-32
9	05/07/2023	11:32:05	14
10	05/07/2023	11:34:45	17
11	05/07/2023	11:37:11	19
12	05/07/2023	13:12:07	18
13	05/07/2023	13:14:25	18
14	05/07/2023	13:16:37	16
15	05/07/2023	15:45:52	7
16	05/07/2023	15:47:56	6

* Flow sign relative to upstream river flow direction. Outgoing ebb flows are positive, while incoming flood flows are negative.

Table A-4 Upper Pambula River 2023 tidal flow gauging

No.	Date	Time	Flow (m^3/s) *
1	05/07/2023	10:41:27	-8
2	05/07/2023	10:43:07	-5

* Flow sign relative to upstream river flow direction. Outgoing ebb flows are positive, while incoming flood flows are negative.

A3 Channel flow distribution

The below figures summarise velocity distribution results from the 2023 field campaign. For more information, refer to Section 3.3. Note that all measurements are at a different stage of the tidal cycle so the magnitude of flow will vary. The primary purpose is to illustrate flow distribution across the channel.

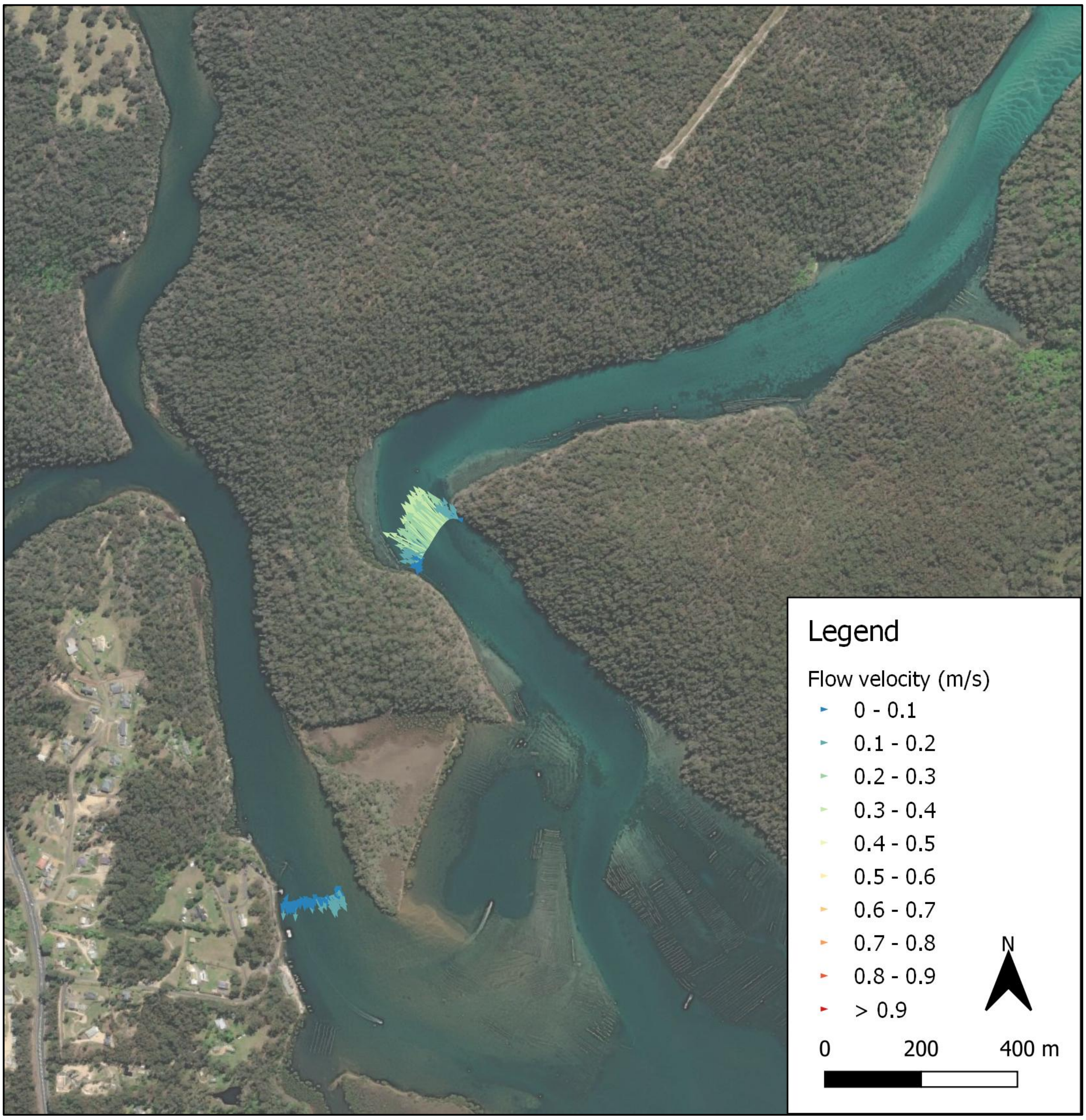

