# Assessing the impact of sewage overflows on oyster harvest areas: Wagonga Inlet (Narooma) estuary technical summary

WRL TR 2023/25, May 2025

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

UNSW Water Research Laboratory

UNSW SYDNEY

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## Project details

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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 Wagonga Inlet 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 the Wagonga estuary 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 (this report) |
| Merimbula Lake | WRL TR2023/26 |
| Pambula Lake | WRL TR2023/27 |

## 1.3 Wagonga Inlet site description

Wagonga Inlet is a coastal estuary on the far south coast of NSW, Australia, located 285 km south of Sydney and 55 km north of Bega. Towns in the area include Narooma, Kianga, Tilba, and Dalmeny. The Wagonga Inlet estuary system is a drowned river valley comprised of a deep lake (up to 16 m) connected to Wagonga Heads and the ocean via a 3 km inlet channel. The estuary catchment is 110 $km^2$ with two primary inflows: Punkally Creek and Billa Bilba Creek. The waterway area is 6.9 $km^2$ and the tidal prism is between $2.8 \times 10^6$ and $7.0 \times 10^6$ $m^3$ depending on the tidal cycle (MHL, 2001).

The inlet channel to the estuary system is heavily modified and was first stabilised with rock armour units in the 1920s. Current stabilisation works are comprised of a 1 km long eastern training wall from Apex Park to Wagonga Inlet Beach, and a 780 m western training wall from Narooma Bridge to Narooma Wharf. Both training walls overtop at high tide and form an eastern and western lagoon. The entrance to Wagonga Inlet has been trained since the construction of a breakwater in 1977 (MHL, 2001). Since the training walls were completed, the tidal range in Lake Wagonga has been increasing, as the channel becomes increasingly efficient through scouring (Nielsen and Gordon, 2016). The estuary has five oyster harvest areas: Lower Lavendar Point A, Lower Lavendar Point B, Upper Lavendar Point, Lower Honeymoon Bay, and Upper Honeymoon Bay. These harvest areas, along with key features, are shown in Figure 1-1.

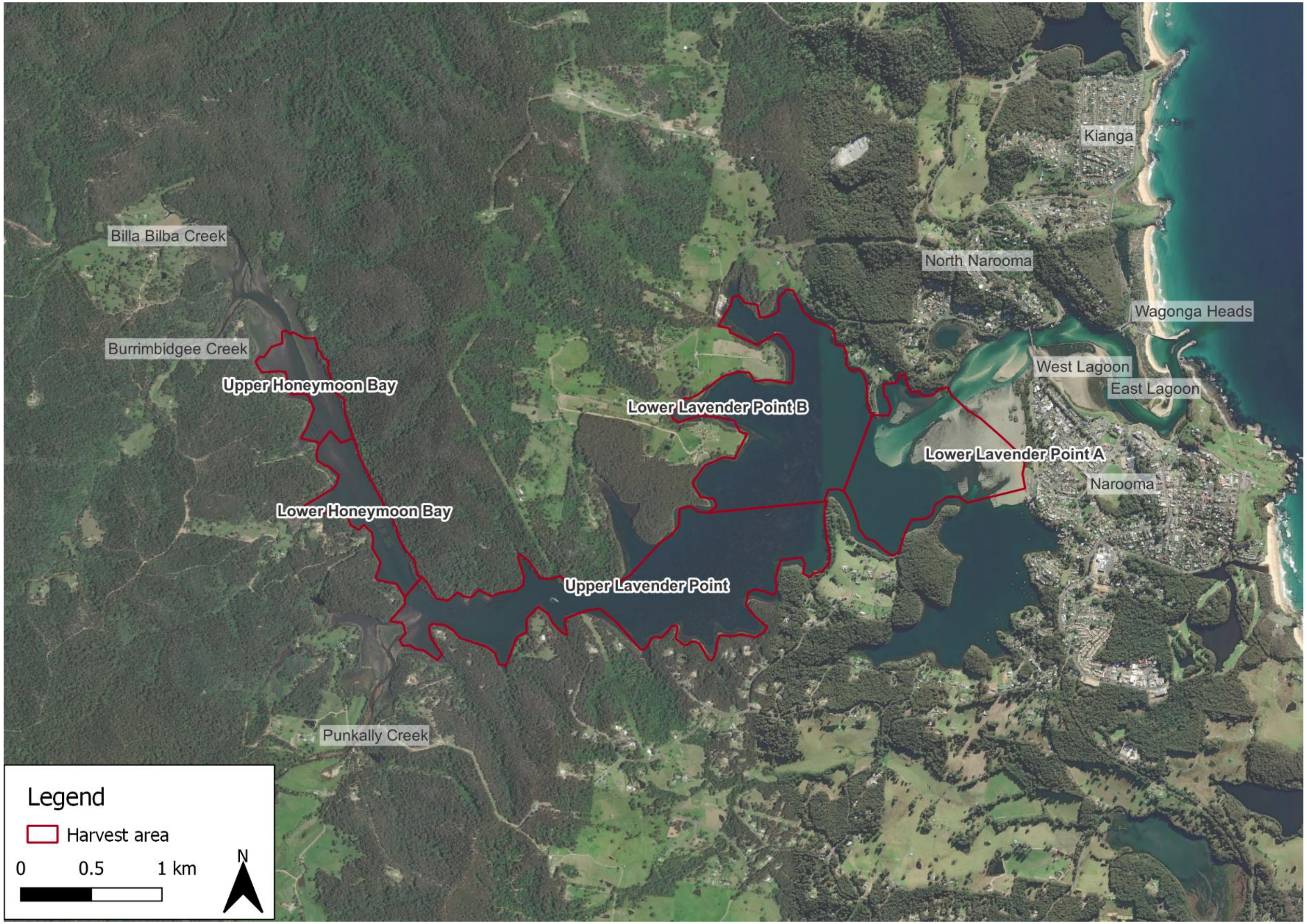


**Figure 1-1 Oyster harvest areas in Wagonga Inlet**

## 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 of the estuary, 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 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 (2023b)<br>MHL (2023c) | One long term water level gauge in Wagonga Inlet and one nearby ocean tide gauge. | 2.2 |
| Water level data | NSW Food Authority (2023) | Single water level sensor in lower Honeymoon Bay. | 2.2 |
| Water level data | MHL (1997) | Temporary water level gauge at Narooma Public Wharf. | 2.2 |
| Tidal flow and water level | MHL (1989) | Tidal flow gauging at two locations and temporary water level gauges at four locations in December 1986. | 2.2 |
| Tidal flow and water level | MHL (1976) | Tidal flow gauging at one location and temporary water level gauging at five locations May 1976. | 2.2 |
| Catchment discharge | WaterNSW (2023) | One nearby 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)<br>OEH (1997)<br>NSW Spatial Services (2012)<br>NAVONICS (2023)<br>NearMap (2024) | Bathymetry primarily sourced from 2018 marine LiDAR survey with supplementary data from 1997 single beam survey, 2012 Digital Elevation Model (DEM), NAVONICS SonarChart and NearMap aerials. | 2.5 |

## 2.2 Water level and tidal flow gauging

Manly Hydraulics Laboratory (MHL) have one permanent water level gauge installed on Wagonga Inlet, and one nearby ocean tide gauge at Bermagui. Historic water level data is available from field campaigns run by MHL in 1976, 1986 and 1997. Flow gauging data was also collected by MHL for the 1976 and 1986 campaigns. Due to hydrodynamic changes to the system arising from the construction of the breakwater in 1977, only the 1986 and 1997 campaigns were considered for this study. As water level data was unavailable in digital format and as separate water level data is available from a 1999 MHL study, water levels from the 1986 study were not used in this study. NSW Food Authority maintain an additional water level and salinity sensor in lower Honeymoon Bay 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 on Wagonga Inlet and relevant ocean tide gauges**

| Water level gauge | Location label | Station number | Provider | Date range | MHL report number |
|---|---|---|---|---|---|
| Bermagui | – | 219470 | MHL | 1987 – present | – |
| Eden | – | 220470 | MHL | 1970 – present | – |
| Narooma Public Wharf | 1 | – | MHL | 30/08/1996 – 04/01/1998 | MHL888 |
| Barlows Bay | 2 | 218415 | MHL | 1996 – present | – |
| Lower Honeymoon Bay | 3 | – | NSW Food Authority * | 2022 – present | – |
| Eastern Lagoon (South) | 4 | – | 2023 fieldwork | 03–06/07/2023 | – |
| Western Lagoon | 5 | – | 2023 fieldwork | 03–07/07/2023 | – |
| Eastern Lagoon (North) | 6 | – | 2023 fieldwork | 06–07/07/2023 | – |
| Narooma boat ramp | 7 | – | 2023 fieldwork | 03–07/07/2023 | – |

* 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 on Wagonga Inlet**

| Tidal flow gauge | Location label | Date | Study |
|---|---|---|---|
| Wagonga Entrance | A | 03/12/1986 | MHL499 |
| Narooma Bridge West | B | 03/12/1986 | MHL499 |
| Narooma Wharf | C | 06/07/2023 | 2023 fieldwork |
| Narooma Boat Ramp | D | 07/07/2023 | 2023 fieldwork |
| Narooma Bridge East | E | 07/07/2023 | 2023 fieldwork |
| Honeymoon Bay | F | 07/07/2023 | 2023 fieldwork |

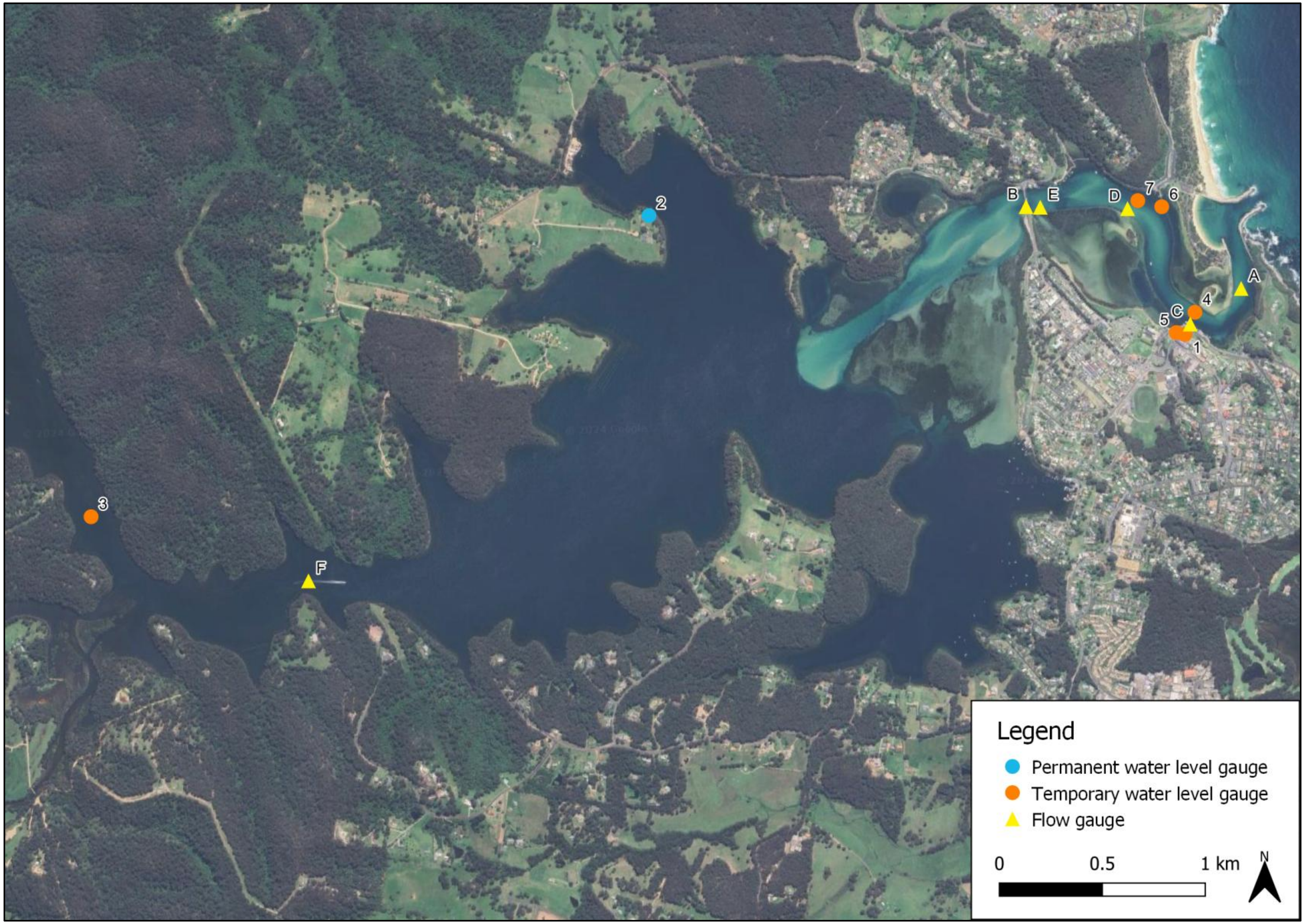


**Figure 2-1 Water level and tidal flow gauging locations**

## 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 Wagonga estuary. No catchment inflow gauges within the Wagonga catchment were available thus, to estimate catchment inflows, flows were scaled from the closest WaterNSW station: Narira River at Cobargo (23 km to the southwest), operational from 1965 to the present. Table 2-4 lists the model boundaries, the gauges 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).

Note that the lack of gauged catchment inflows within the Wagonga Inlet catchment means that cathment inflows are highly uncertain in this area. However, IFD relationships and design rainfalls from the 2016 Australian Rainfall and Runoff Guidelines are similar for both the gauged and model inflow cacthements (BoM, 2016). Moreover, senstivity tests completed in the modelling stage of this project demonstrate that the results are not sensitive to catchment inflows, so this is not regarded as a significant limitation for this project. This is discussed further in Section 5.3.2.

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

| Model boundary | Base WaterNSW gauge | Scaling factor |
|---|---|---|
| Billa Bilba Creek* | 219016 | 0.54 |
| Punkally Creek* | 219016 | 0.25 |

*This catchment was ungauged, so the gauge in the nearby Narira River catchment was scalled 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 | Narira River at Cobargo (219016) ML/d *($m^3$/s)* |
|---|---|
| 5th | 0.0 *(0.0)* |
| 20th | 0.52 *(0.01)* |
| 50th (median) | 5.4 *(0.06)* |
| 80th | 26 *(0.30)* |
| 95th | 198 *(3.3)* |

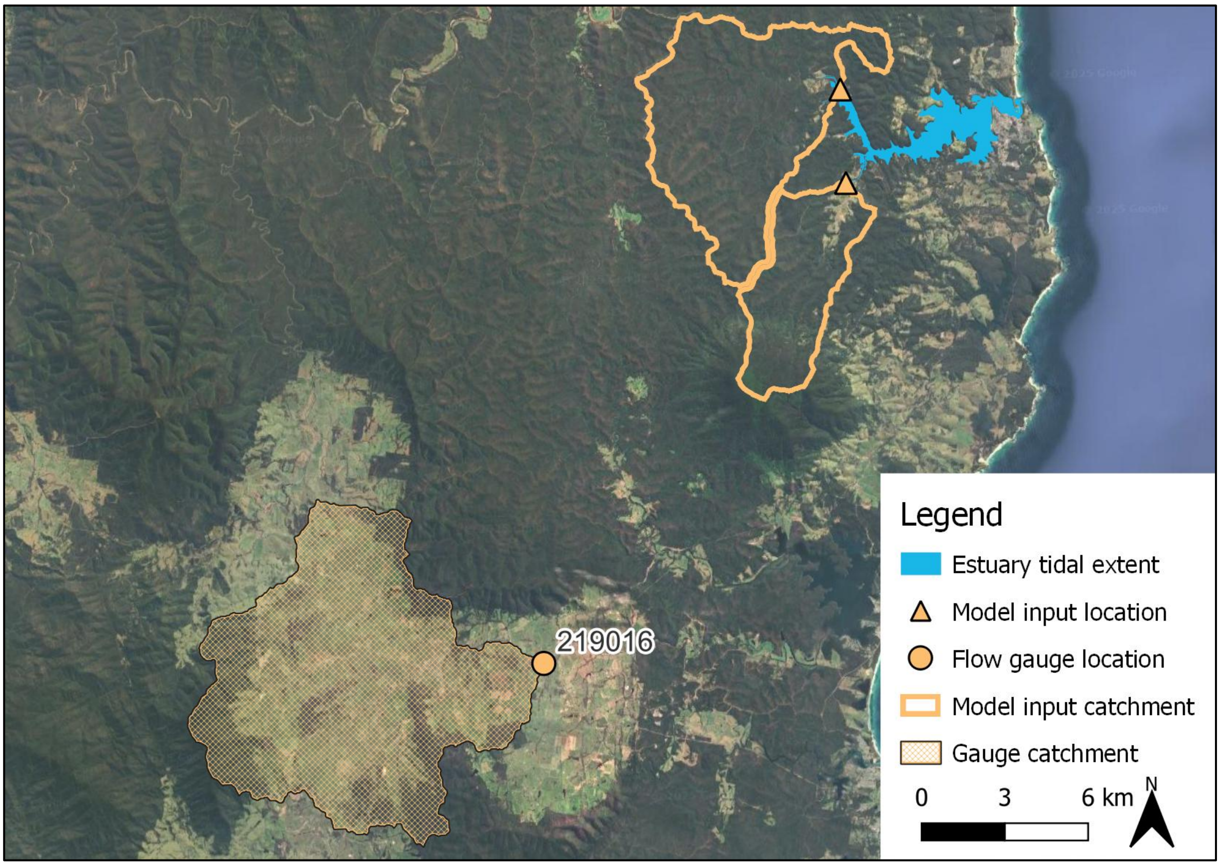


**Figure 2-2 Catchment flow gauging stations***

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

## 2.4 Sewage overflow data

Eurobodalla Shire Council (ESC) is the agency responsible for wastewater treatment and sewage management in the catchment surrounding the Wagonga estuary. The sewerage system is comprised of a reticulation network of pipes and sewage pumping stations (SPS), in addition to the Kianga wastewater treatment plant (WWTP). When sewage overflows occur, ESC 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.

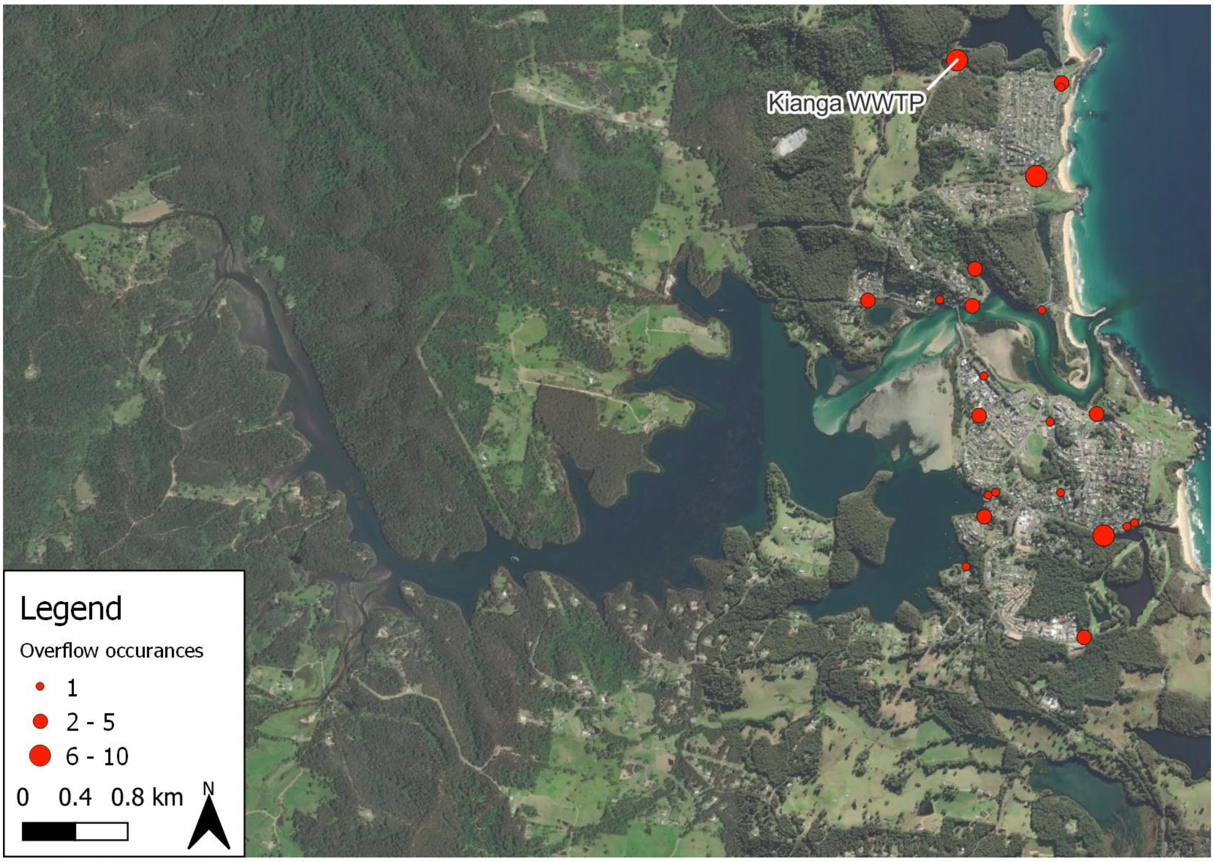


**Figure 2-3 Locations of reported sewage overflows in Wagonga Inlet**

## 2.5 Bathymetry

Three 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 Wagonga Inlet region, this survey covers areas within 1 km of the coast and corresponds to all estuary regions east of Narooma Bridge (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. Several regions of the survey extent were noted to have no data values, particularly in deep sections of the main channel.
- Single beam bathymetry data collected in 1997. 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 lower estuary at 20 m transect spacing, with the lake and upper estuary covered at a transect spacing of 50 to 100 m (refer to Figure 2-5). This dataset was used in regions not covered by the marine LiDAR.