Figure A-5 Pambula Lake channel ebb tide velocity distribution

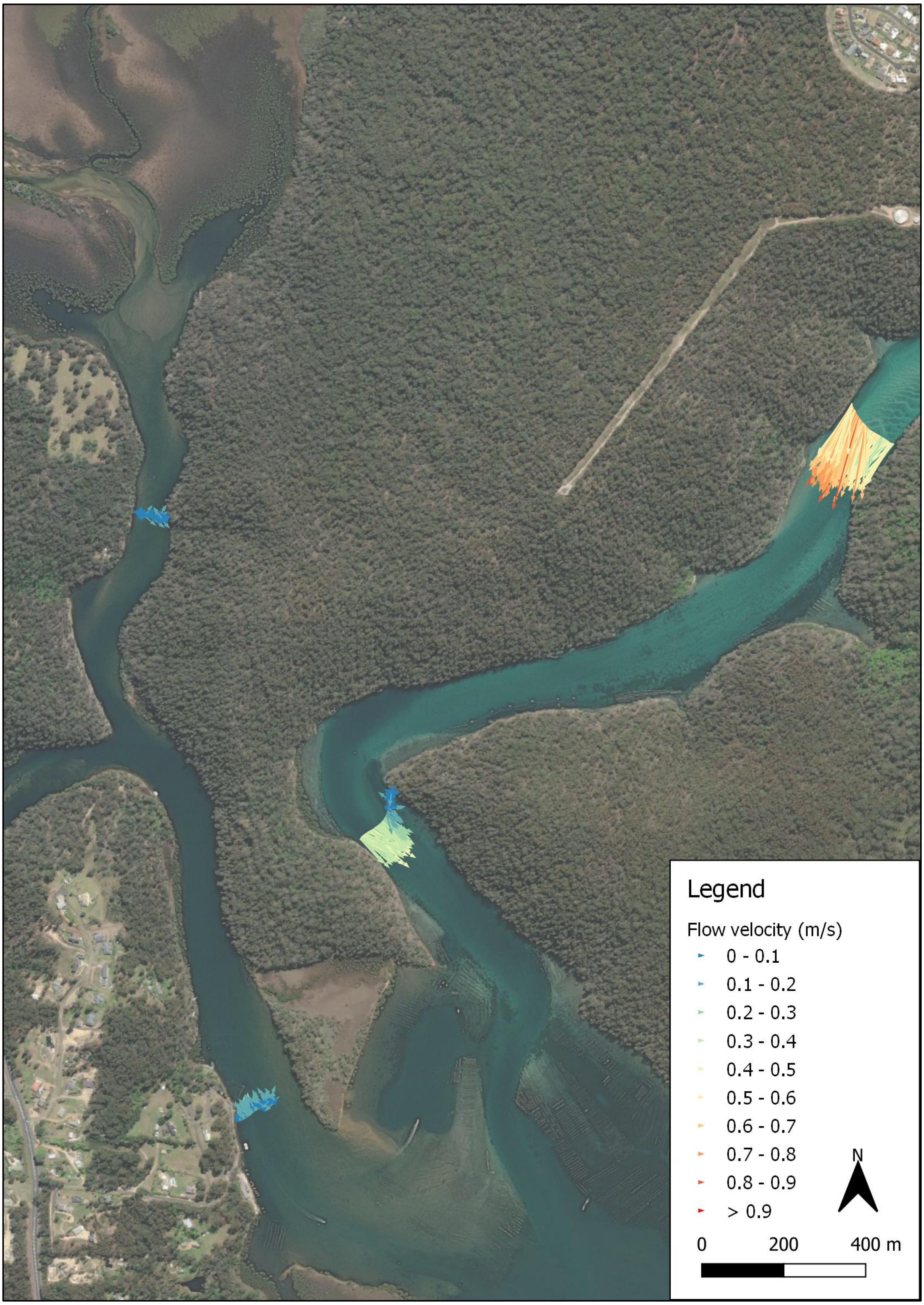

Figure A-6 Pambula Lake channel flood tide velocity distribution

A4 Vertical velocity distributions

The following figures show the vertical distribution of horizontal speed for select transects measured during the 2023 field campaign. This was used to help assess whether vertical velocity stratification was significant. For more information, refer to Section 3.3 and 4.7.2. Bathymetry sometimes varies between ebb and flood transects because transects were not always taken at the exact same location due to boat manoeuvrability limitations. Transects were usually taken within a 50 m reach in which flow would be equivalent.

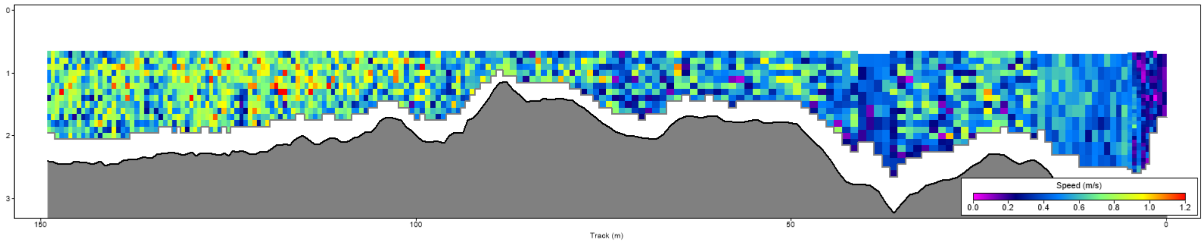

Figure A-7 Vertical velocity distribution – Pambula Entrance – Incoming flow – (2023/07/05 07:57:46)

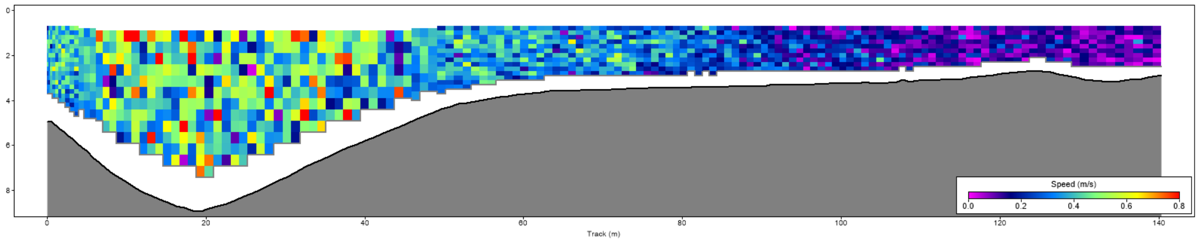

Figure A-8 Vertical velocity distribution – Pambula Lake Downstream – Incoming flow – (2023/07/05 09:19:17)