For areas where the 1997 single beam survey overlapped with the 2018 marine LiDAR extent, the difference in depth was investigated (refer to Figure 2-6). Covering between Narooma Bridge and the entrance mouth (including the two lagoon systems), 65% of the sampled readings had a difference of <50 cm, while the remaining 35% varied by 0.5 to 2.5 m. Areas associated with large changes in bathymetry corresponded to scour and sand bar regions of the main channel. In most places, the channel deepened by around 0.25 to 1 m, as is consistent with the trend of increasing channel efficiency since the instillation of the training walls (Nielsen and Gordon, 2016). Based on aerial imagery, it is apparent that the sand bars and shoals within the main entrance channel and immediately west of Narooma Bridge are mobile but appear to be in a state of dynamic equilibrium with no obvious long-term trends.

Additional bathymetric, topographic, and aerial data utilised include:

- 1 x 1 m DEM LiDAR data, collected in 2012 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.
- NAVONICS SonarChart™ 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.

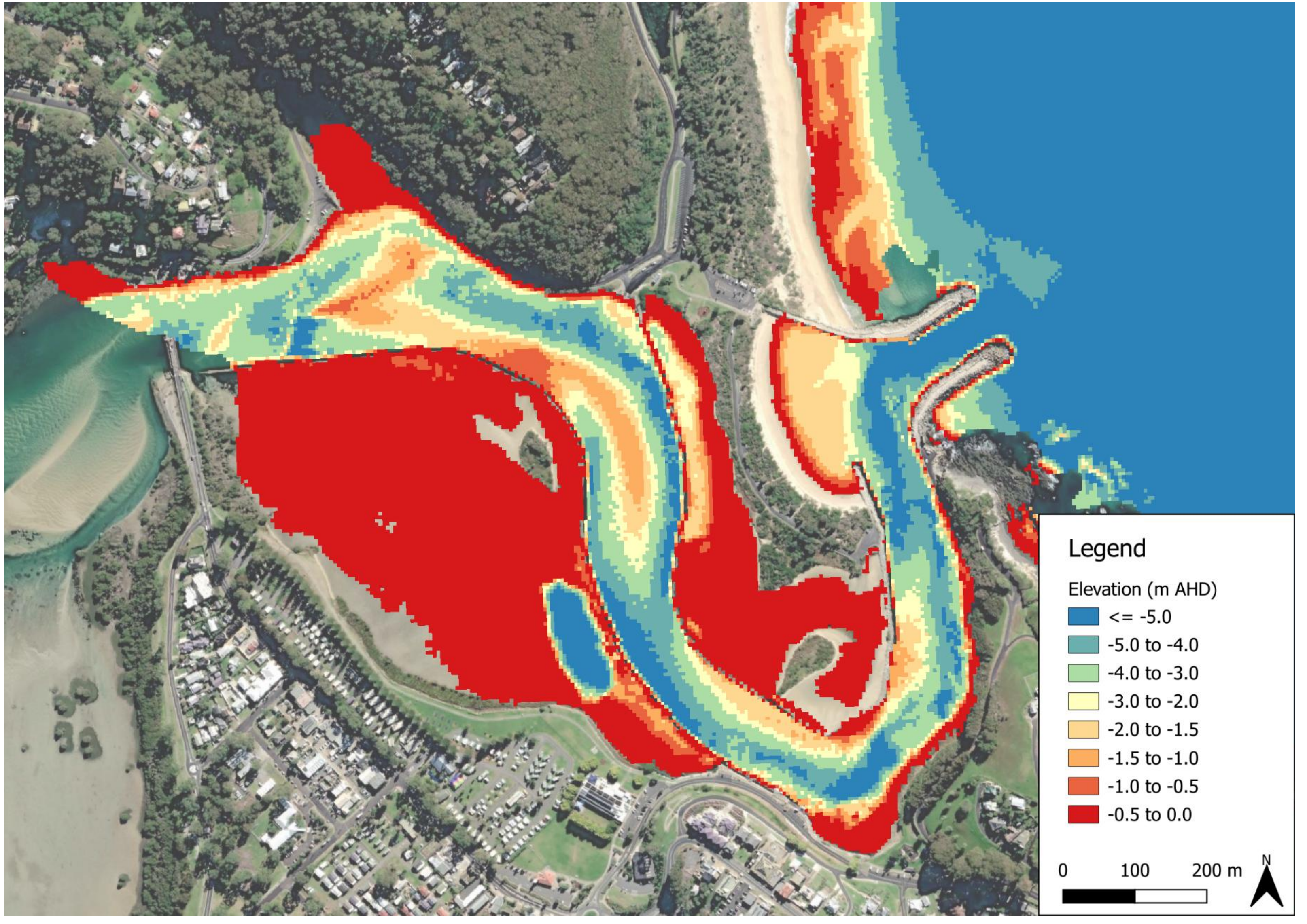


**Figure 2-4 Coverage of 2018 LiDAR survey**

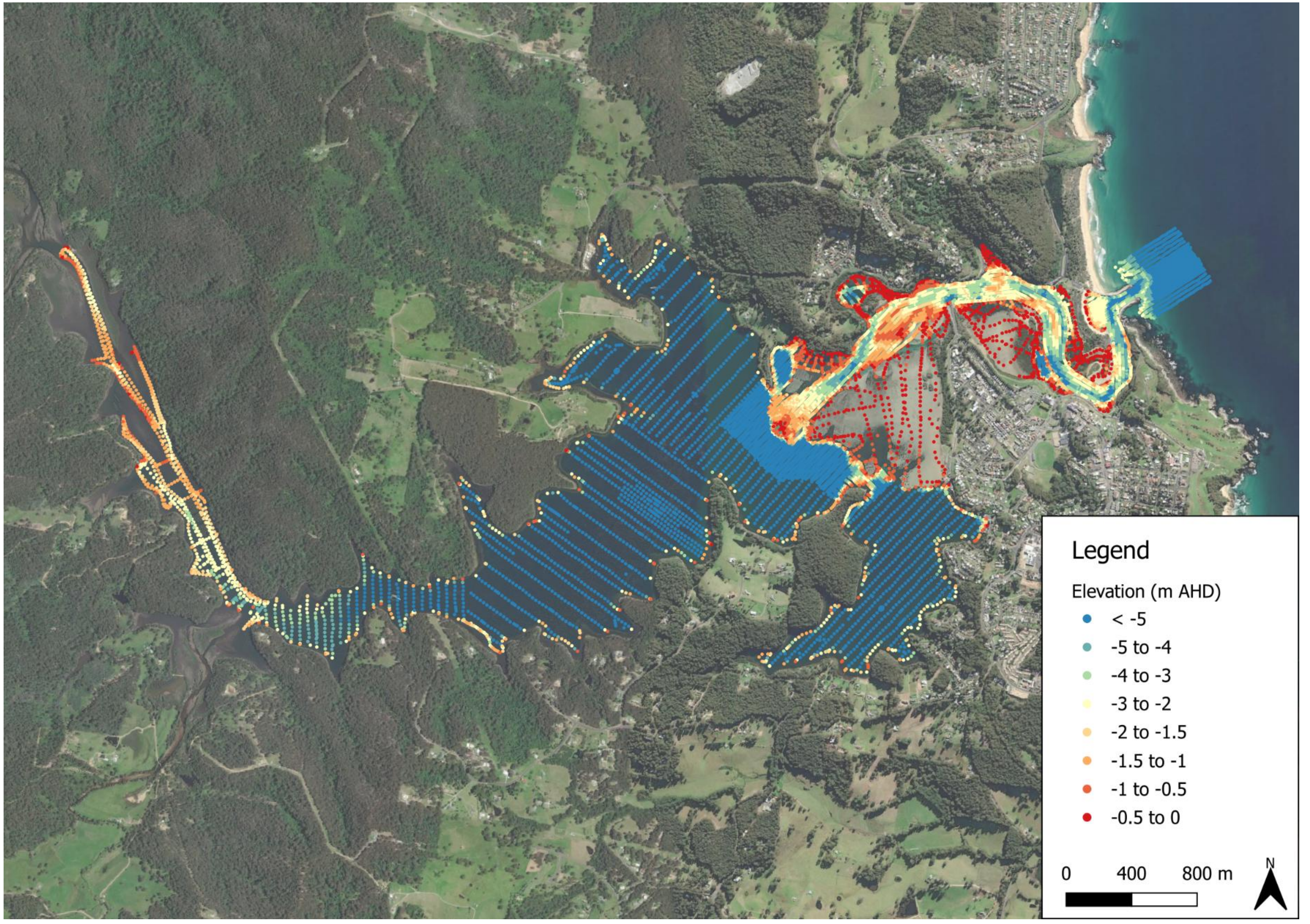


**Figure 2-5 Coverage of 1997 single beam survey**

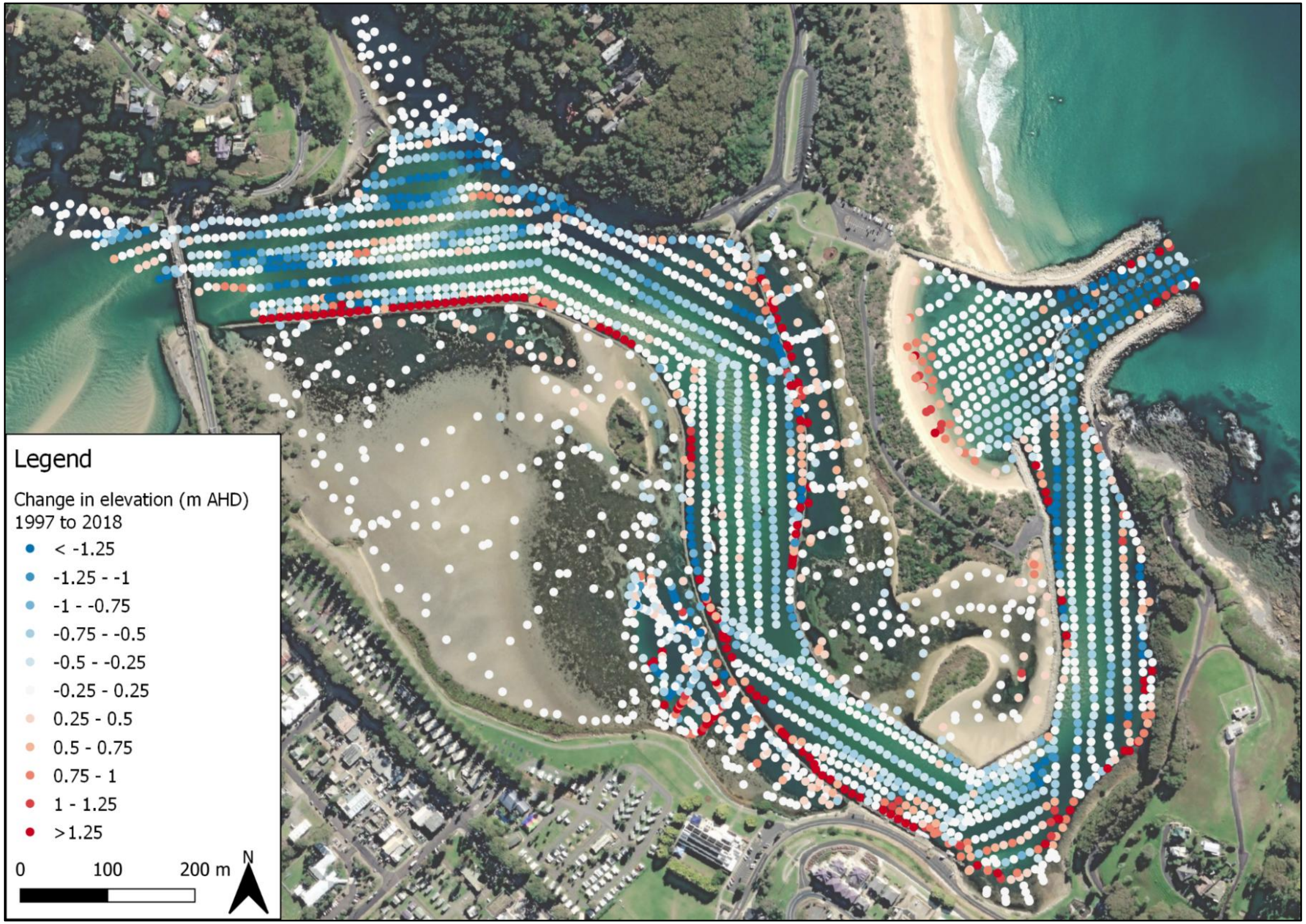


**Figure 2-6 Bathymetry change between 1997 survey and 2018 marine LiDAR. Blue corresponds to erosion and red accretion**

# 3 Field data collection

## 3.1 Preamble

A data collection campaign was completed on 6 and 7 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
- Monitoring of water level data and collation of data from MHL water level monitoring sites
- Conductivity measurements
- RTK-GPS survey of the Wagonga Inlet eastern and western training walls

## 3.2 Weather and tides

Data collection on Wagonga Inlet was undertaken on both ebb and flood tides. Tides during field investigations were similar both days, with relatively small tidal ranges between approximately -0.40 to 0.40 m AHD recorded at Bermagui. The observed water levels at Bermagui, alongside the timing of key fieldwork components is shown in Figure 3-1. Predicted and observed tides at the Bermagui ocean tide station are shown in Figure 3-2. The sensor appears to have gone dry at around -0.55 m AHD. This did not occur during other gauging periods, such as the 2019 tides used for scenario runs. The increased residuals at these low tides should be ignored. Other residuals were small, although there was an increasing positive anomaly towards the end of fieldwork, as barometric pressure decreased (MHL, 2023a).

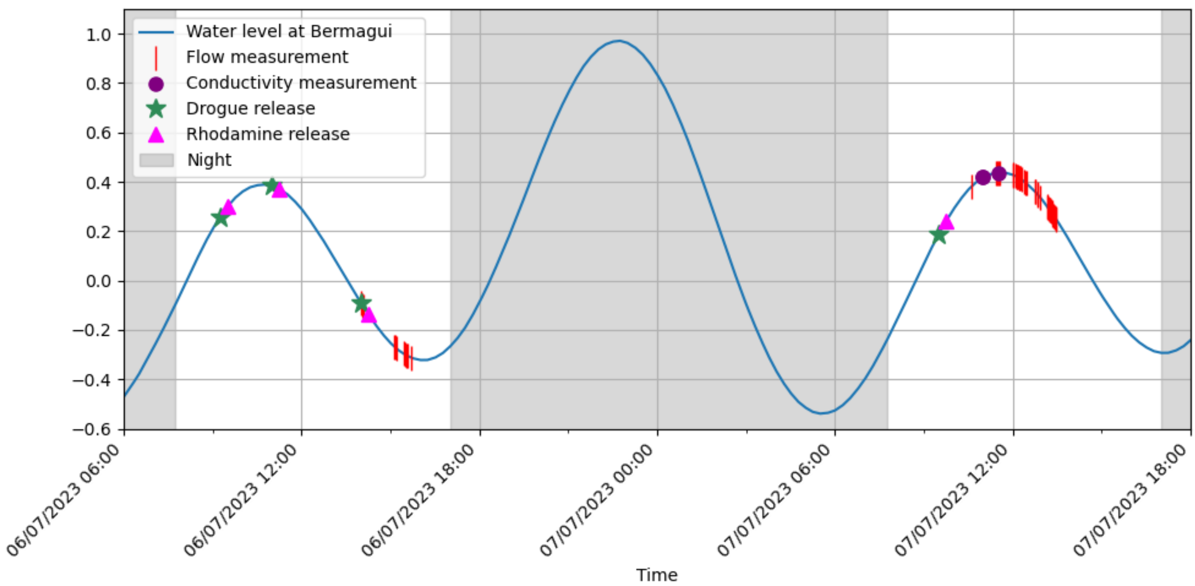


**Figure 3-1 Tides at Bermagui with timing of key data collection events**

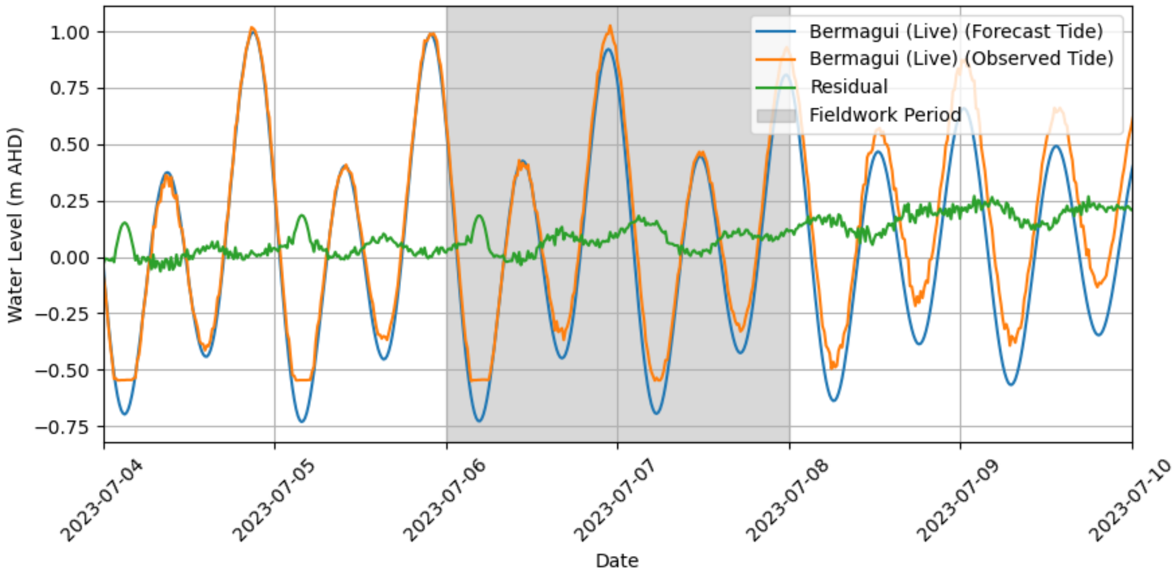


**Figure 3-2 Forecast and observed tides at Bermagui**

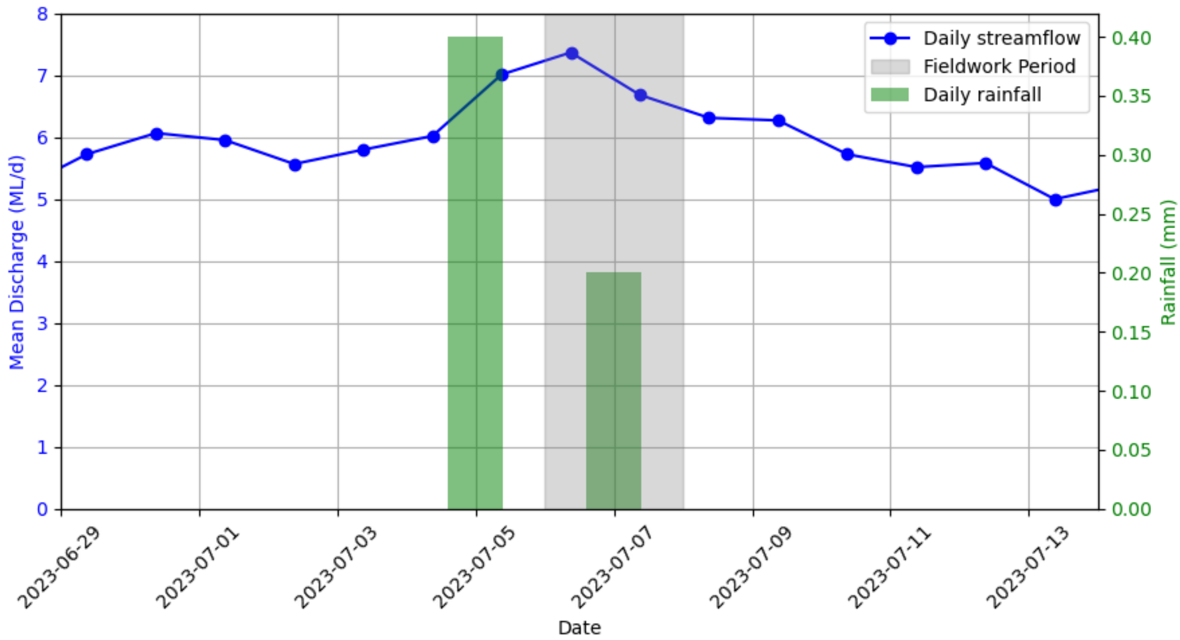


**Figure 3-3 Rainfall recorded at Narooma and streamflow recorded at Narira River at Cobargo for the period surrounding fieldwork**

No rainfall was observed in the field during fieldwork, and only negligible rainfall was recorded during the fieldwork and the preceding week at Narooma Marine Rescue (BoM station 069022), as can be seen in Figure 3-3. Freshwater inflows in the nearby Narira River catchment were low (as can be seen in Figure 3-3, approximately equal to median flows, discussed in Section 2.3). Light northwest winds of 5 km/h were observed in the morning on both days at Narooma Marine Rescue. Afternoon winds of 10 km/h from the southeast were observed on 6 July, and 20 km/h from the east on 7 July.

## 3.3 Tidal flow gauging

Flow was measured using a boat mounted Workhorse 1200 kHz ADCP at six targeted 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 Wagonga Inlet 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 Appendix to B1.1. Particular attention was given to measuring flow under Narooma Bridge to understand the volume of flow entering the lake system. Additional measurements were taken 100 m east of Narooma Bridge in an attempt to quantify flow out of the western lagoon.

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

| Location | Location label* | 6 July # transects | 7 July # transects |
| --- | --- | --- | --- |
| Entrance | A | - | 5 |
| Narooma Wharf | B | 2 | - |
| Narooma Boat Ramp | C | - | 3 |
| Narooma Bridge (East) | D | - | 6 |
| Narooma Bridge (West) | E | 9 | 17 |
| Honeymoon Bay | F | - | 4 |

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

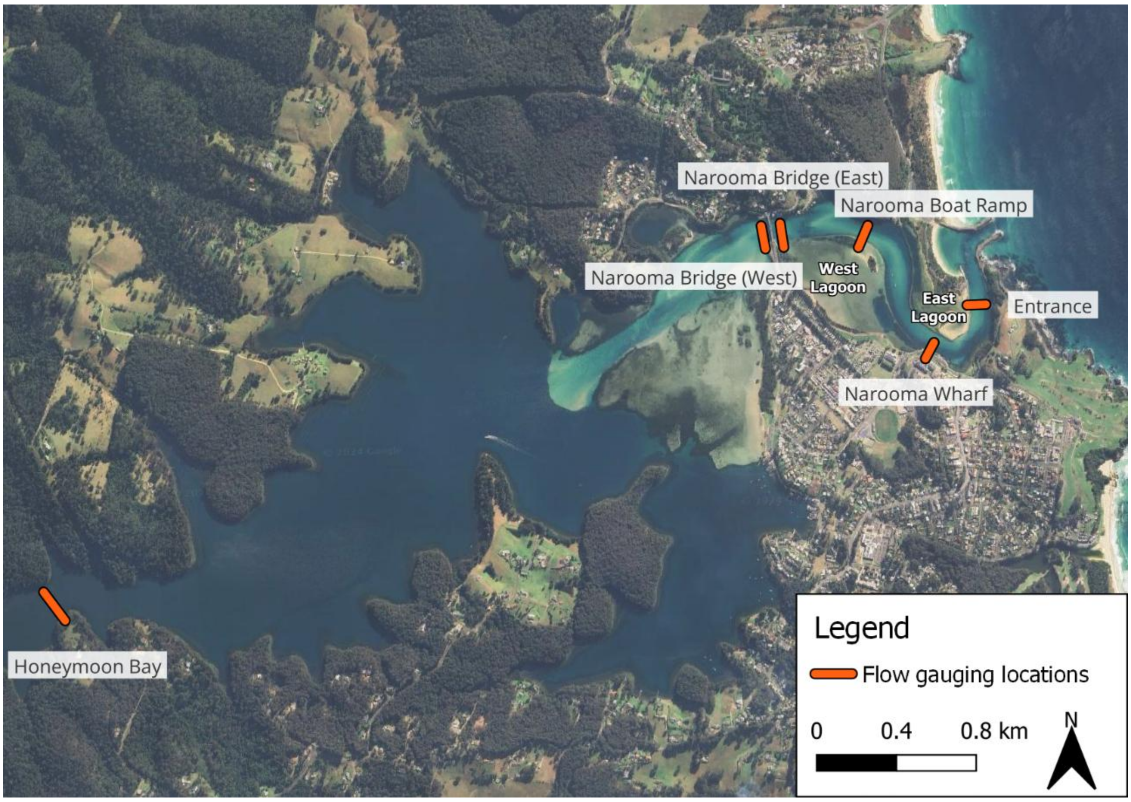


**Figure 3-4 Tidal flow gauging locations from 2023 fieldwork**

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). In addition to gauging sites, additional bathymetry was collected through the main entrance channel east of Narooma Bridge, and west towards the flood tide delta drop off. Bathymetry data for all locations is shown in Figure 3-5, and change between the 2018 LiDAR data and field captured bathymetry is shown in Figure 3-6.

Compared with the 2018 marine LiDAR survey, the 2023 field survey bathymetry results show minor to moderate changes over the last 5 years. The median of the observed bathymetric change is zero, with a standard deviation of 0.5 m. With no clear evidence for net sediment gain or loss, the bathymetric changes likely correspond to a state of dynamic equilibrium between channel scour and sand bar deposition. Key regions of bathymetric change correspond to:

- Deposition and shallowing in the centre of the main channel in the order of 50 cm, particularly towards the ocean entrance.
- Scour and deepening of channel bends of up to 1.5 m, particularly adjacent to the Narooma Boat Ramp and Mill Bay Boardwalk.
- Sand bar migration east of Narooma Bridge with scour underneath the bridge, and deposition further downstream near Mill Bay.

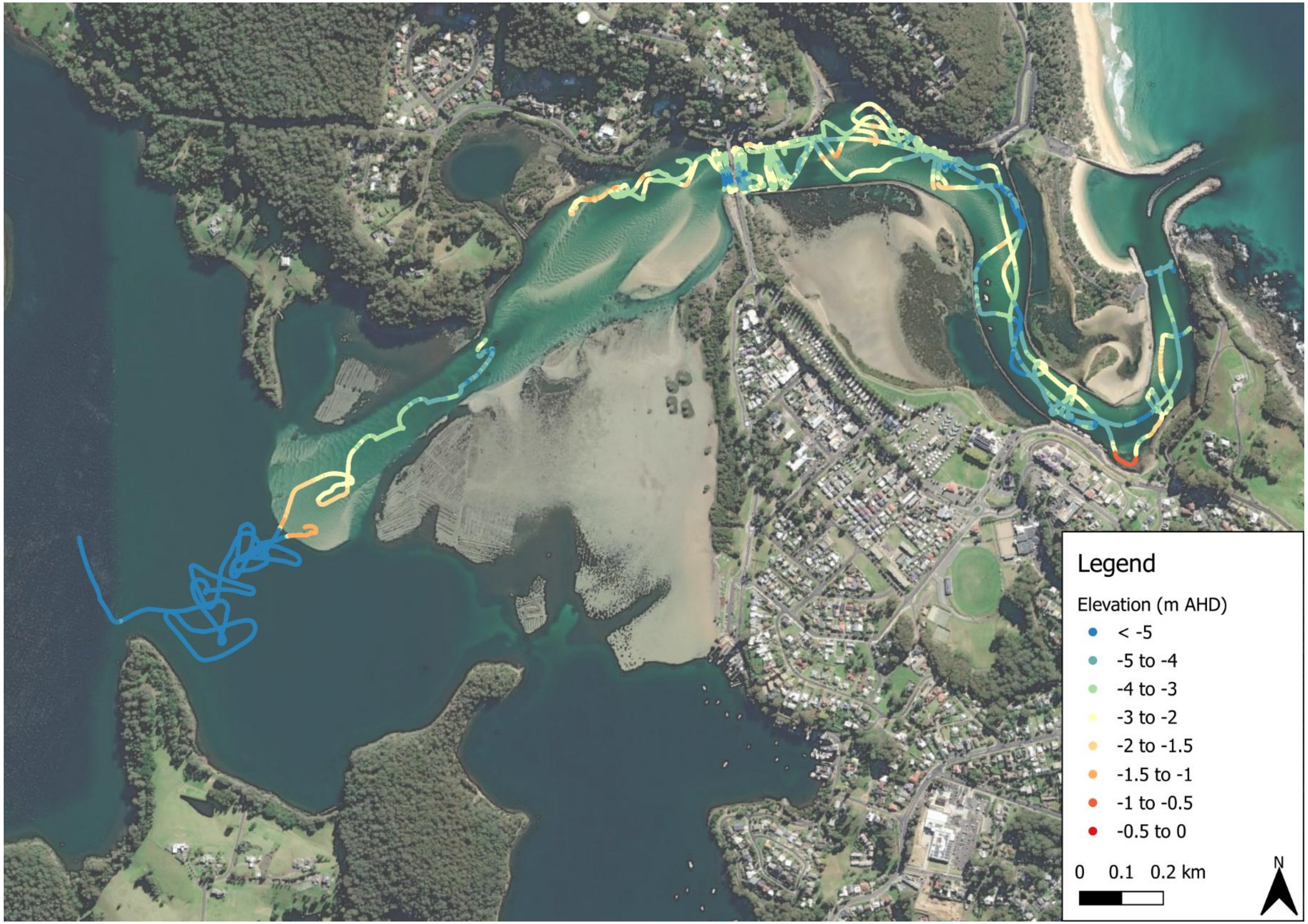


**Figure 3-5 Bathymetry collected during 2023 fieldwork**


**Figure 3-6 Change between 2018 LiDAR and 2023 fieldwork bathymetry. Blue corresponds to erosion and red accretion**

### 3.4.1 Lagoon systems

The eastern and western lagoon systems, located adjacent to the main entrance channel of Wagonga Inlet, are important features with regard to pollutant transport and fate. Both lagoons are bounded by a rock training wall which is overtopped at high tide. Although the rock wall is semi-permeable, both lagoons remain at an elevated water level above the main channel during low tide (refer to Section 3.7). During these periods, any pollutant in the lagoons may remain trapped until flushed back towards the lake on the next incoming tide. This feature may prevent effluent spills from effectively flushing out the heads under certain circumstances. To ensure these breakwaters were accurately captured in the hydrodynamic model, an RTK-GPS survey of breakwater elevation was conducted for regions safely accessible on foot. A map of surveyed data is shown in Figure 3-7.

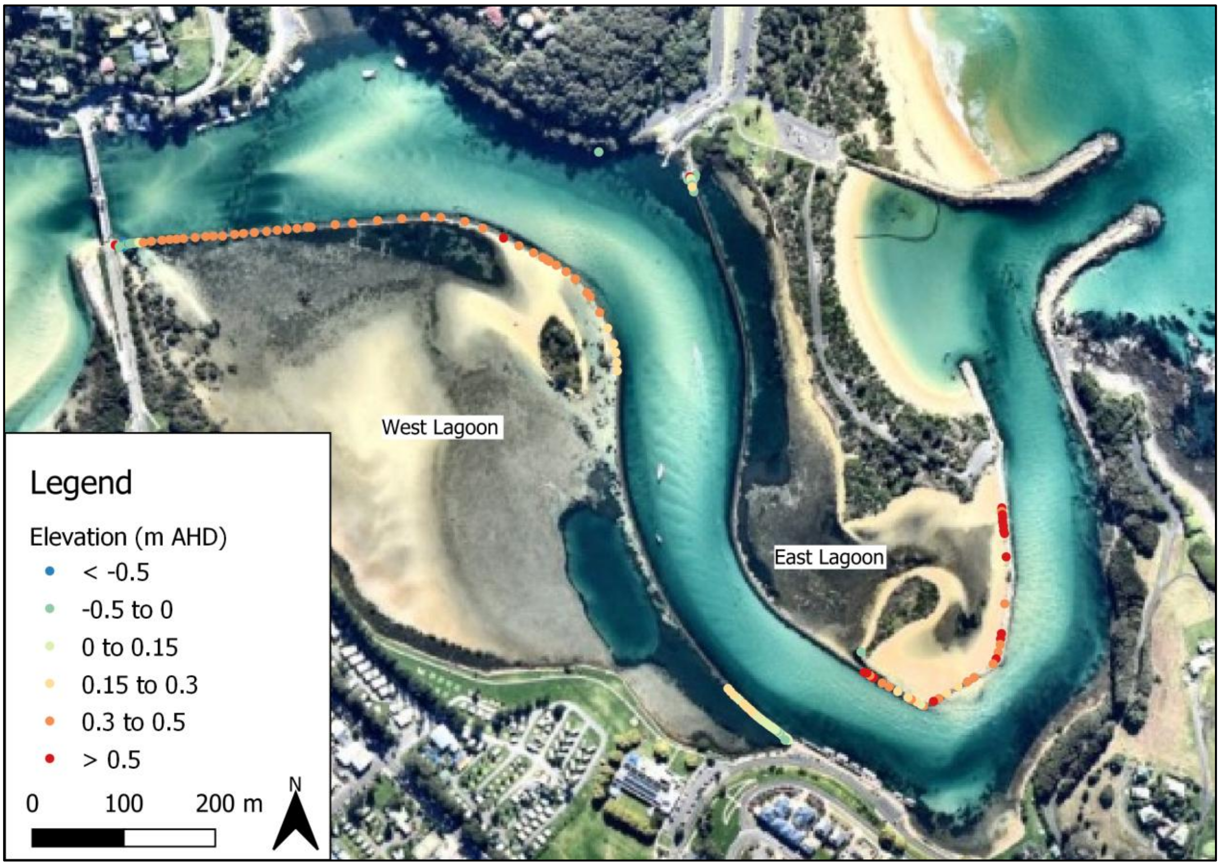


**Figure 3-7 Lagoon breakwater crest survey data**

To get a proxy for breakwater elevation for regions not surveyed, water level from the temporary Narooma boat ramp logger was time matched to images taken in the field during periods where the main channel water level was at the breakwater weir crest (see Figure 3-8 for an example). Based on the survey and crest estimate methods, the breakwater crest elevations were found to vary from -0.1 to 0.4 m AHD with large variability along each length.

**Figure 3-8 Breakwater weir crest estimate using main channel water level**

## 3.5 Rhodamine WT dye releases

To simulate pollutant advection and dispersion in Wagonga Inlet, four Rhodamine WT dye releases were performed over the 2 day field campaign (refer to WRL TR2023/32 Section 4.4 for methods). These are summarised in Table 3-2, with locations shown in Figure 3-9. The initial release concentration is 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 | 06/07/2023 | 9.31am | 10.50am | 500 | Narooma Bridge | Flood |
| 2 | 06/07/2023 | 11.17am | 11.58am | 500 | Narooma Entrance | Flood |
| 3 | 06/07/2023 | 2.21pm | 3.13pm | 500 | Narooma Bridge | Ebb |
| 4 | 07/07/2023 | 9.40pm | 10.33am | 500 | Lavender Point | Flood |


**Figure 3-9 Rhodamine WT dye release locations**

### 3.5.1 Release 1 – Narooma Bridge

Dye release 1 was started mid-channel 100 m west of Narooma Bridge (Figure 3-10). This release was completed to understand transport rates from Narooma Bridge into the Wagonga Inlet lake system and to determine pollutant dispersion rates. The release occurred on an incoming tide, approximately 30 minutes before peak inflow at Narooma Bridge. Dye was released around 9.30am and tracked for 1 hour 15 minutes. Figure 3-11 shows the observed dye concentrations over the period of monitoring, with the maximum plume concentration along select transects highlighted.

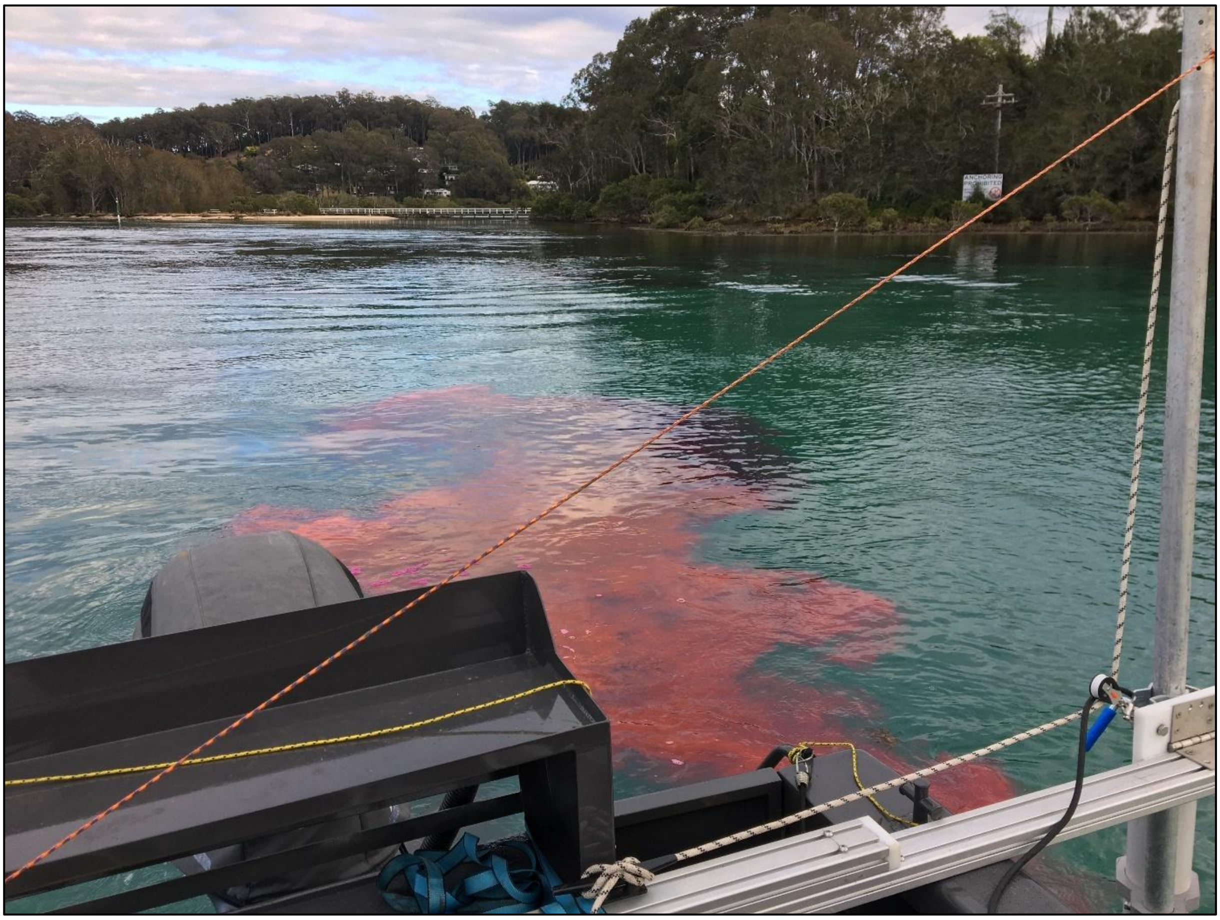

**Figure 3-10 Narooma Bridge flood release immediately after dye drop**

Due to high channel velocities, rapid mixing was observed immediately after the dye release and by 15 minutes, the plume was visually vertically well mixed. The plume continued spreading with decreasing peak concentrations as it moved upstream towards the sand spit drop off at the edge of the lake. Prior to reaching the lake the plume measured approximately 110 x 50 m. No obvious dye excursion was observed outside of the main channel and no dye was observed crossing the southern sand bar. Upon reaching the lake, the length of the plume contracted due to low velocities in the deep (14 m+) water, slowing the front end of the plume. Over the next 45 minutes, the plume slowly travelled southeast across the lake, spreading evenly in all directions. Immediately before dye tracking was finished, the plume measured at 150 x 150 m. Drogues released at the time of dye release were observed to travel further south than the plume after reaching the lake (refer to Section 3.6). This is likely due to light winds observed from the northeast.