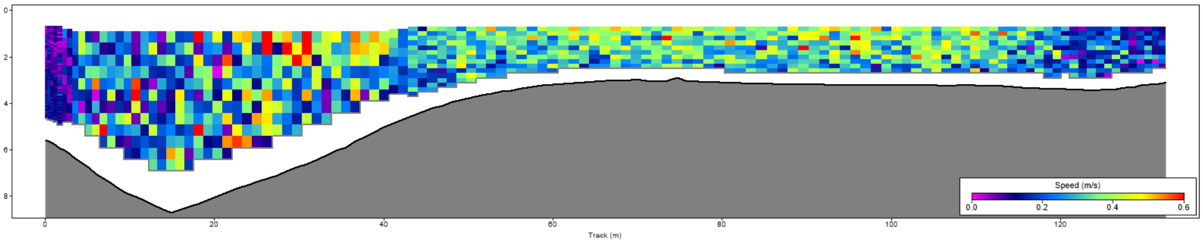

Figure A-9 Vertical velocity distribution – Pambula Lake Downstream – Outgoing flow – (2023/07/05 13:33:45)

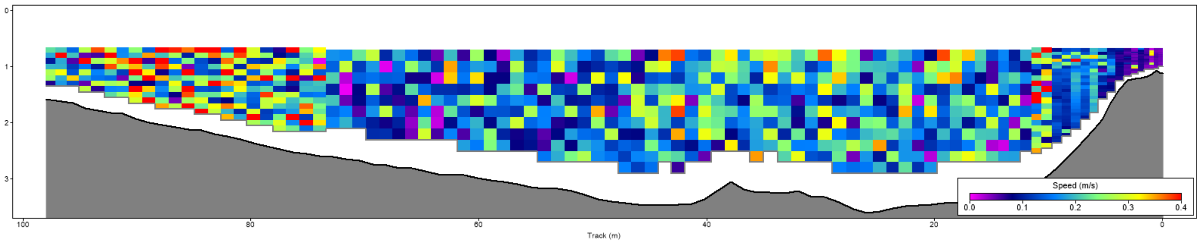

Figure A-10 Vertical velocity distribution – Pambula Lake Upstream – Incoming flow – (2023/07/05 09:55:31)

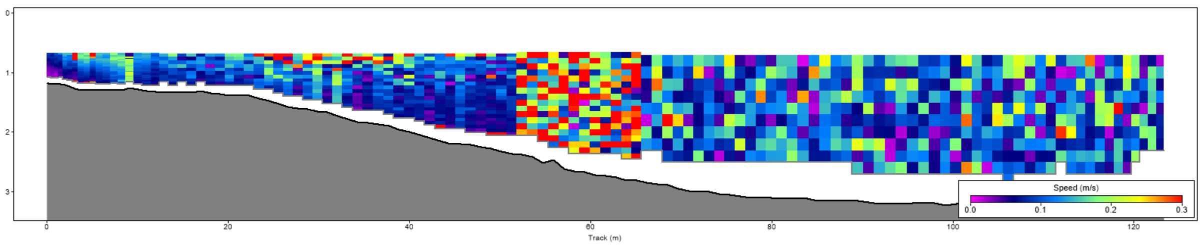

Figure A-11 Vertical velocity distribution – Pambula Lake Upstream – Outgoing flow – (2023/07/05 11:34:45)

Appendix B Model calibration

B1 Hydrodynamic calibration results

The below figures summarise results from the Pambula Lake estuary hydrodynamic calibration process. For more information, refer to Section 4.5.