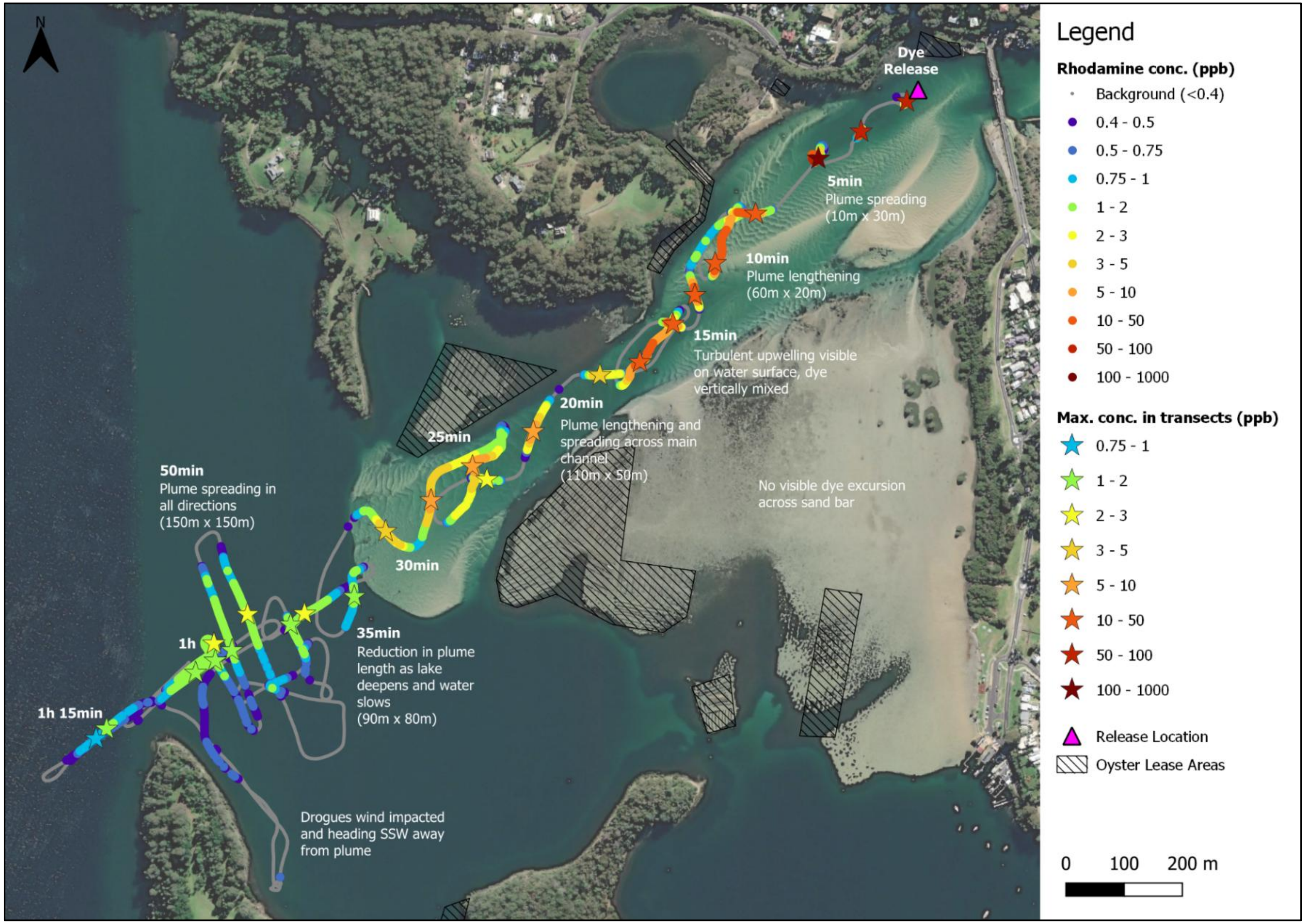


**Figure 3-11 Dye release 1 at Narooma Bridge All observed concentrations (circles) and maximum concentration observed in select transects (stars)**

### 3.5.2 Release 2 – Narooma Entrance

Dye release 2 was conducted mid-channel at the entrance to Wagonga Inlet approximately 300 m upstream of the ocean (Figure 3-12). The aim of this release was to observe plume dispersion in the main entrance channel, and to observe any incursion of dye into the eastern and western lagoons on an incoming tide. The release was approximately 1 hour after peak tidal inflow at the heads and was tracked for 45 minutes from 11.10am. 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 2 after 3 minutes**

Upon release, the plume elongated, spread laterally, and moved rapidly downstream with the fast moving currents. After 5 minutes, the plume measured 10 x 25 m. Around the bend adjacent to Narooma Wharf, further mixing, dilution and spreading were observed in the turbulent flow. Although hugging the inside of the bend, no visible dye was observed entering the eastern lagoon. The plume stayed in the centre of the channel heading north and no dye was visibly observed entering the western lagoon via the lower southern end of the breakwater. As the plume approached Narooma Boat Ramp and rounded the corner, plume mixing and dilution made visual tracking of the plume difficult. The plume was tracked for another 15 minutes, however, the plume had dispersed significantly and was recorded across the width of the channel.

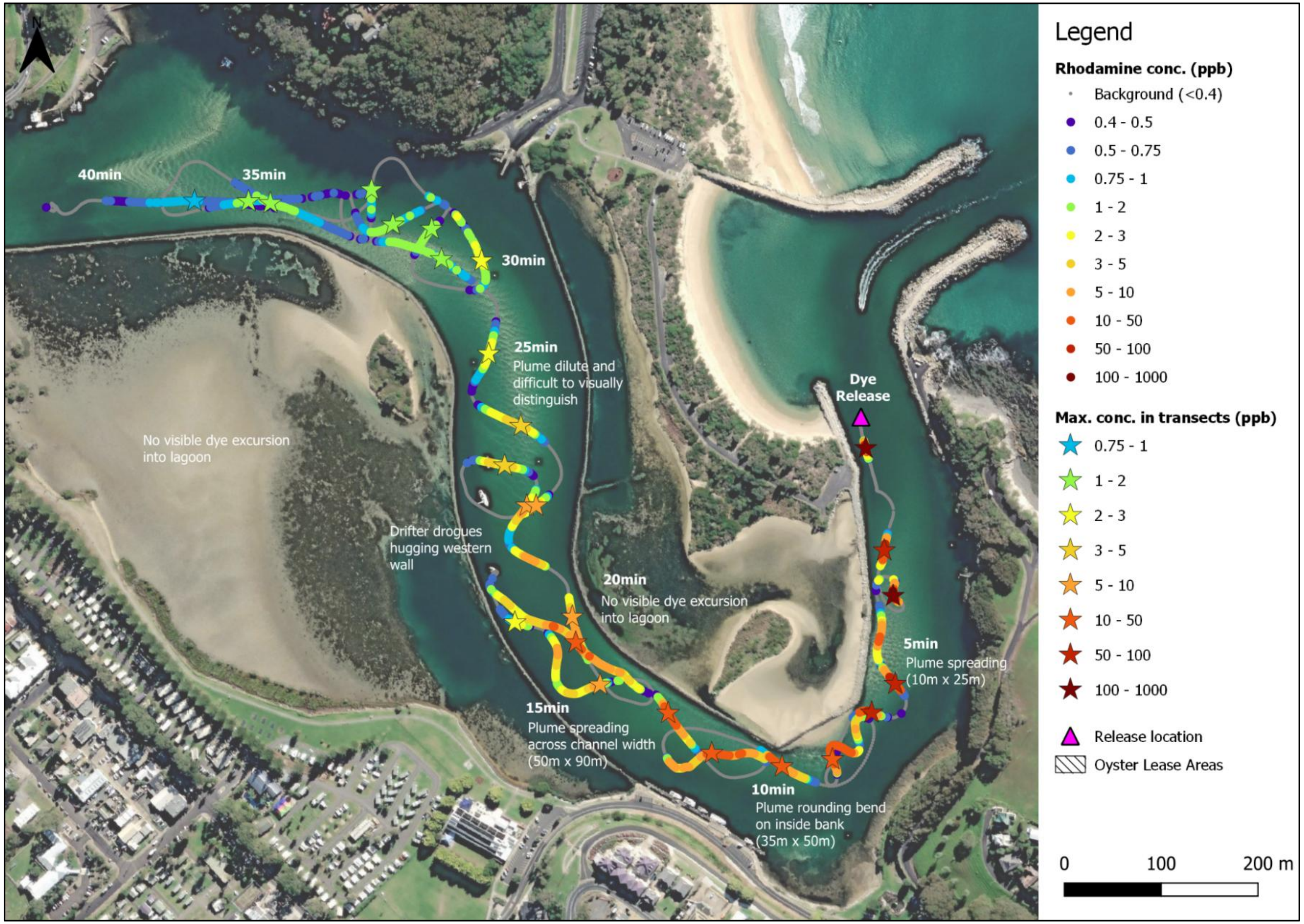


**Figure 3-13 Dye release 2 at Narooma Entrance. All observed concentrations (circles) and maximum concentration observed in select transects (stars)**

### 3.5.3 Release 3 – Narooma Bridge

Dye release 3 was completed mid-channel in Wagonga Inlet approximately 375 m upstream of Narooma Bridge (Figure 3-14). This release was completed to understand plume transport and dispersion rates from Narooma Bridge towards the estuary entrance, and to observe any incursion of dye into the eastern and western lagoons on an outgoing tide. The release occurred on an outgoing tide, approximately 20 minutes before peak outflow at Narooma Bridge. Dye was released around 2.20pm and was tracked for 50 minutes. Figure 3-15 shows the observed dye concentrations over the period of monitoring, with the maximum plume concentration along select transects highlighted.

**Figure 3-14 Dye release 3 after 3 minutes**

Similar to dye release 1 and 2, longitudinal spreading was greater than lateral spreading, and after 10 minutes the plume was approximately 20 by 40 m. As the plume passed under Narooma Bridge, significant mixing was observed with the rapid and turbulent flow around the bridge pylons. Hugging the northern bank of the main channel, dye was observed entering and remaining in the slow moving lagoon of Mill Bay. As the plume continued along Mill Bay boardwalk and past Narooma boat ramp, further mixing made visual tracking of the plume difficult. A fixed rhodamine sensor in the northern end of the eastern lagoon did not detect any dye incursion over the breakwater. The boat was then driven ahead of the plume, and consecutive transects made across the width of the channel at Narooma Wharf to capture the plume width and peak as it flowed past. The plume was observed at Narooma Wharf on the shallow northern bank and not in the deeper channel on the southern bank.

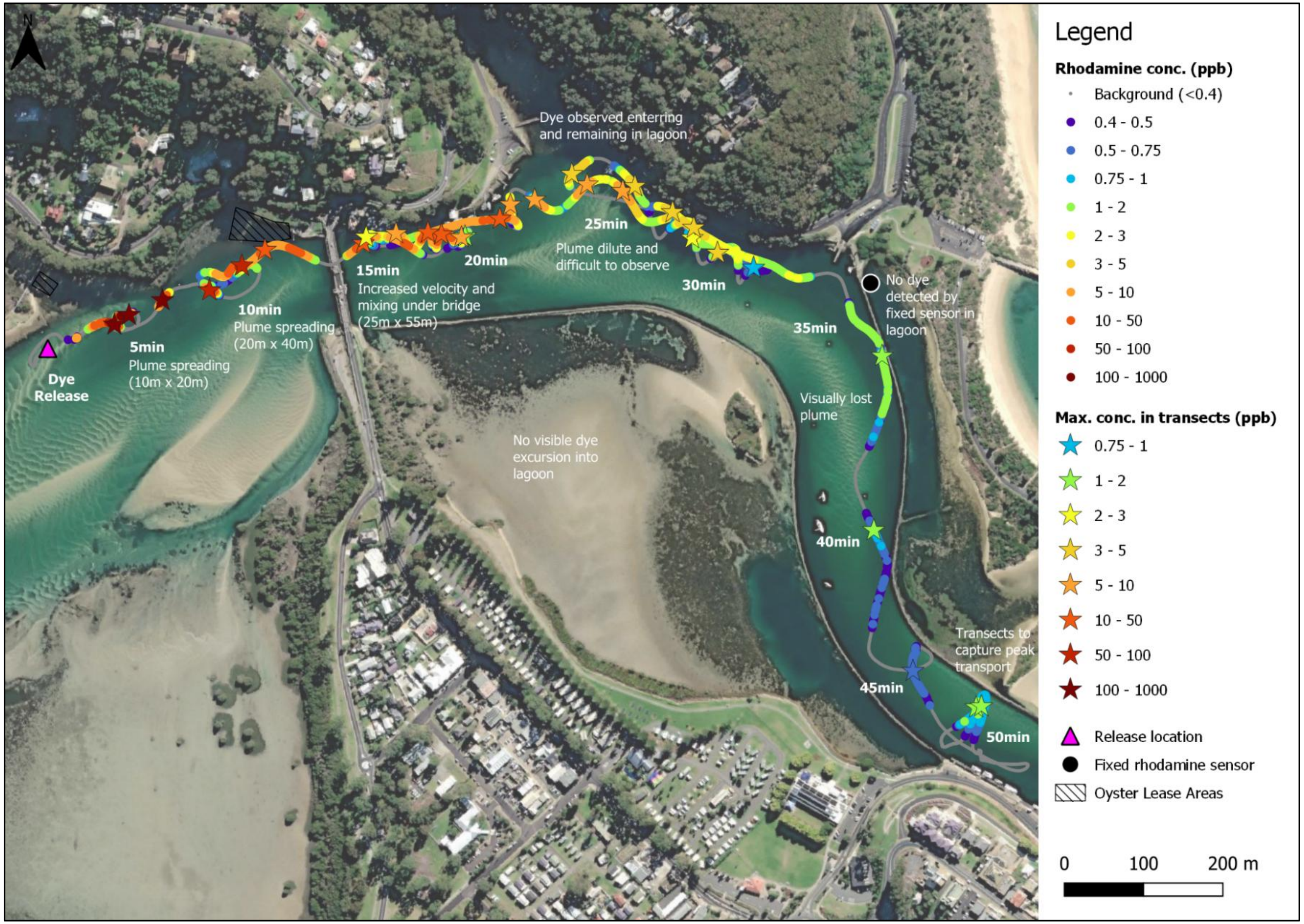


**Figure 3-15 Dye release 3 at Narooma Bridge. All observed concentrations (circles) and maximum concentration observed in select transects (stars)**

### 3.5.4 Release 4 – Lavender Point

Dye release 4 was released mid-channel approximately 400 m downstream of the sand spit drop off at the lakes edge. This release was completed to better understand the transport and dispersion of plumes moving from the fast-flowing main channel into the slow-moving lake system. The release occurred on an incoming tide, approximately 1 hour before peak outflow at Narooma Bridge. The dye was released at 9.30am and was tracked for 50 minutes. Figure 3-17 shows the observed dye concentrations over the period of monitoring, with the maximum plume concentration along select transects highlighted.

After the initial dye release, rapid vertical mixing was observed in the turbulent flow. A vertical depth profile was conducted and the plume was found to be well mixed over the 3.5 m water column. After 15 minutes, the plume reached the channel drop off into the lake. Similar to release 1, the length of the plume reduced as it entered the slow moving, deep water. Over the lip of the drop off, vertical mixing was observed and the plume became less visually discernible (refer Figure 3-16). Ten minutes after reaching the lake edge, another vertical profile was conducted. This profile demonstrated the presence of dye over the 14 m water column, however a linear gradient from 0.5 ppb at the bed to 4 ppb at the surface was observed. Another profile 15 minutes later indicated a vertically well mixed water column at a concentration of 1-2 ppb. Drifter drogues were released at the same time as the dye release (refer to Section 3.6). The northernmost drogue continued past Ringlands Point into the lake, while the southernmost drogue travelled south towards Ringlands Bay. These bounds roughly matched the observed boundary and trajectory of the plume.


**Figure 3-16 Dye release 4 after reaching the lake edge drop off**

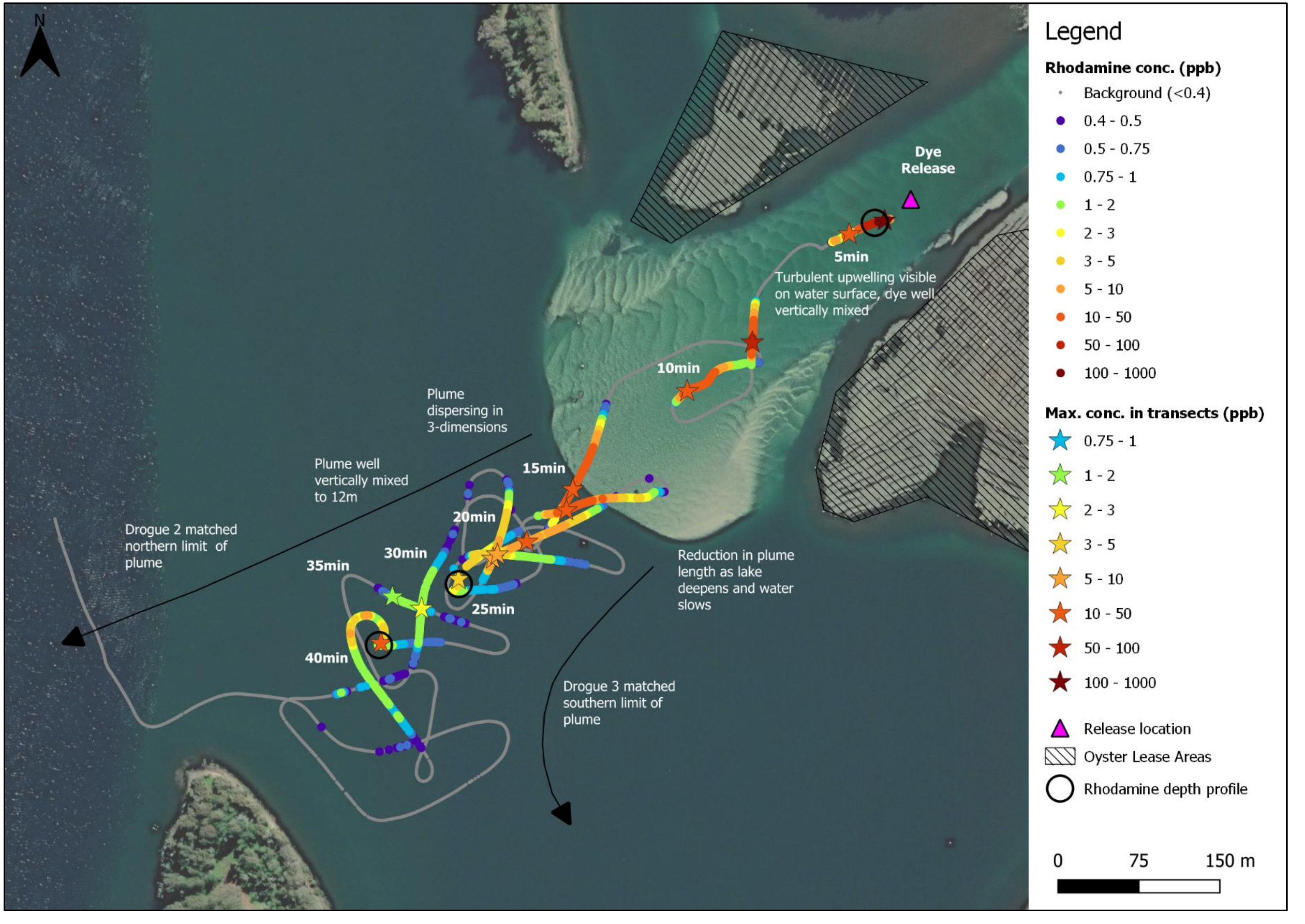


**Figure 3-17 Dye release 4 at Lavender Point. All observed concentrations (circles) and maximum concentration observed in select transects (stars)**

### 3.5.5 Field derived dispersion values

Field dye experiments were used to obtain estimates of plume spreading dispersion rates in Wagonga Inlet, 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 3-18.