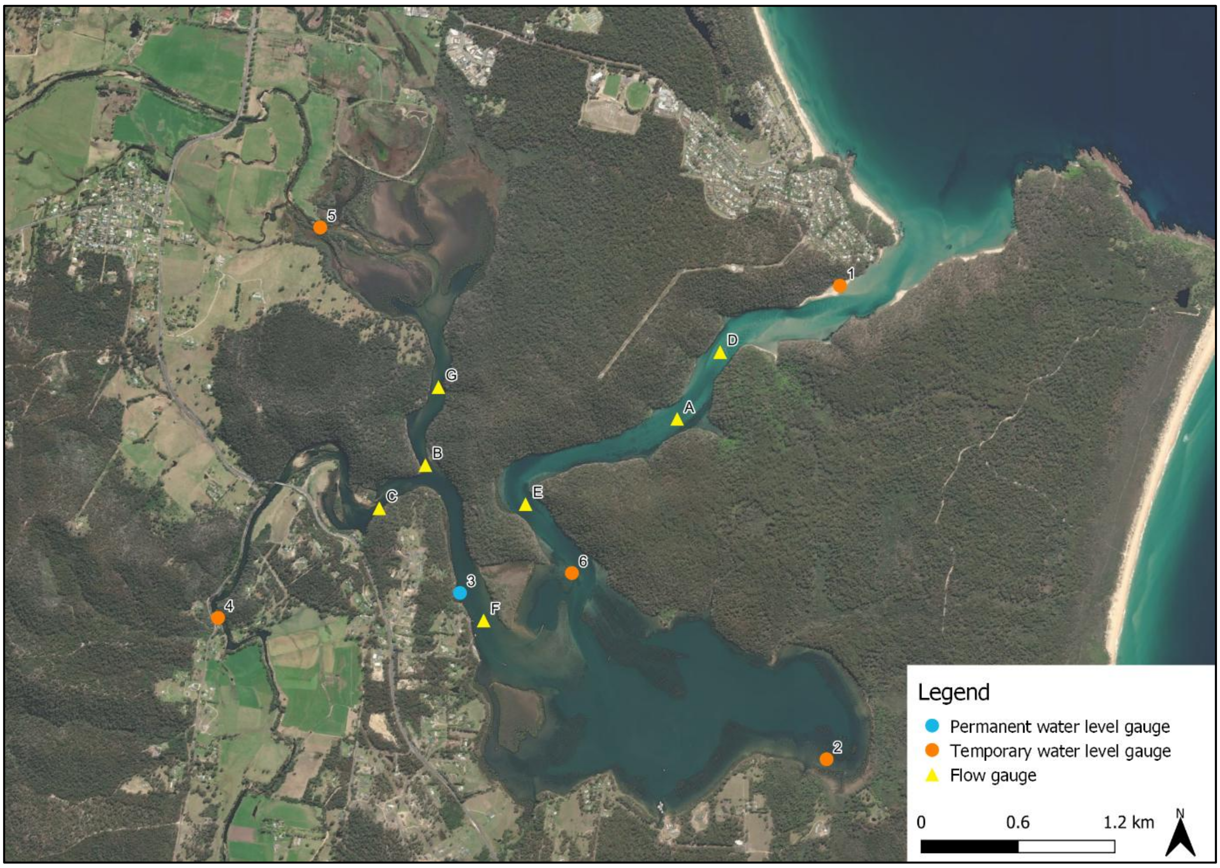

Figure B-1 Water level and tidal flow gauging locations

B1.1 Tidal flow gauging calibration – 2003

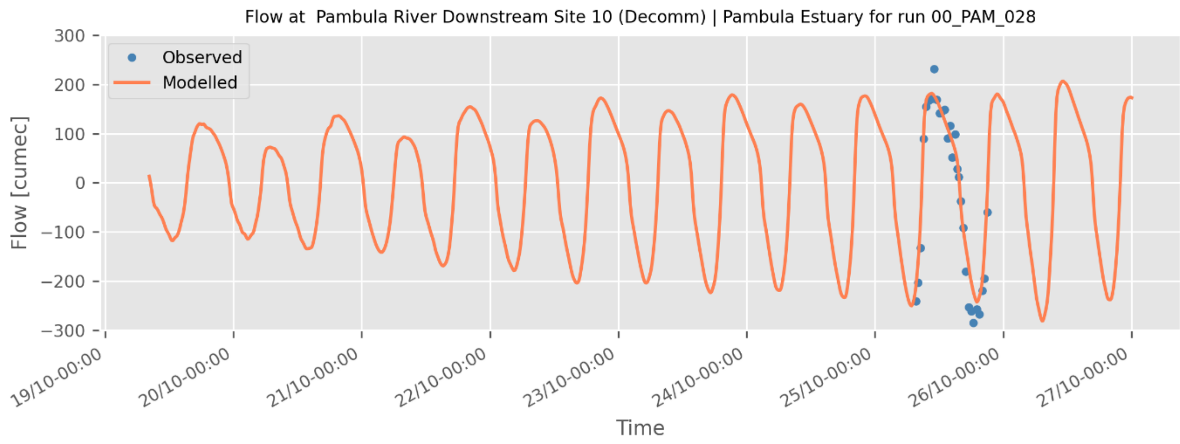

Figure B-2 2003 tidal flow calibration – Location A – Pambula River Downstream

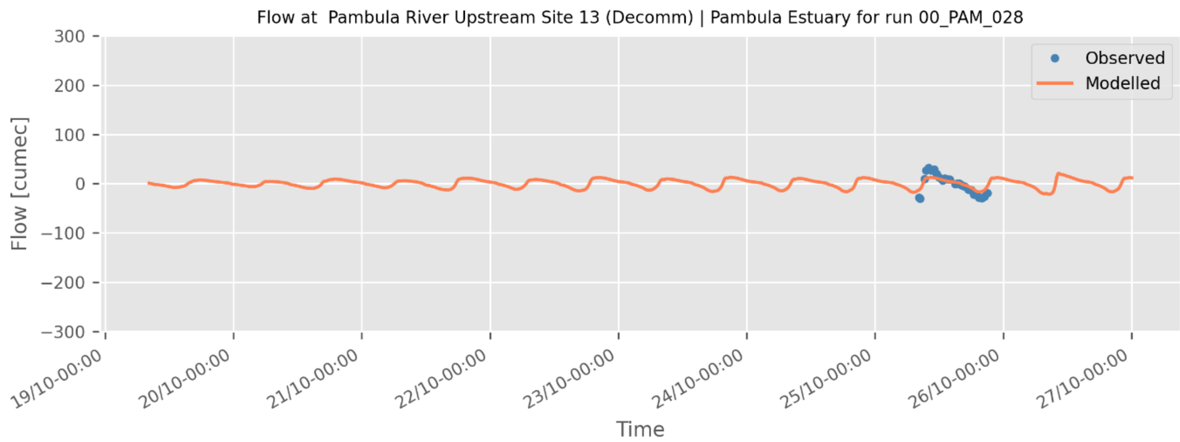

Figure B-3 2003 tidal flow calibration – Location B – Pambula River Upstream

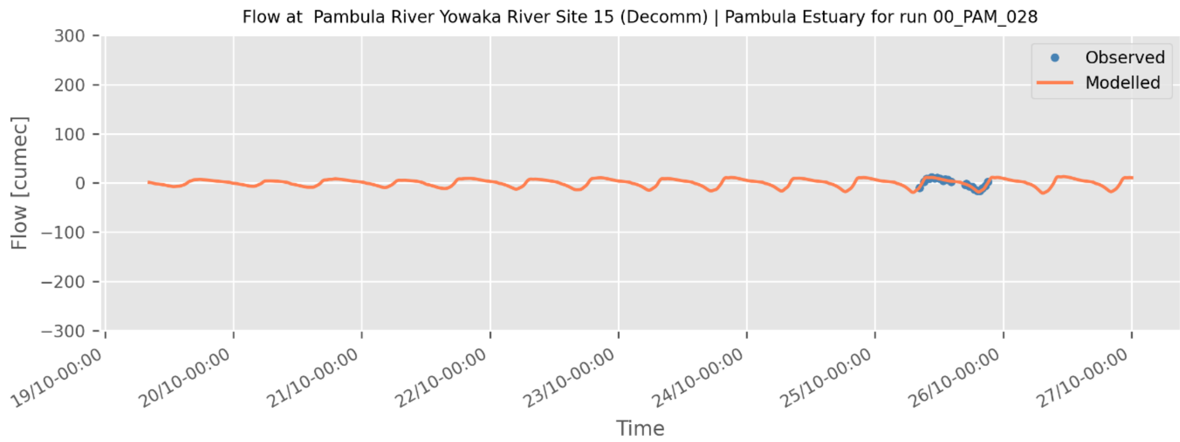

Figure B-4 2003 tidal flow calibration – Location C – Yowaka River

B1.2 Water level calibration – 2003

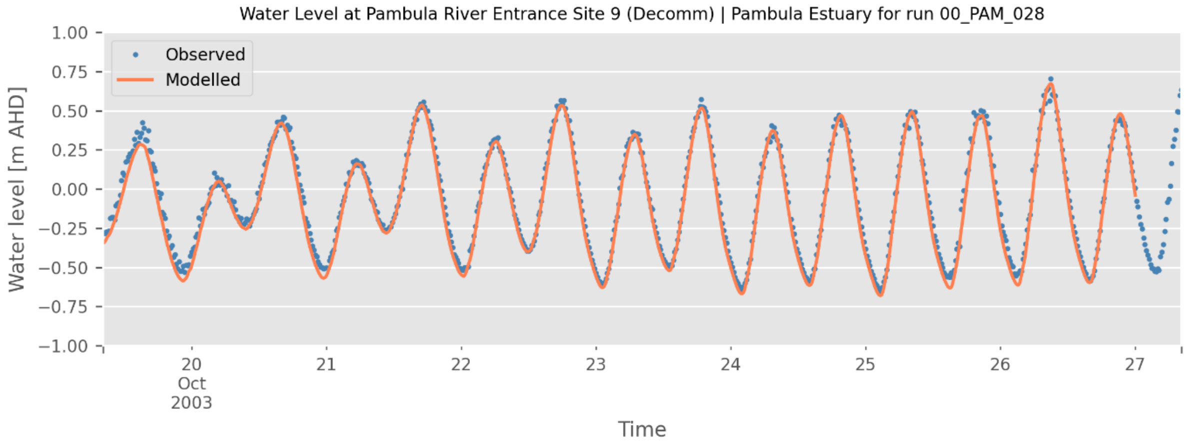

Figure B-5 2003 water level calibration – Location 1 – Pambula River Entrance

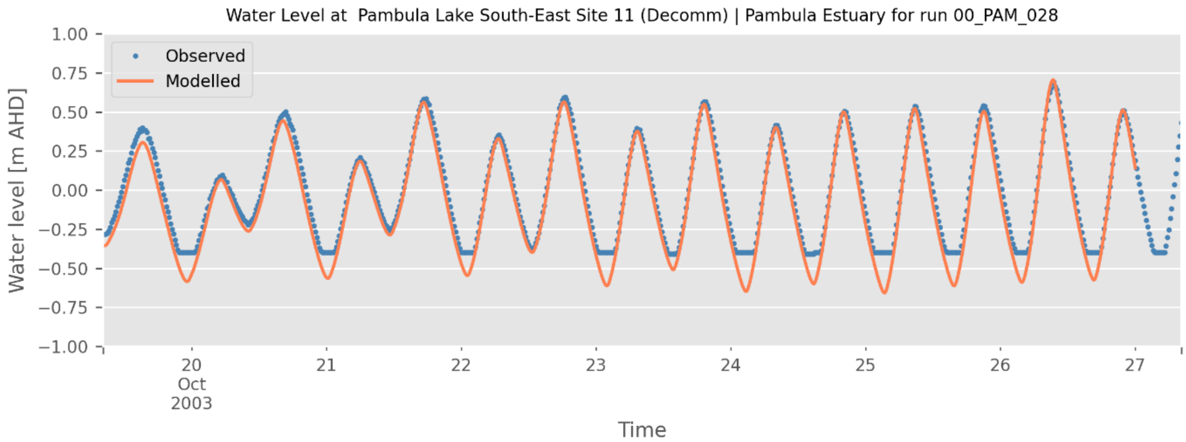

Figure B-6 2003 water level calibration – Location 2 – Pambula Lake South-East