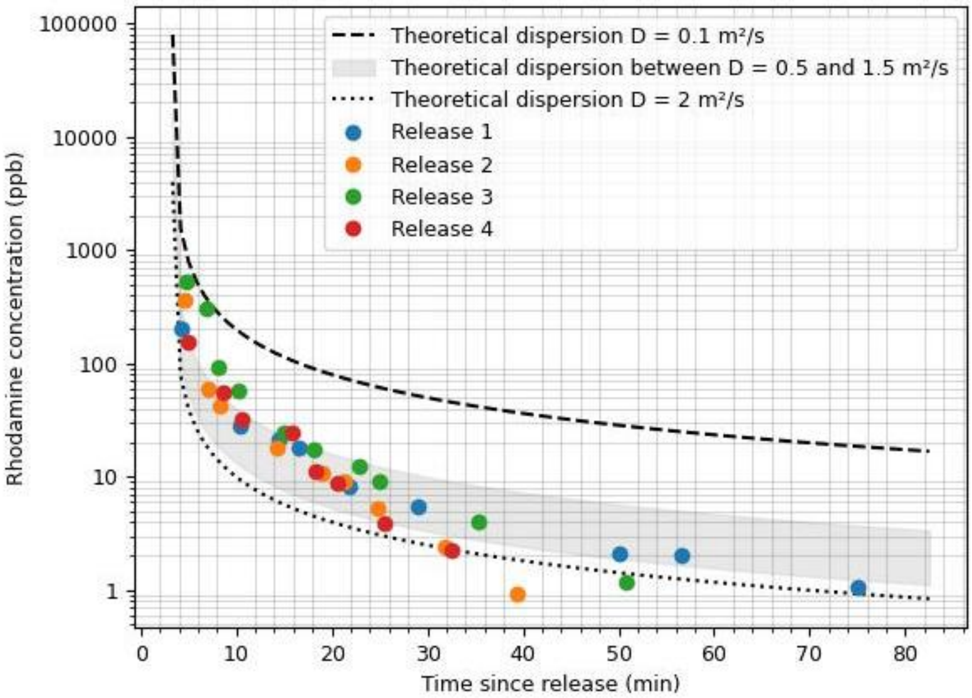


**Figure 3-18 Peak concentration of transects plotted against theoretical dispersion**

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 $m^2/s$, which was consistent in Wagonga. When comparing the observed peak observations to theoretical dispersion, most field dispersion values fall within D = 0.5 to 1.5 $m^2/s$.

## 3.6 GPS drifter drogue releases

To monitor surface current speeds and flow paths in Wagonga Inlet, 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 four dye releases to aid plume tracking (see 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 | 06/07/2023 | 9.31am | Flood | 1:05 | Narooma Bridge | Released with dye drop 1 |
| 2 | 06/07/2023 | 11.17am | Flood | 0:40 | Narooma Entrance | Released with dye drop 2 |
| 3 | 06/07/2023 | 2.21pm | Ebb | 1:10 | Narooma Bridge | Released with dye drop 3 |
| 4 | 07/07/2023 | 9.40am | Flood | 4:00 | Lavender Point | Released with dye drop 4 |

All drogue releases 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. Although for some drops all four 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 (refer to Figure 3-19).

**Figure 3-19 Longitudinal spreading of drifter drogue units during dye release 2**

For drogue releases 1 and 4, significant variability in drogue tracks were observed after reaching the slow-moving, deep water of the lake. During dye release 1, the drogues separated from the dye plume in the lake and headed south while the plume continued southeast. During dye release 4, there was a larger degree of variability between the drogue tracks, with the northern most drogue continuing into the main lake system, while the southernmost drogue headed south into Ringlands Bay.

## 3.7 Water level monitoring

To supplement the water level data available from the long term MHL water level gauge, water level loggers were installed at four locations during the 2023 fieldwork to capture water levels in the main channel, eastern lagoon and western lagoon. Locations are shown in Figure 3-20. The logger in the Eastern Lagoon was moved from the South to the North on 6 July 2023. The water level data recorded at the other two locations can be seen in the calibration data in Appendix B1.4.


**Figure 3-20 Location of water level monitoring during 2023 fieldwork**

## 3.8 Conductivity measurements

To measure saline intrusion, conductivity profiles were taken in the upper harvest areas of Wagonga Inlet during the fieldwork campaign with a Sontek EXO3, as detailed in WRL TR2023/32 Section 4.7. At all locations, conductivity measured was high (specific conductivity > 52,000 µS/cm), comparable to ocean water, and no vertical stratification was detected.

# 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 campaigns in 1986 and 1997 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.

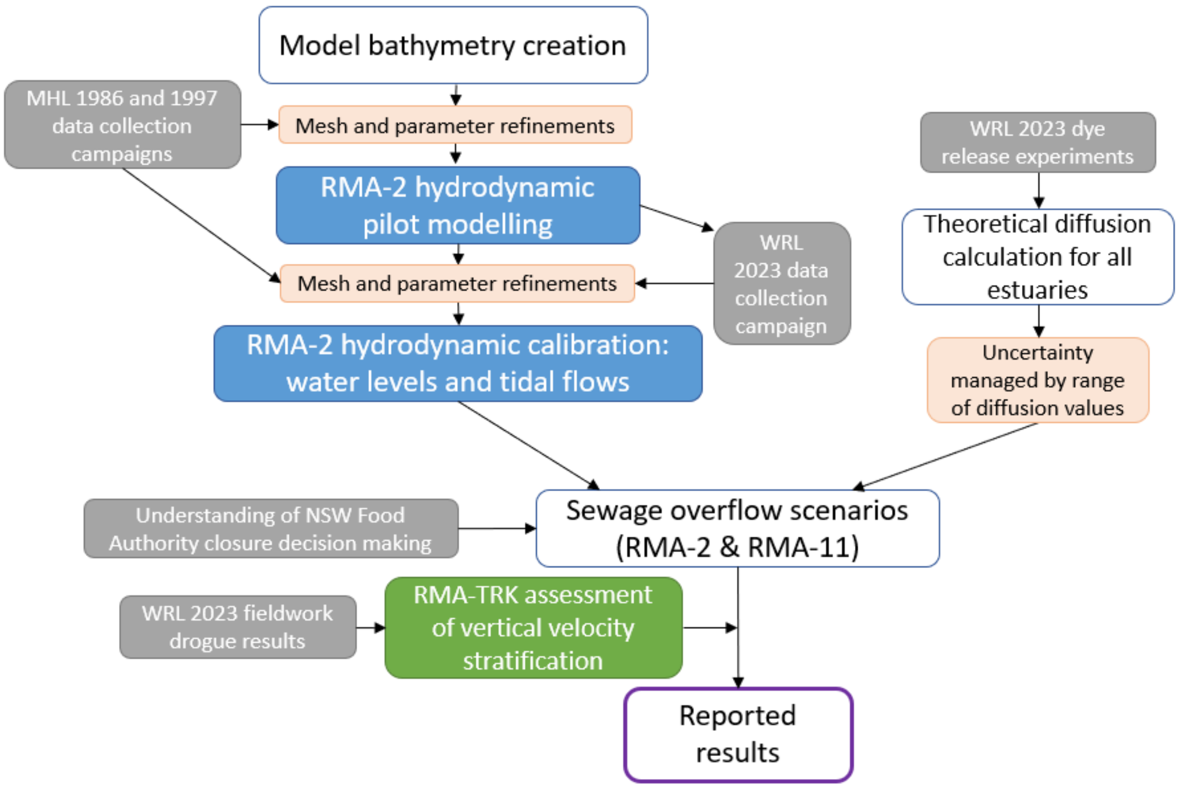


**Figure 4-1: Overview of modelling approach**

## 4.2 Model mesh development

The model domain extends from approximately 1 km offshore of the ocean entrance of Wagonga Inlet, to the tidal limits of the estuary and its major tributaries (refer to Figure 4-2). The model mesh consists of over 13,000 nodes and 5,200 two dimensional elements varying in size from 15 to over 15,000 $m^2$. A two-dimensional, depth averaged model mesh was chosen for Wagonga, where advective transport in the areas of interest (the channels) is largely driven by tidal and riverine flow (not wind). 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, with lower resolution in the upper lake system. Refer to WRL TR2023/32 Section 6.2.3 for a discussion of model resolution. The semi-submerged breakwaters along the edges of the eastern and western lagoons have been modelled as submerged breakwaters in RMA, meaning no marshing (slow seepage below the surface elevation) occurs through these elements.

## 4.3 Model bathymetry

Model bathymetry was based on the sources discussed in Section 2.5 and primarily utilised the 2018 DPIE (now DPE) coastal marine LiDAR topo-bathy survey for the lower estuary. For regions outside of the LiDAR extent, the OEH 1997 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. Breakwater crest elevations were based on survey data and observations from the 2023 field campaign. The lake reaches depths greater than -14 m AHD, however, the majority of estuary channels are around -6 to -2 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 Wagonga estuary has a trained entrance, which prevents extreme short-term changes in the entrance conditions. While change to bathymetry over time is evident in some fast moving sections of the estuary (e.g. movement of sand shoals, or deepening of the channel), as well as evidence of a trend of long term scour, 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 across the main channel across multiple years, discussed further in Section 4.5.

## 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 Wagonga Inlet entrance (refer to Figure 4-2). This modelled water level boundary was based on observed tidal elevation data collected by MHL at Bermagui (station number 219470), or from Eden (station number 220470) for models run prior to the installation of the tide gauge at Bermagui in 1987. 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).

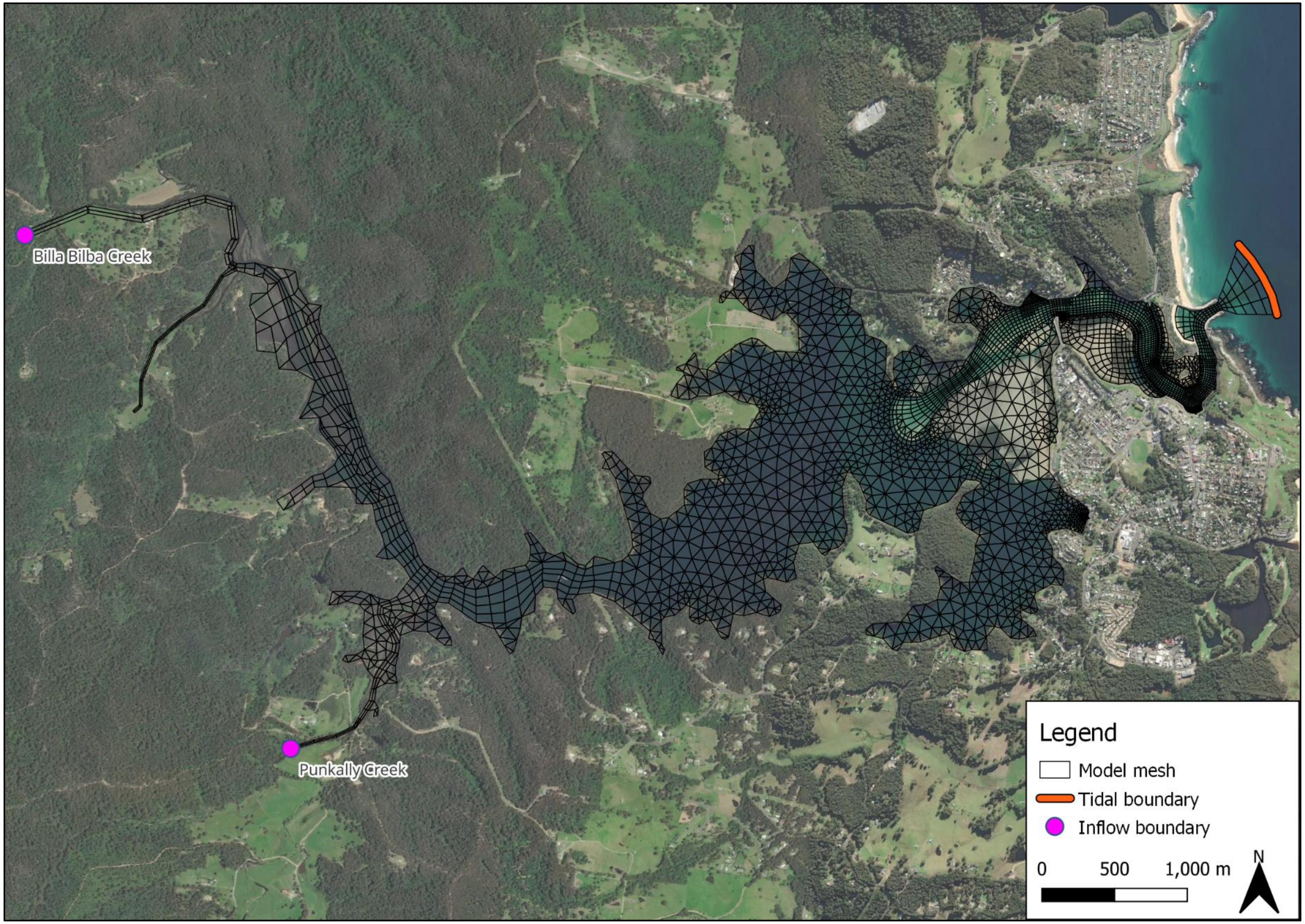


**Figure 4-2 RMA model mesh showing boundary condition locations**

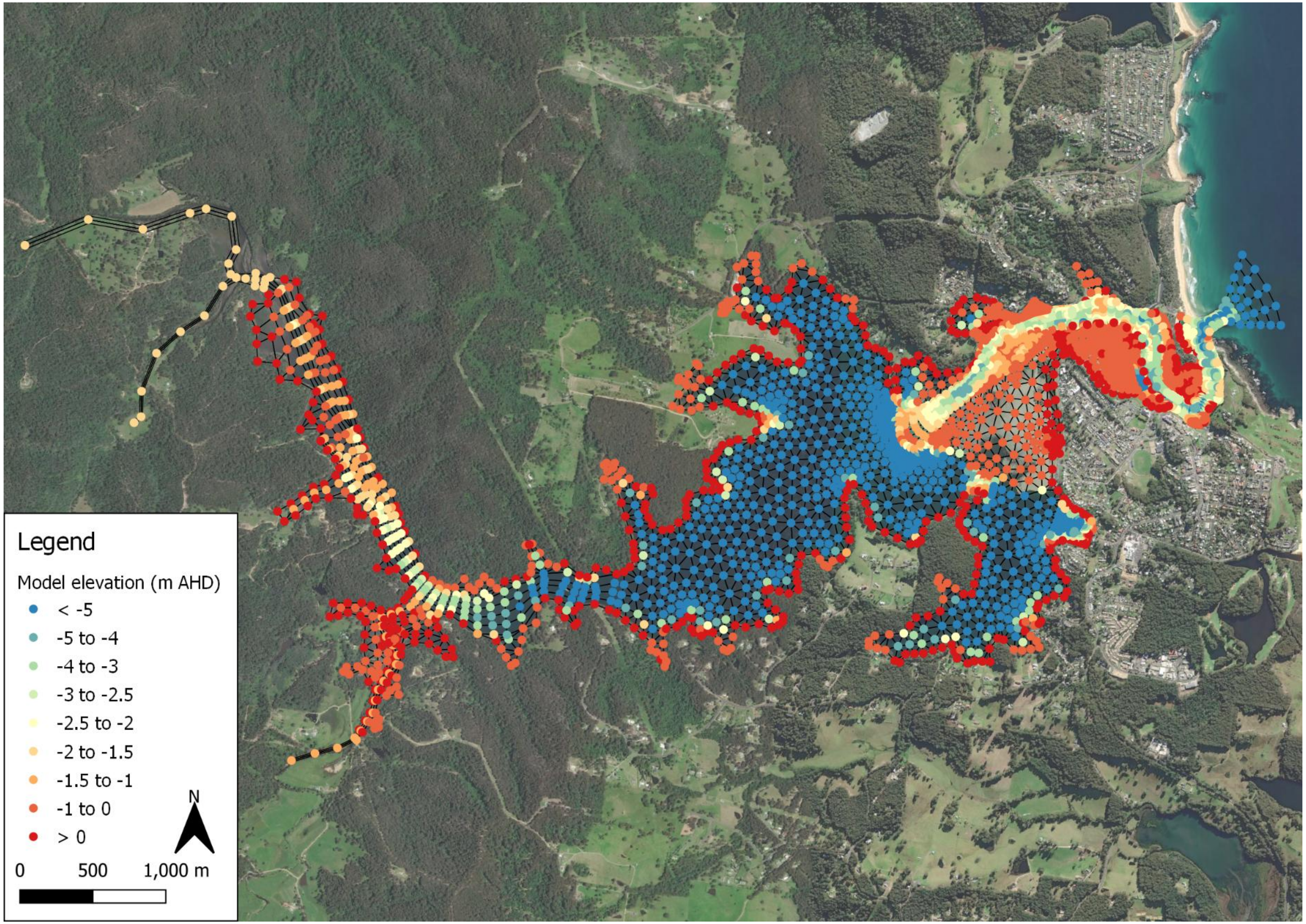


**Figure 4-3 RMA model bathymetry**

## 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 hydrodynamic and elevation information about the eastern and western lagoon entrances.

## 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. Three preexisting sets of hydrodynamic calibration data were available, collected by MHL in 1978, 1986 and 1997 and described in Section 2.2. Due to changes in the bathymetry and hydrodynamics of the system since the construction of the breakwater in the 1970s, the 1986 and 1997 studies were used as calibration datasets for the hydrodynamic model. These were 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 2.4). For each period, a minimum 3 day model warmup period was run.

### 4.6.1 December 1986 calibration period

During the 1997 MHL data collection campaign in Wagonga Inlet, tidal flow data was collected at two transects (refer to Section 2.2). Measured tide levels (from Eden, as this was before operation of the Bermagui gauge) were applied at the ocean boundary and scaled measured catchment inflows were applied at the two upstream model inflow boundaries. All plots of observed water level and flow compared with model results are shown in Appendix B1.1, while select results are shown below.

A reasonable model flow match was achieved for the two MHL flow gauging sites at the entrance and Narooma Bridge (Figure 4-4 and Figure B-3). Timing of the peak outflow and change of the tide were matched, however, the peak magnitude of model flow underestimated observations. This underestimation of flows may be due to the use of the Eden tide gauge, which has consistently lower water levels than the Bermagui tide gauge for periods when they overlap. It could also be caused by bathymetric changes since the data collection campaign. Due to the age of the 1986 data, and lack of nearby driving ocean tides, emphasis was placed on the 1997 water level and 2023 field data calibration runs instead.

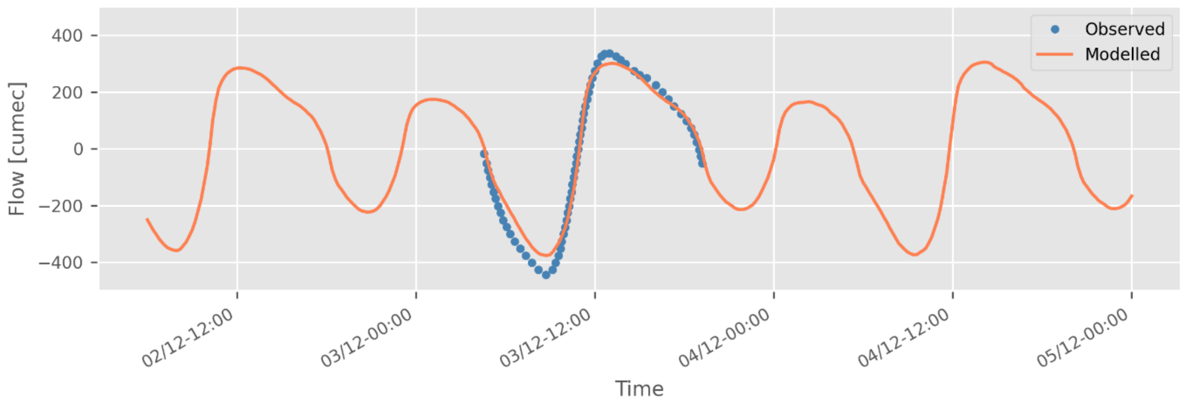


**Figure 4-4 1997 tidal flow calibration – Location A – Wagonga Inlet Entrance**

### 4.6.2 1996 to 1997 water level calibration period

During the 1996 to 1997 MHL water quality data collection campaign on Wagonga Inlet, water level data was collected at two locations (refer to Section 2.2). No tidal gauging data was collected. The model parameters were further calibrated to this period. Measured tide levels were applied at the ocean boundary. Complete catchment inflow data was not available from WaterNSW for this period, thus (based on rainfall records) median catchment inflows were applied at the two upstream model inflow boundaries as constant flows. Plots of observed water level and flow compared with model results are shown in Appendix B1.2.

A reasonable model match was achieved for both water levels at Barlow's Bay and Narooma Wharf (see Figure 4-5). Tidal range is slightly greater and modelled peaks were slightly earlier, as might be expected as channel efficiency increased between 1997 and 2018, the source of bathymetry in the model (see Figure 2-6). However, as the error was minor, only one bathymetry was deemed necessary for this model.

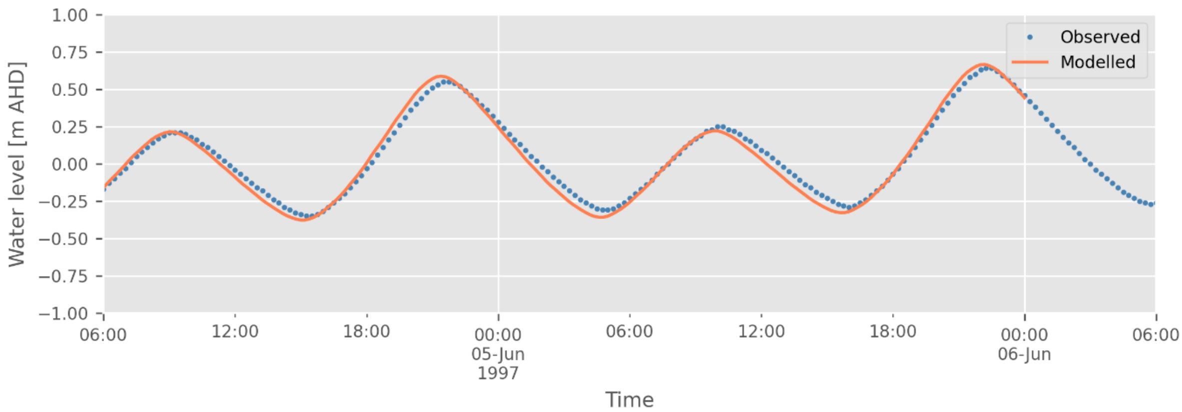


**Figure 4-5 1997 water level calibration – Location 2 – Barlows Bay**

### 4.6.3 July 2023 field data calibration period

The 2023 field campaign involved the collection of tidal flow gauging at six transects, and water level data at six 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 1997 and 1986 model runs. Plots of observed water level and flow compared with model results are shown in Appendix B1.3 and B1.4.

Water level and flow results from the 2023 calibration improved compared to the results from the 1986 and 1997 calibration periods for all locations (see Figure 4-6 for an example) This provides confidence that the model is fit for purpose and best suited for running present day overflow simulations.

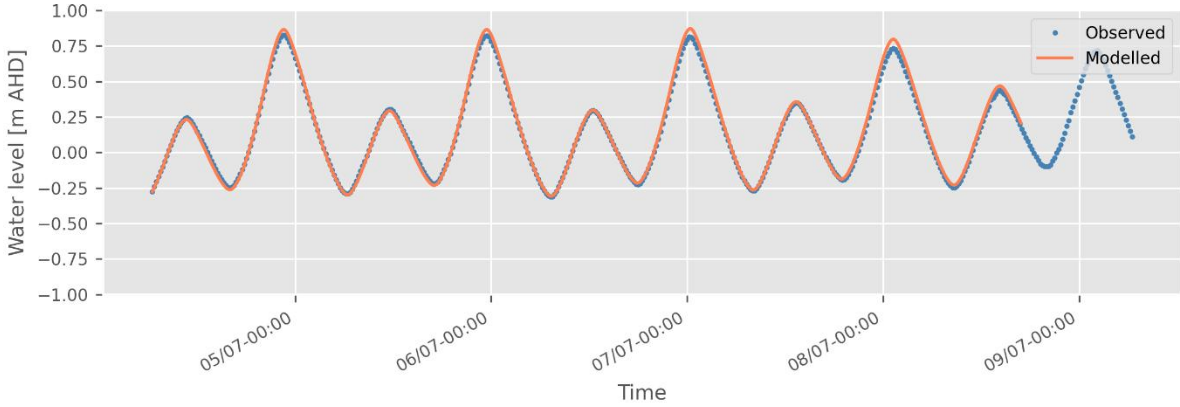


**Figure 4-6 2023 water level calibration – Location 2 – Barlows Bay**

### 4.6.4 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. The rip rap entrances to the lagoons have a higher frictional coefficient to account for the large amount of friction created by the rock.

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

| Location | Manning's n roughness coefficient |
|---|---|
| Entrance to Narooma Bridge | 0.025 |
| Narooma Bridge to Lake | 0.030 |
| Lake | 0.020 |
| Seagrass beds | 0.040 |
| Intertidal areas | 0.050 |
| Rip rap entrances to Eastern and Western Lagoons | 0.200 |

## 4.7 Water quality model development

### 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.

**Table 4-2 Summary of RMA-TRK 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 | Narooma Bridge | Flood | 2.80 | 2.20 | 1.23 |
| 2 | Narooma Entrance | Flood | 2.77 | 1.98 | 1.41 |
| 3 | Narooma Bridge | Ebb | 2.30 | 1.94 | 1.19 |
| 4 | Lavender Point | Flood | 2.80 | 1.76 | 1.6 |

In the Wagonga system, depth varying vertical velocity distributions were observed when comparing drogues to modelled particles, with ratios of an average of 1.4. However, these ratios were similar on the ebb and flood tides, thus do not indicate tidal straining (A. rather than B. on Figure 4-7).

As vertical velocity distributions are tidally symmetrical, net movement of the plume over multiple tidal cycles would remain unaffected, as the surface is travelling faster on both ebb and flood tides. The observed distribution may still affect transport times within a single tidal cycle. However, as travel times are banded by 6 hour (tidal cycle) increments, this is unlikely to have an effect on the reported timing of plume arrival. Hence, despite the observed vertical velocity distributions, no timing adjustments were required for this system.

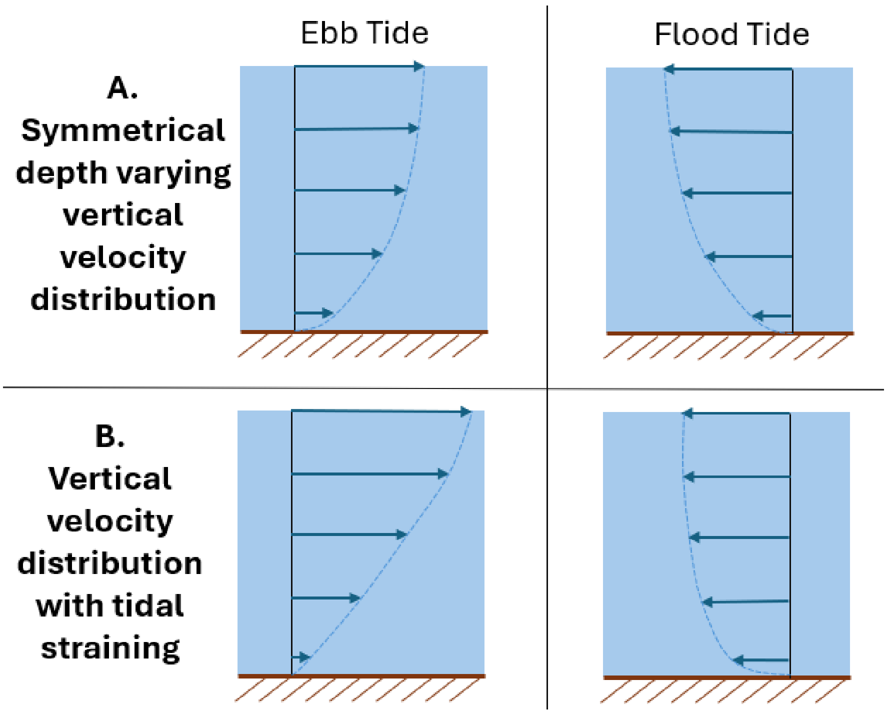


**Figure 4-7 Flow with tidally symmetrical depth varying velocity profiles and tidal straining with non-symmetrical vertical velocity profiles**

## 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 Wagonga Inlet model include:

- There is less hydrodynamic data available for calibration purposes in this estuary than in others used for this project. The only full tidal gauging study occurred in 1986, almost 40 years ago and shortly after the training walls were completed, and bathymetric changes have occurred since then. Nevertheless, as hydrodynamics relevant to the use case of this model were relatively simple (with the exception being the flow into and out of the lagoons, on which extra attention was placed while modelling), and the calibration was acceptable, the model was deemed fit for purpose. However, this may not be true for other use cases.
- The lake transport processes are likely to be driven by wind, not captured in this model. Uncertainty about the lake transport processes for the Forsters Bay location (in the main lake) are dealt with 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.
- There is ongoing bathymetry change in this system, as a result of the installation of the training walls in 1977. There is a long term trend of channel erosion, leading to increasing tidal ranges in the lake (Nielsen and Gordon, 2016). Due to the satisfactory fit to calibration periods over a wide range of time, this was not deemed to be significant for the model’s current purpose, however, may affect future use cases and updated bathymetries may be required.
- 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.
- There is no catchment gauging in the Wagonga catchment, and stream flow data from a nearby catchment has been used instead. This was deemed acceptable for this model, as the catchment was very small relative to the lake and results varied little with catchment inflows, however, may not be acceptable for other use cases.

# 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 Wagonga Inlet, a total of 54 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 Wagonga 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. 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 considered. 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.

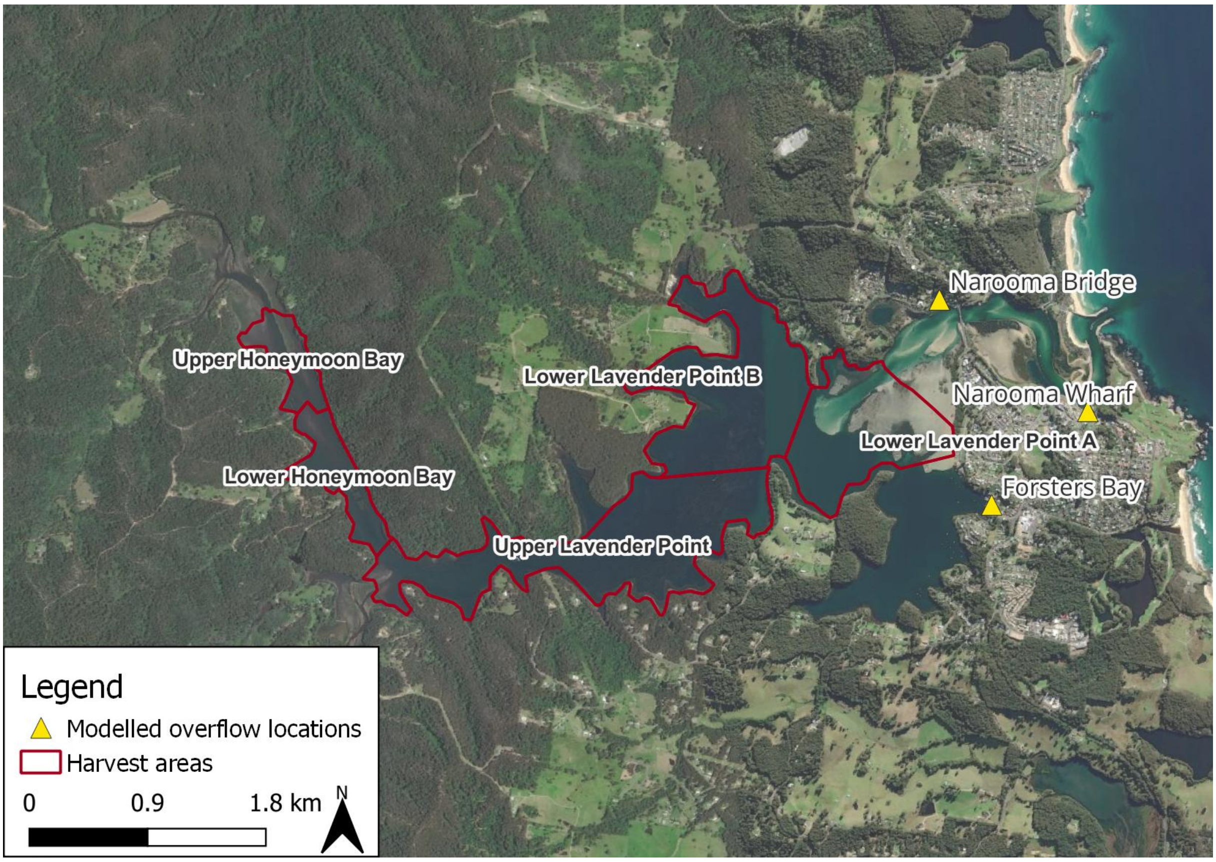


**Figure 5-1 Modelled overflow locations in Wagonga estuary**

## 5.3 Environmental variables

Two environmental variables were tested for Wagonga:

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 Barlows Bay, via the relationship described in Table 5-1. Because of the nature of a lake system, slack tides do not correspond to the highest and lowest water levels, and instead lag behind. Table 5-1 specifies the appropriate lags.

**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 | Barlows Bay (218415) | 1 hr before low tide |
| All locations | Mid flood tide | Barlows Bay (218415) | 1 hr 30 mins after low tide |
| All locations | Slack high tide | Barlows Bay (218415) | 1 hr before high tide |
| All locations | Mid ebb tide | Barlows Bay (218415) | 1 hr after high tide |

The stage of the tide is important at all overflow locations (except for Forsters Bay) for all overflows of duration less than 10 hours. Timing of the tide is particularly important at Narooma Wharf, where 1 and 3 hour overflows at slack high tide (the beginning of the outgoing tide), as well as 1 hour overflows on a mid ebb tide, will largely leave the estuary before the turn of the tide. Overflows from Narooma Bridge also have much lower impacts on outgoing tides (slack high and mid ebb tides). This highlights the need for accurate reporting of the timing and duration of overflows from these locations. Figure 5-2 and Figure 5-3 show the differing impacts of a small overflow from Narooma Bridge at differing tides.

Note, as can be seen in Figure 5-3, at a slack high tide Lower Lavender Point A is still affected. This occurs because the initial part of the scenario is occurring as the tide is still coming in. Because of the limited water level gauging available at Wagonga, as well as complex hydrodynamics of a lake system, it is difficult to assess when exactly slack tide is, as tidal lags vary depending on tide size, and only a single tidal lag has been specified for the use of scenarios. Thus, this possibility (some upstream movement before the change of the tide) should be considered possible for all overflows occurring near slack high tide, and this result is indicative of what may occur in such a case. For this reason, overflows on mid ebb tide from this location are considered safer.

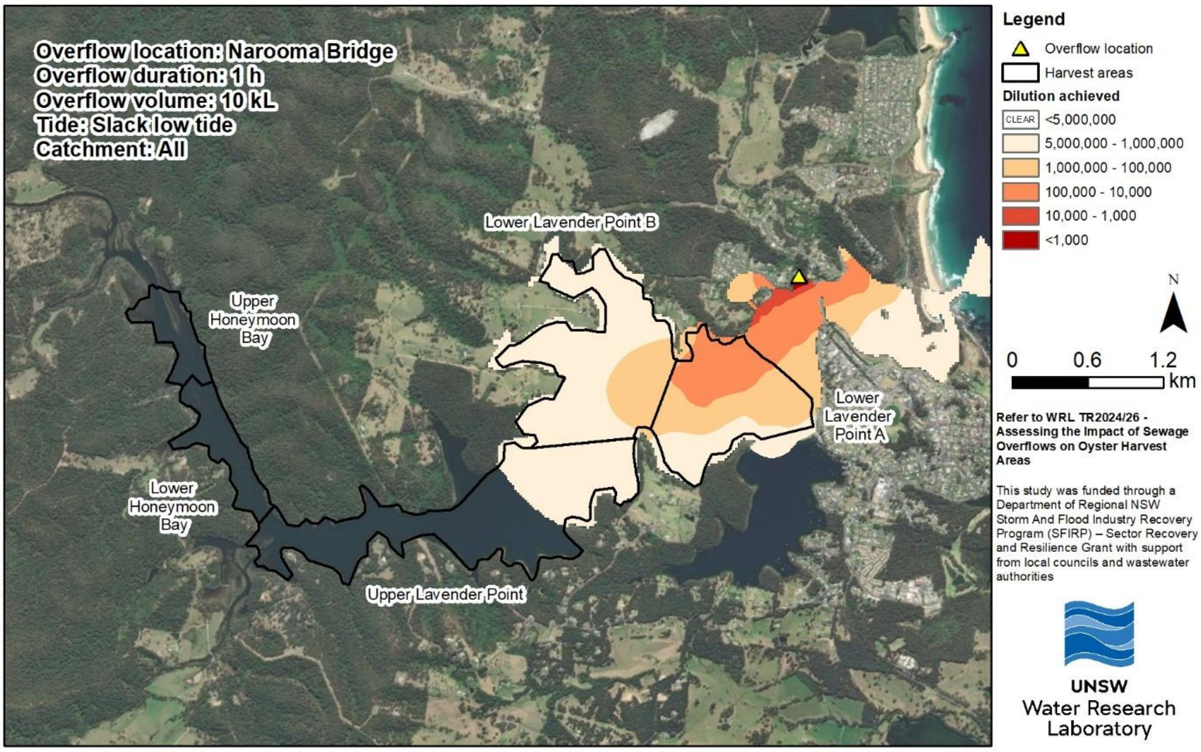


**Figure 5-2 Example of a 1 hour overflow at Narooma Bridge at slack low tide***

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

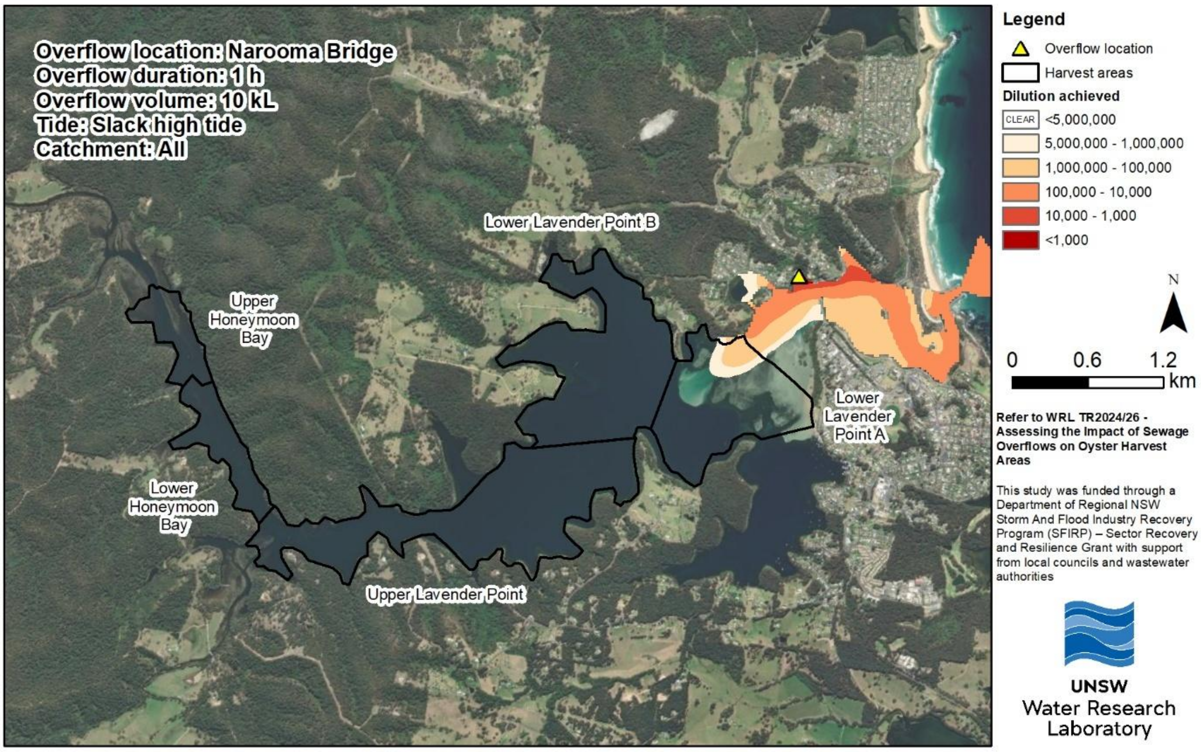


**Figure 5-3 Example of a 1 hour overflow at Narooma Bridge at slack high tide***

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

### 5.3.2 Catchment inflows

Catchment inflow had negligible effect on plume transport, thus a full suite of catchment inflow conditions was not simulated. Multiple catchment inflow scenarios were only run for 1 hour overflows. For context, the total catchment inflows (from all three upstream boundaries into the model, shown in Figure 4-2) for the 95$^{th}$ percentile flow is approximately 3 $m^3/s$, less than 1% of the peak tidal flows through the entrance, which highlights the relative importance of tidal flows in transport and dilution of overflows in this estuary. For ease of use, results for different catchment inflow have been combined when multiple catchment inflow scenarios were run, and in cases where only the median case was run, the scenario has been labelled to apply to all catchment inflow conditions (sub-runs are not available in this case). See WRL TR2023/32 Section 8.3.4 for more details on scenario grouping.