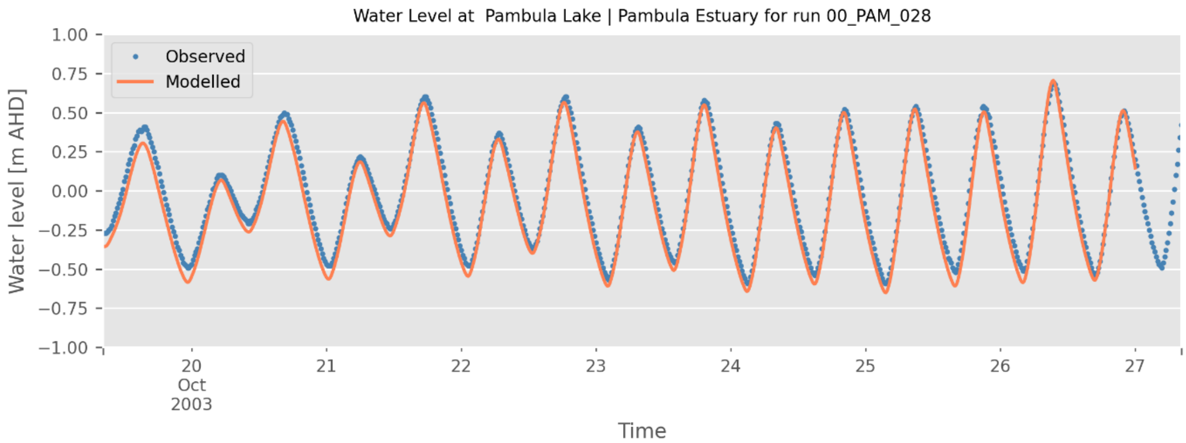

Figure B-7 2003 water level calibration – Location 3 – Pambula Lake North-West

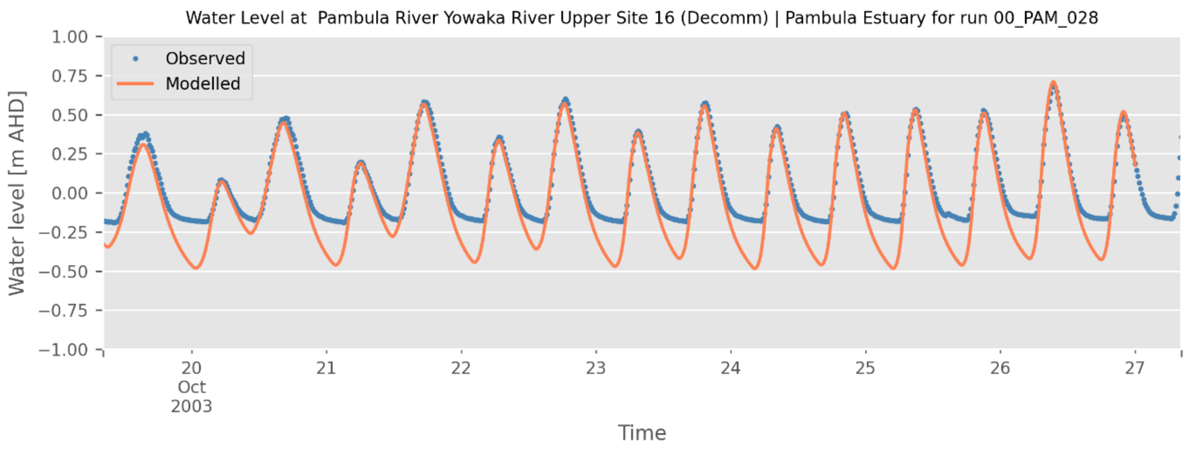

Figure B-8 2003 water level calibration – Location 4 – Upper Yowaka River

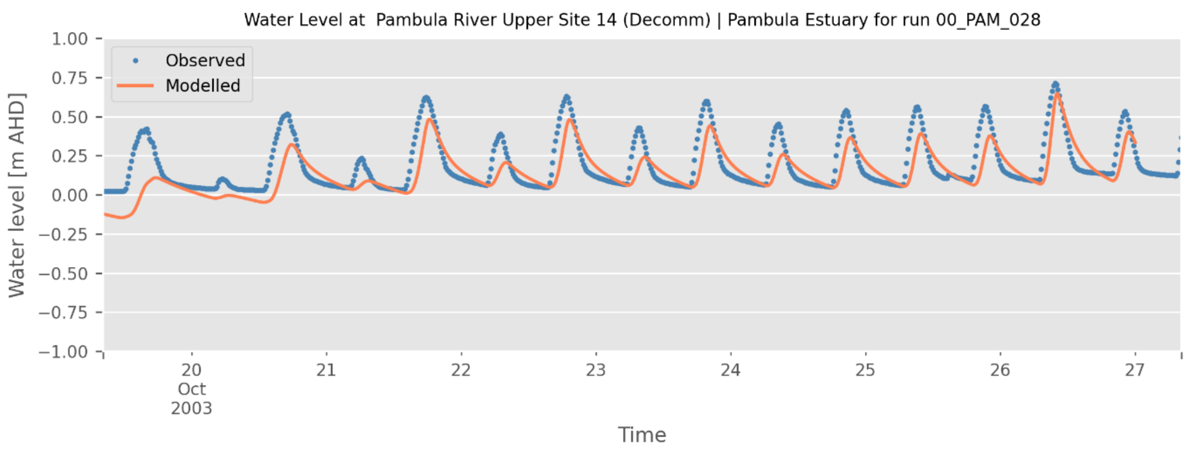

Figure B-9 2003 water level calibration – Location 5 – Upper Pambula River

B1.3 Tidal flow gauging verification – 2023

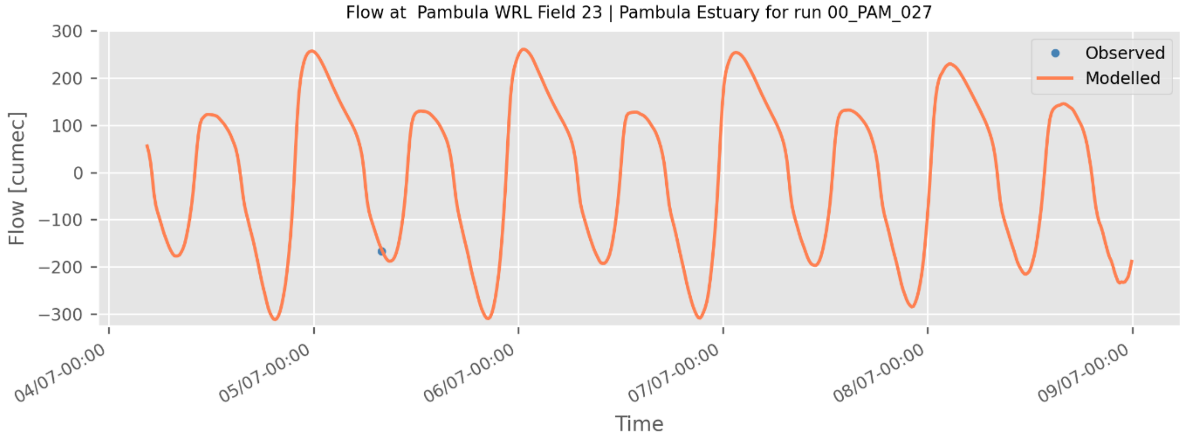

Figure B-10 2003 tidal flow calibration – Location D – Pambula River Entrance

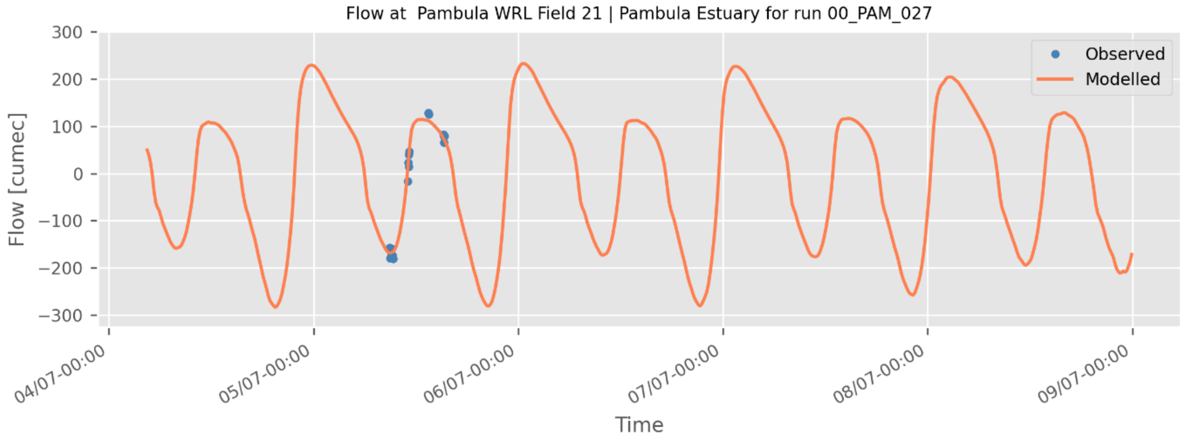

Figure B-11 2003 tidal flow calibration – Location E – Pambula Lake Downstream

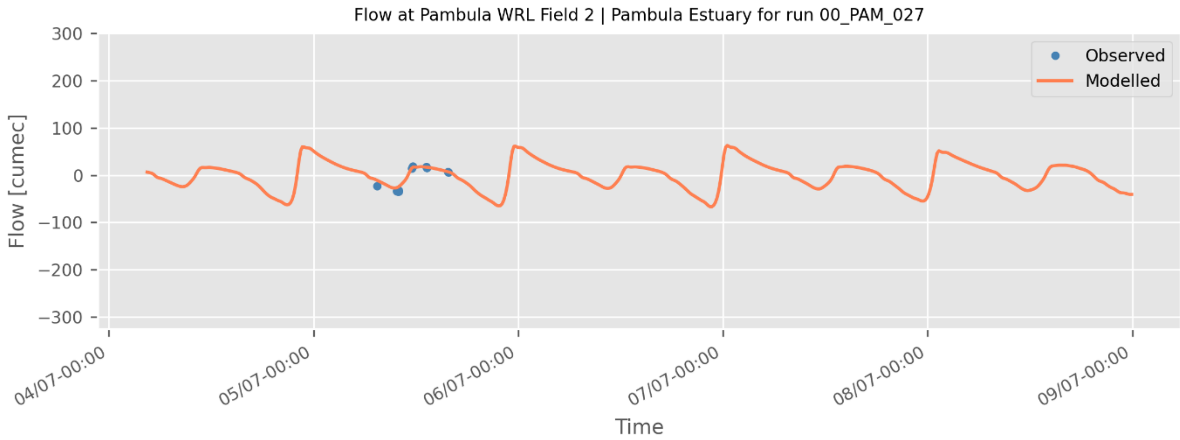

Figure B-12 2003 tidal flow calibration – Location F – Pambula Lake Upstream