# 6 Conclusion

This report is focussed on the Wagonga Inlet 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 Wagonga Inlet 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 Wagonga) 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 3.6.

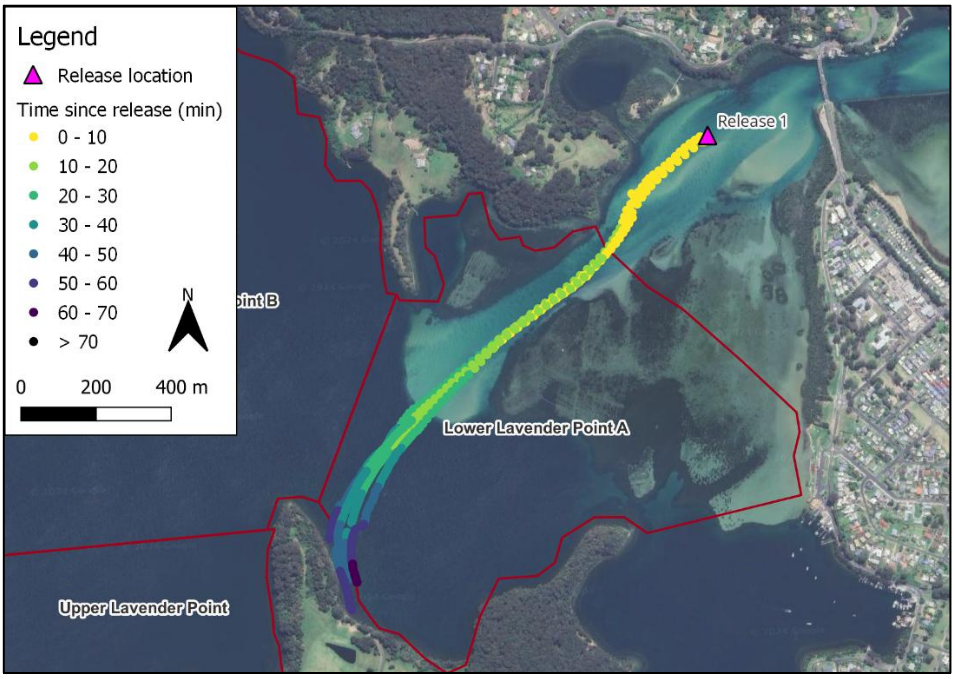


Figure A-1 GPS drifter drogue release 1 – Narooma Bridge – incoming tide

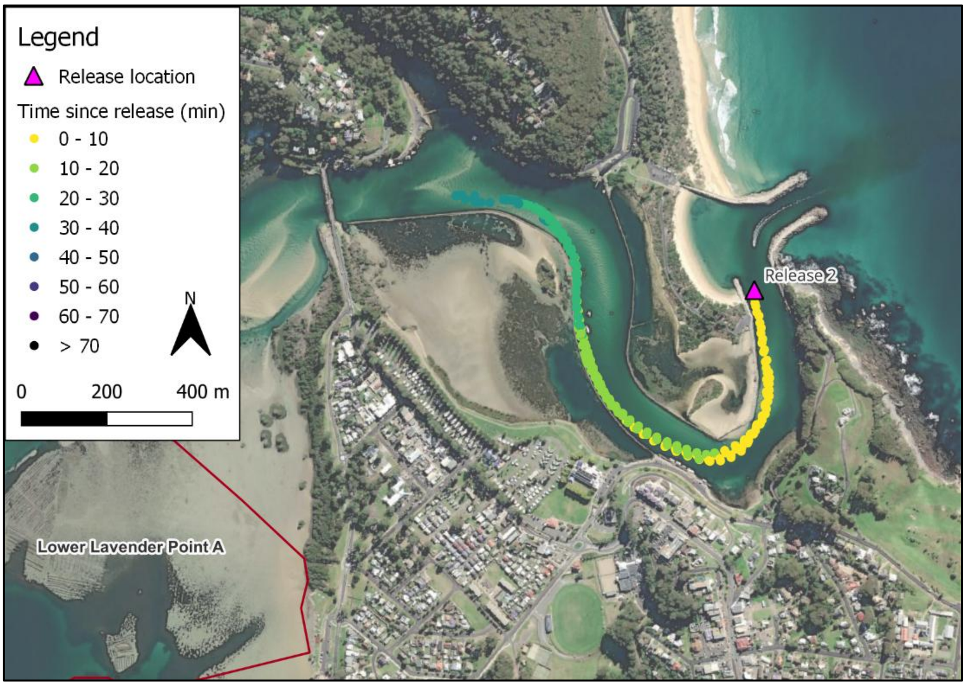


Figure A-2 GPS drifter drogue release 2 – Entrance – incoming tide

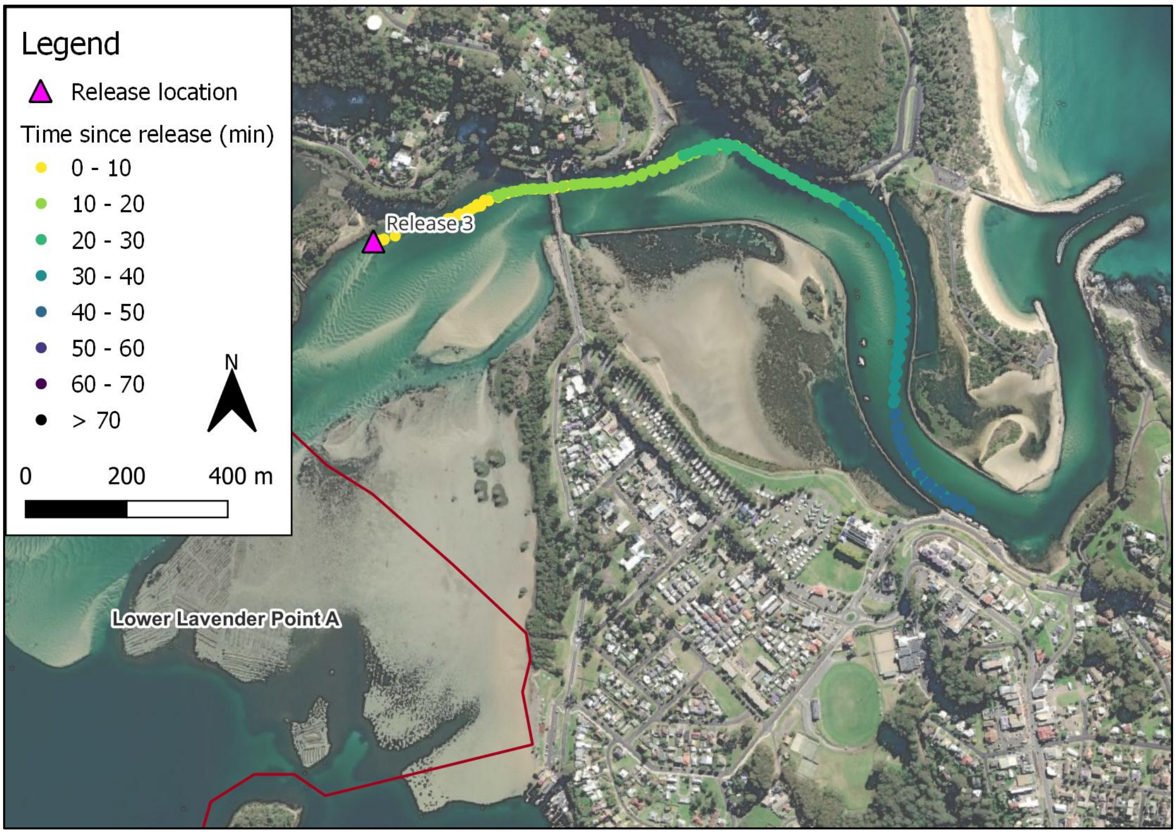


**Figure A-3 GPS drifter drogue release 3 – Narooma Bridge – outgoing tide**

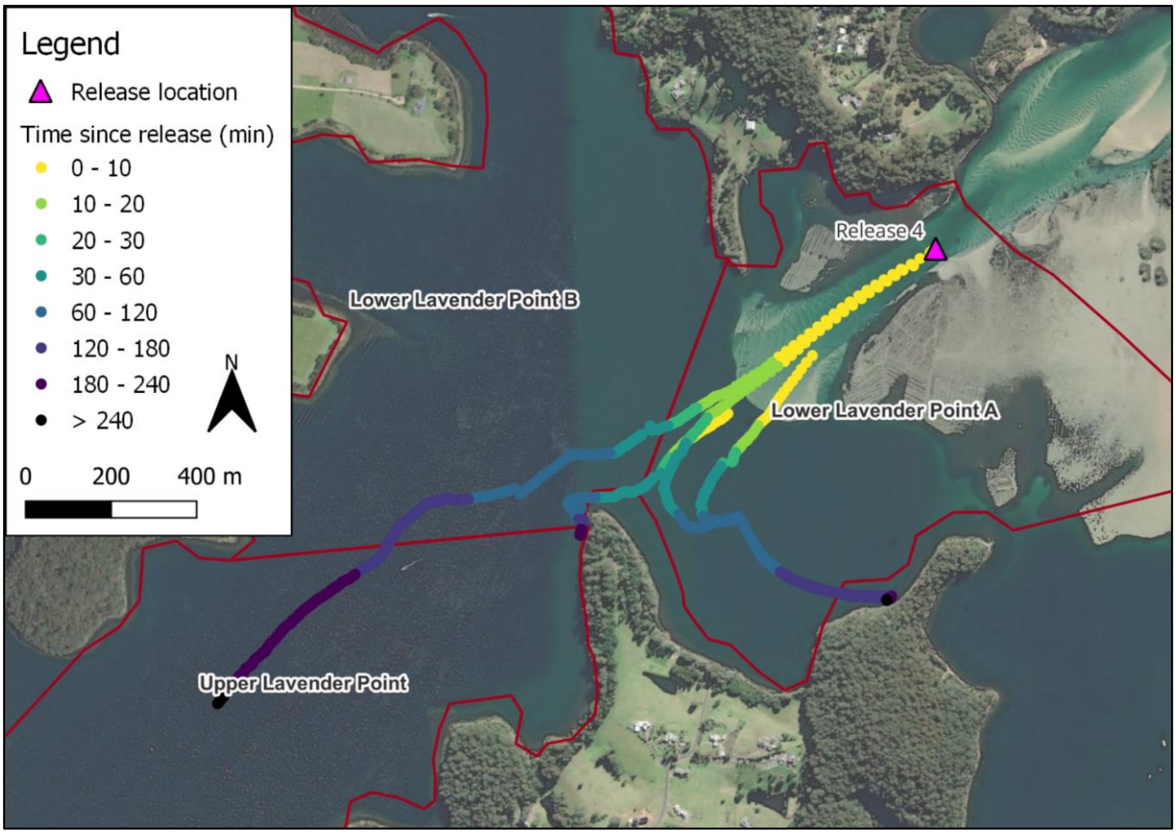


**Figure A-4 GPS drifter drogue release 4 – Lavendar Point – incoming tide**

# A2 Tidal flow gauging

The below figures summarise tidal flow gauging results from the 2023 field campaign. For more information, refer to Section 3.

**Table A-1 Wagonga Inlet Entrance 2023 tidal flow gauging**

| No. | Date | Time | Flow ($m^3/s$) * |
|---|---|---|---|
| 1 | 07/07/2023 | 12:45:27 | -108 |
| 2 | 07/07/2023 | 12:46:39 | -132 |
| 3 | 07/07/2023 | 12:50:29 | -104 |
| 4 | 07/07/2023 | 12:51:48 | -99 |
| 5 | 07/07/2023 | 12:55:12 | -100 |

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

**Table A-2 Narooma Wharf 2023 tidal flow gauging**

| No. | Date | Time | Flow ($m^3/s$) * |
|---|---|---|---|
| 1 | 06/07/2023 | 15:08:47 | 222 |
| 2 | 06/07/2023 | 15:10:33 | 186 |

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

**Table A-3 Narooma Boat Ramp 2023 tidal flow gauging**

| No. | Date | Time | Flow ($m^3/s$) * |
|---|---|---|---|
| 1 | 07/07/2023 | 12:24:05 | -160 |
| 2 | 07/07/2023 | 12:25:30 | -152 |
| 3 | 07/07/2023 | 12:27:41 | -156 |

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

**Table A-4 Narooma Bridge East 2023 tidal flow gauging**

| No. | Date | Time | Flow ($m^3/s$) * |
|---|---|---|---|
| 1 | 07/07/2023 | 12:08:45 | -190 |
| 2 | 07/07/2023 | 12:11:19 | -188 |
| 3 | 07/07/2023 | 12:12:56 | -195 |
| 4 | 07/07/2023 | 12:14:30 | -180 |
| 5 | 07/07/2023 | 12:15:32 | -177 |
| 6 | 07/07/2023 | 12:17:03 | -171 |

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

**Table A-5 Narooma Bridge West 2023 tidal flow gauging**

| No. | Date | Time | Flow ($m^3/s$) * |
|---|---|---|---|
| 1 | 06/07/2023 | 14:01:38 | 191 |
| 2 | 06/07/2023 | 14:03:41 | 173 |
| 3 | 06/07/2023 | 14:05:41 | 196 |
| 4 | 06/07/2023 | 15:11:40 | 186 |
| 5 | 06/07/2023 | 15:27:58 | 197 |
| 6 | 06/07/2023 | 15:30:04 | 200 |
| 7 | 06/07/2023 | 15:31:58 | 195 |
| 8 | 06/07/2023 | 15:34:01 | 194 |
| 9 | 06/07/2023 | 15:42:04 | 188 |
| 10 | 07/07/2023 | 11:33:54 | -219 |
| 11 | 07/07/2023 | 12:00:44 | -204 |
| 12 | 07/07/2023 | 12:02:24 | -201 |
| 13 | 07/07/2023 | 12:05:03 | -198 |
| 14 | 07/07/2023 | 12:07:16 | -202 |
| 15 | 07/07/2023 | 13:09:19 | -58 |
| 16 | 07/07/2023 | 13:11:18 | -48 |

| No. | Date | Time | Flow ($m^3/s$) * |
|---|---|---|---|
| 17 | 07/07/2023 | 13:12:41 | -56 |
| 18 | 07/07/2023 | 13:14:24 | -45 |
| 19 | 07/07/2023 | 13:15:58 | -35 |
| 20 | 07/07/2023 | 13:17:39 | -27 |
| 21 | 07/07/2023 | 13:19:32 | -4 |
| 22 | 07/07/2023 | 13:21:22 | -4 |
| 23 | 07/07/2023 | 13:23:25 | 1 |
| 24 | 07/07/2023 | 13:25:22 | 11 |
| 25 | 07/07/2023 | 13:27:15 | 22 |
| 26 | 07/07/2023 | 13:28:57 | 33 |

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

**Table A-6 Honeymoon Bay 2023 tidal flow gauging**

| No. | Date | Time | Flow ($m^3/s$) * |
|---|---|---|---|
| 1 | 07/07/2023 | 10:37:04 | -51 |
| 2 | 07/07/2023 | 11:26:55 | -80 |
| 3 | 07/07/2023 | 11:29:43 | -19 |
| 4 | 07/07/2023 | 11:32:02 | -68 |

* 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. 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 Incoming channel flow distribution at Narooma Bridge**


**Figure A-6 Outgoing channel flow distribution at Narooma Bridge**

# 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 distributions were 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.