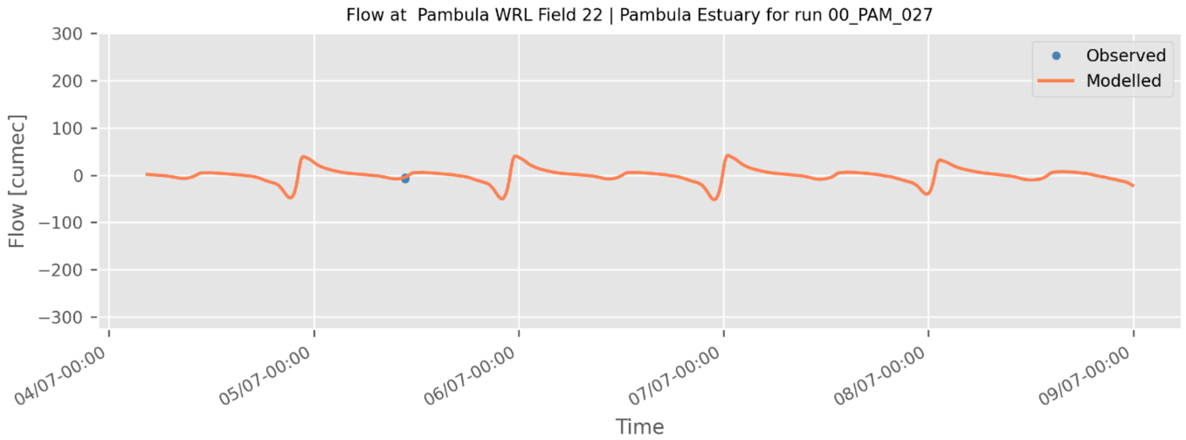

Figure B-13 2003 tidal flow calibration – Location G – Upper Pambula River

B1.4 Water level verification – 2023

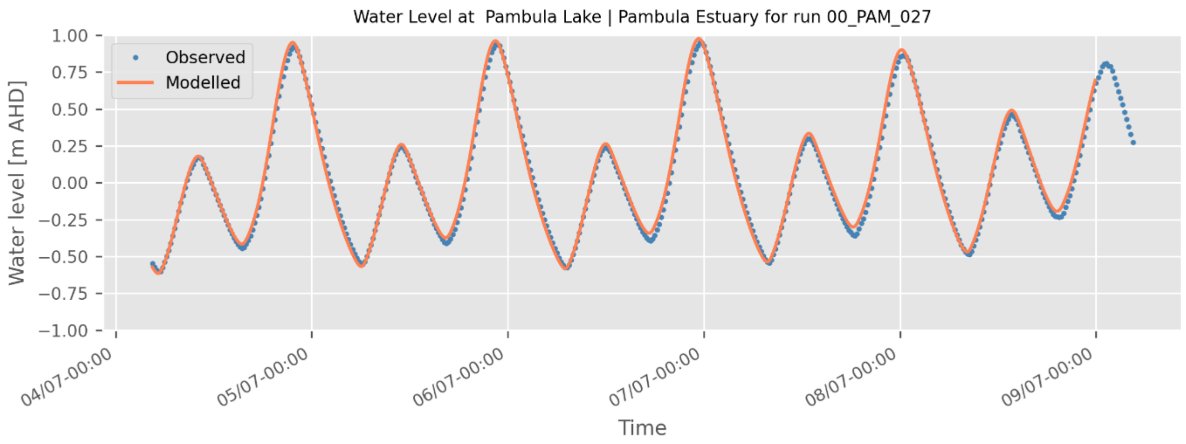

Figure B-14 2003 water level calibration – Location 3 – Pambula Lake North-West

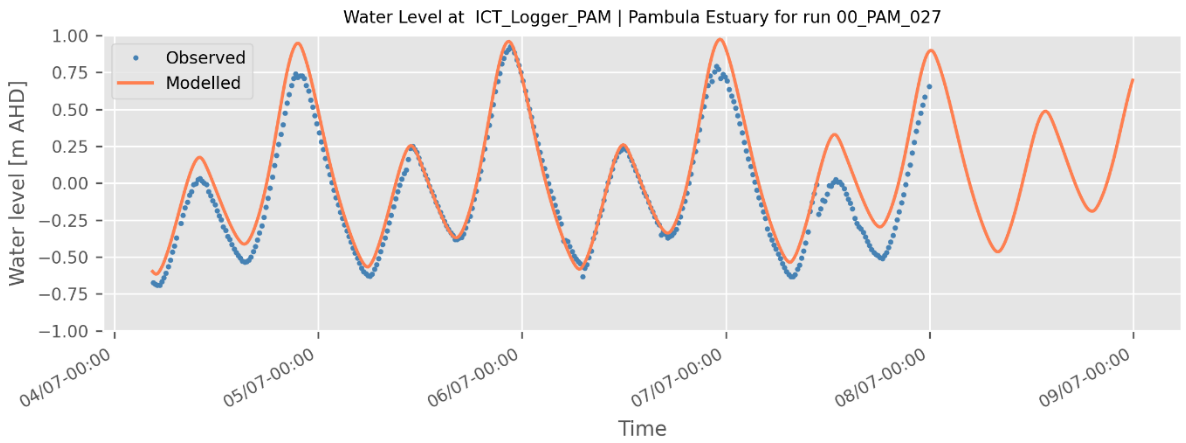

Figure B-15 2003 water level calibration – Location 6 – Pambula Lake (ICT)