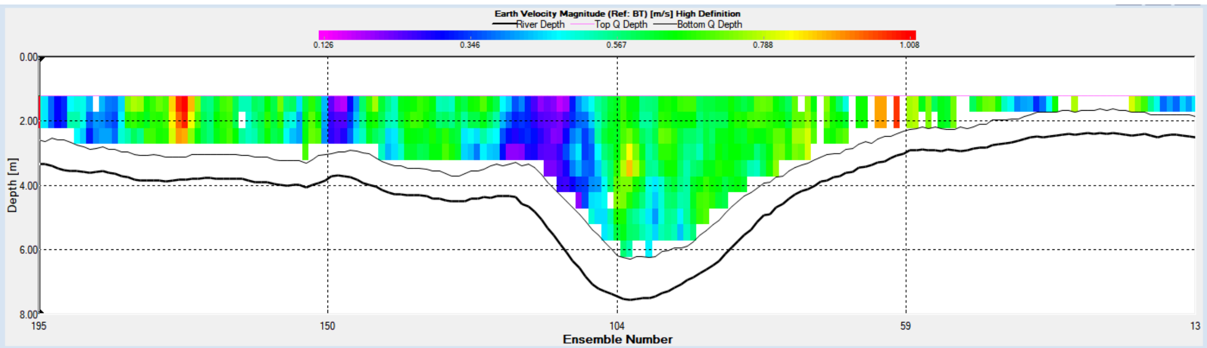


**Figure A-7 Vertical velocity distribution – Narooma Bridge West – Incoming flow – (2023/07/07 12:00:44)**

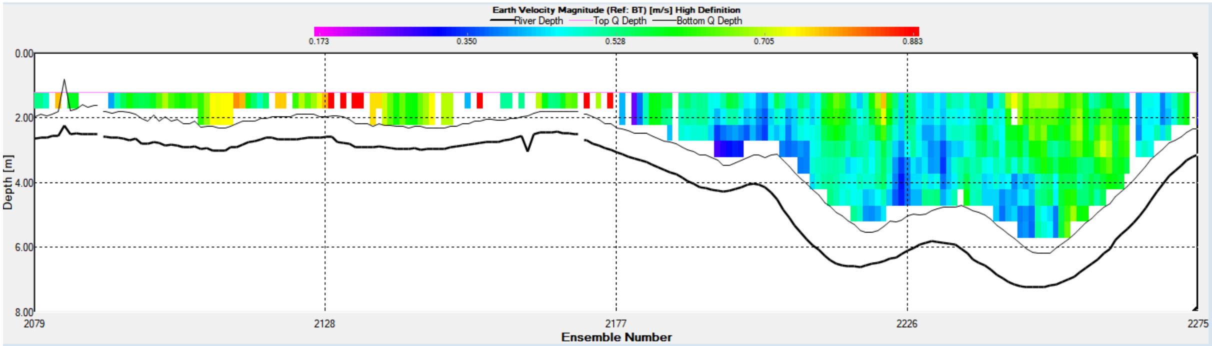


**Figure A-8 Vertical velocity distribution – Narooma Bridge West – Outgoing flow – (2023/07/06 15:42:04)**

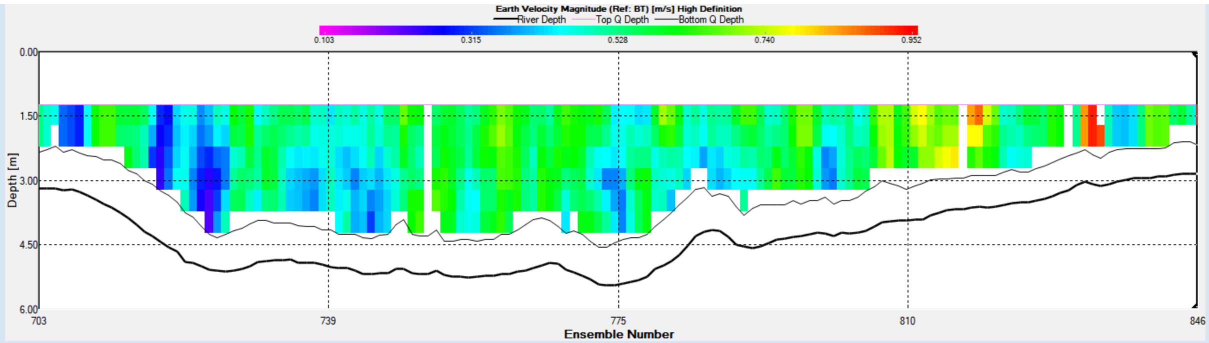


**Figure A-9 Vertical velocity distribution – Narooma Bridge East – Incoming flow – (2023/07/07 12:05:03)**

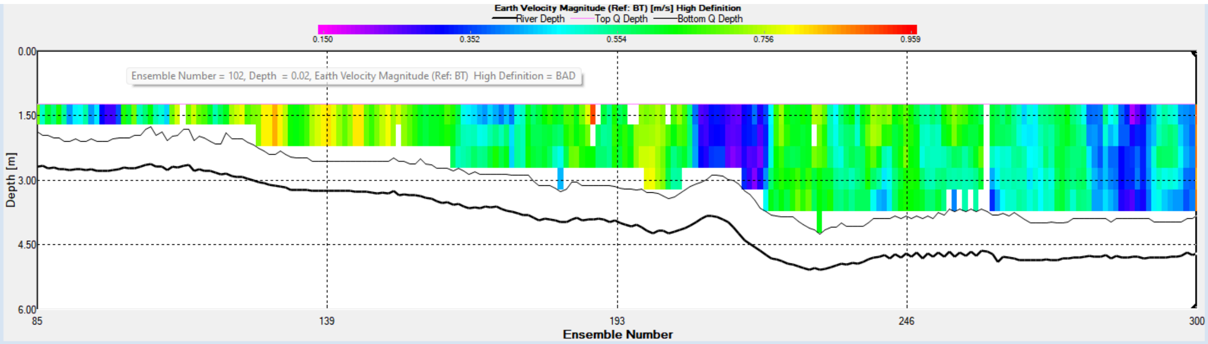


**Figure A-10 Vertical velocity distribution – Narooma Bridge East – Outgoing flow – (2023/07/06 15:11:40)**

# Appendix B Model calibration

## B1 Hydrodynamic calibration

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

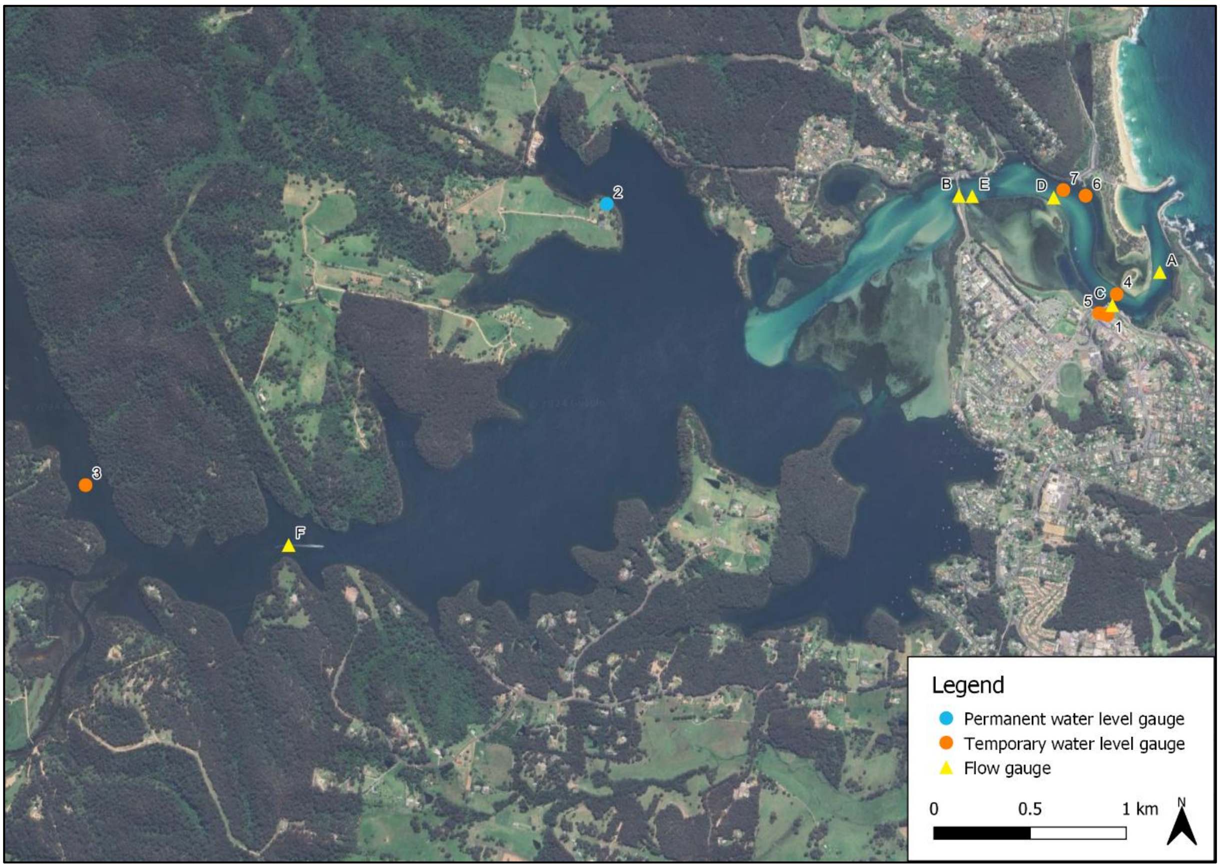


**Figure B-1 Water level and tidal flow gauging locations**

## B1.1 Tidal flow gauging calibration – 1986

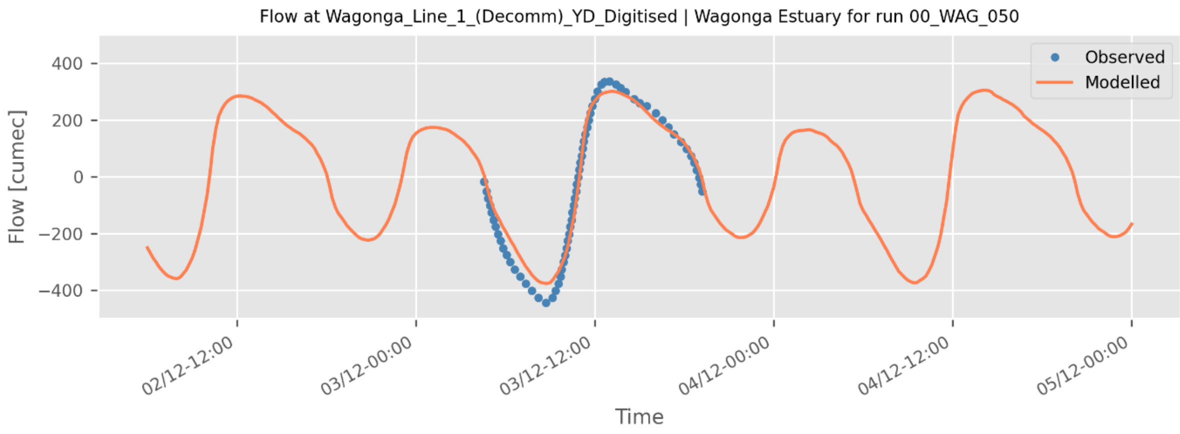


**Figure B-2 1997 tidal flow calibration – Location A – Wagonga Inlet Entrance**

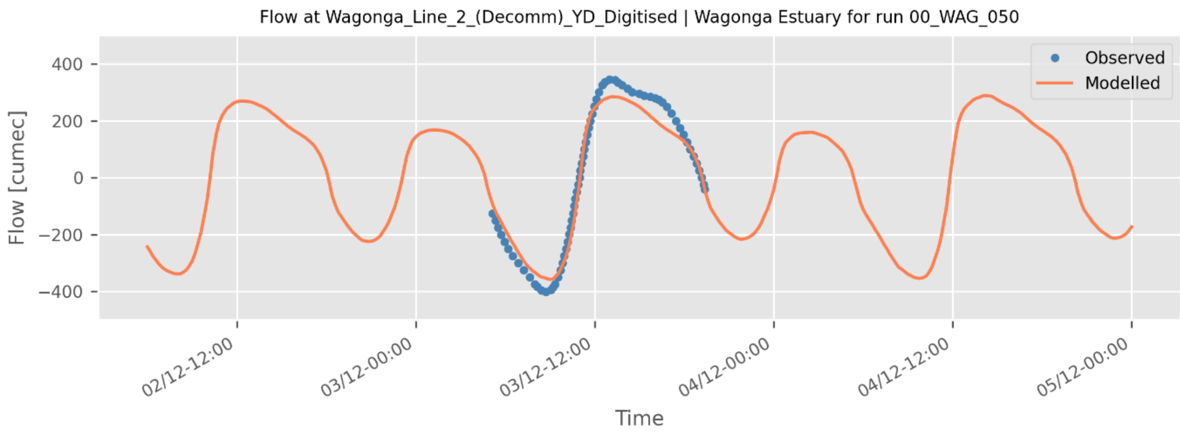


**Figure B-3 1997 tidal flow calibration – Location B – Narooma Bridge West**

## B1.2 Water level calibration – 1997

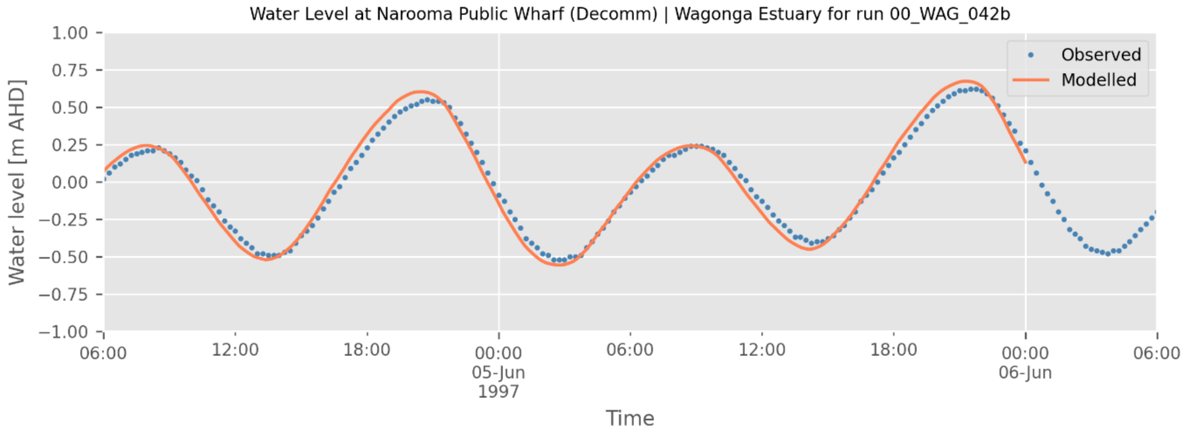


**Figure B-4 1997 water level calibration – Location 1 – Narooma Wharf**

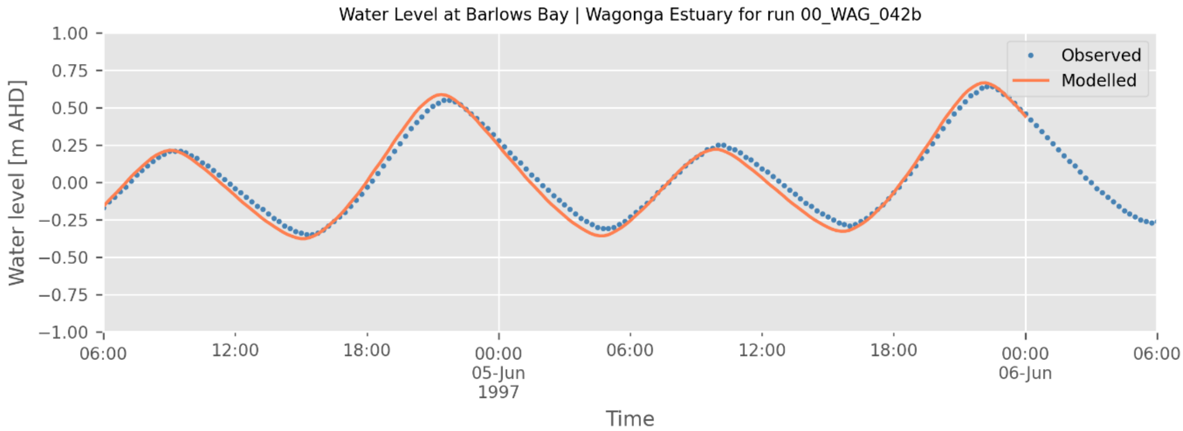


**Figure B-5 1997 water level calibration – Location 2 – Barlows Bay**

## B1.3 Tidal flow gauging calibration – 2023

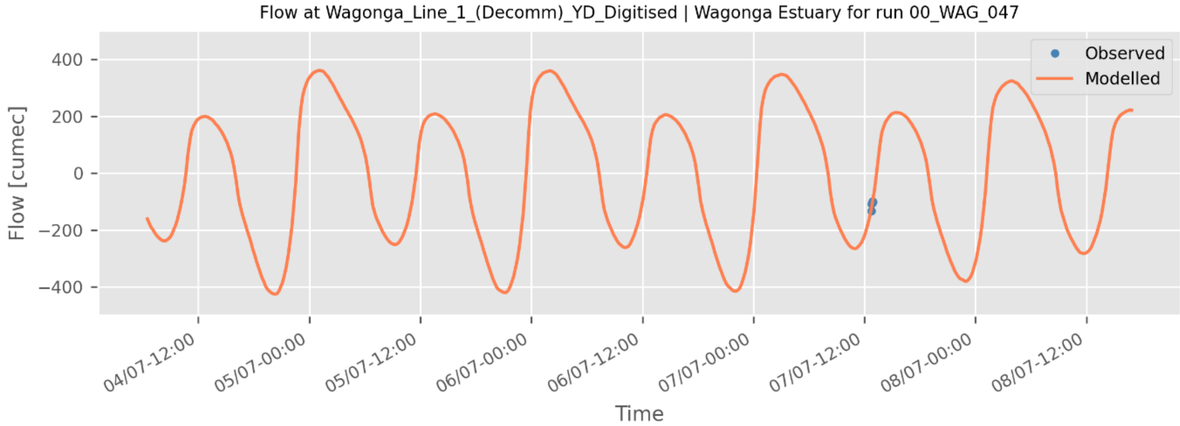


**Figure B-6 2023 tidal flow calibration – Location A – Entrance**

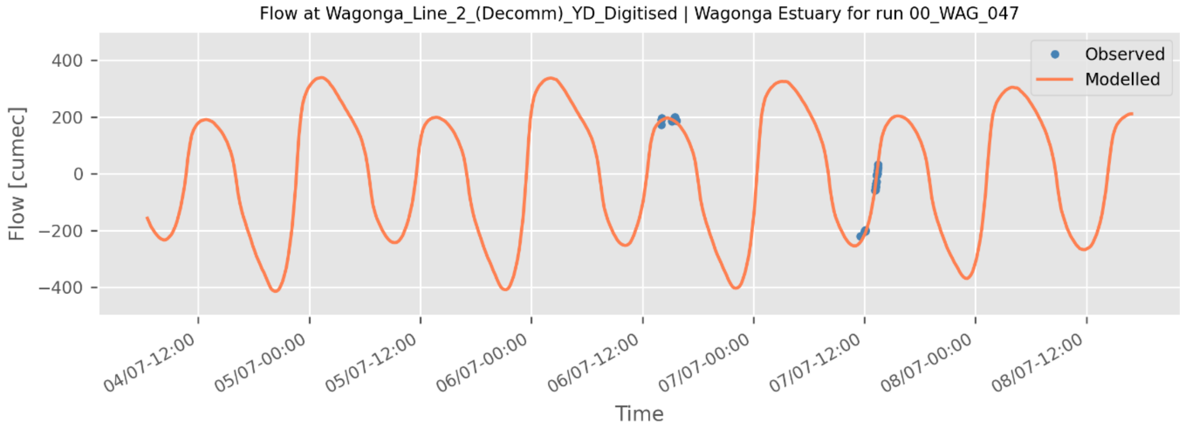


**Figure B-7 2023 tidal flow calibration – Location B – Narooma Bridge West**

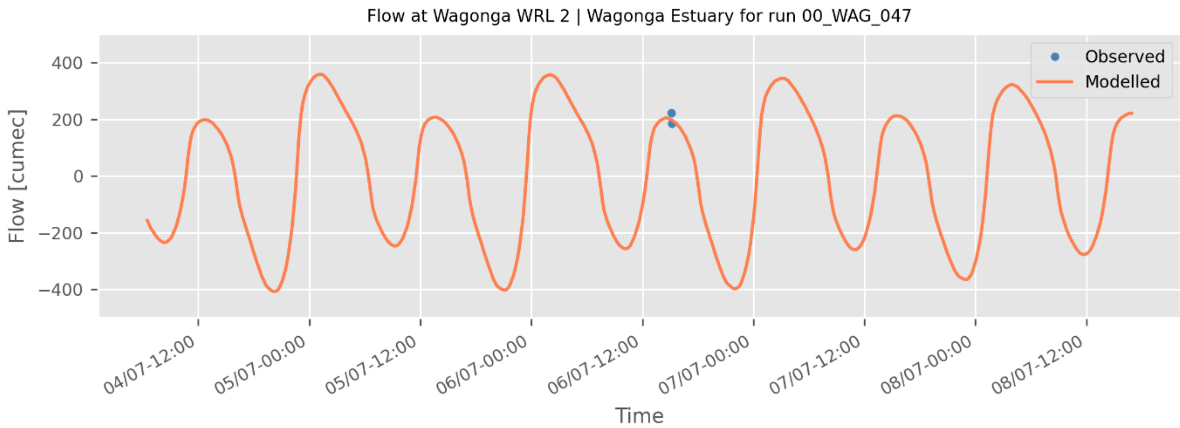


**Figure B-8 2023 tidal flow calibration – Location C – Narooma Wharf**

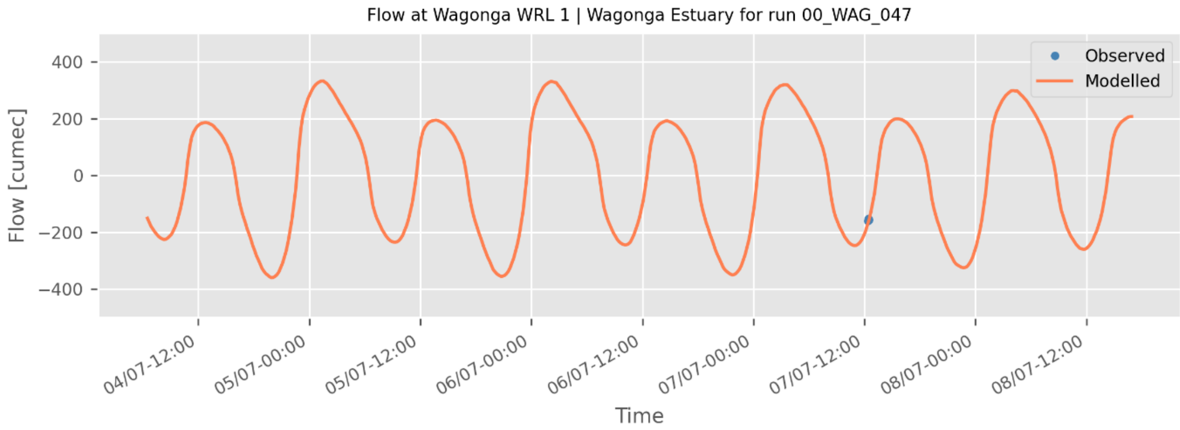


**Figure B-9 2023 tidal flow calibration – Location D – Narooma Boat Ramp**

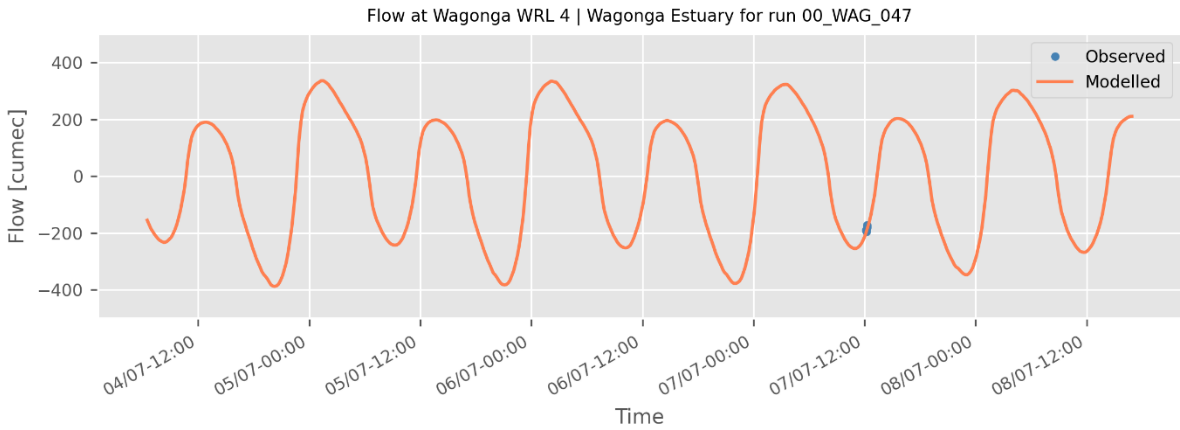


**Figure B-10 2023 tidal flow calibration – Location E – Narooma Bridge East**

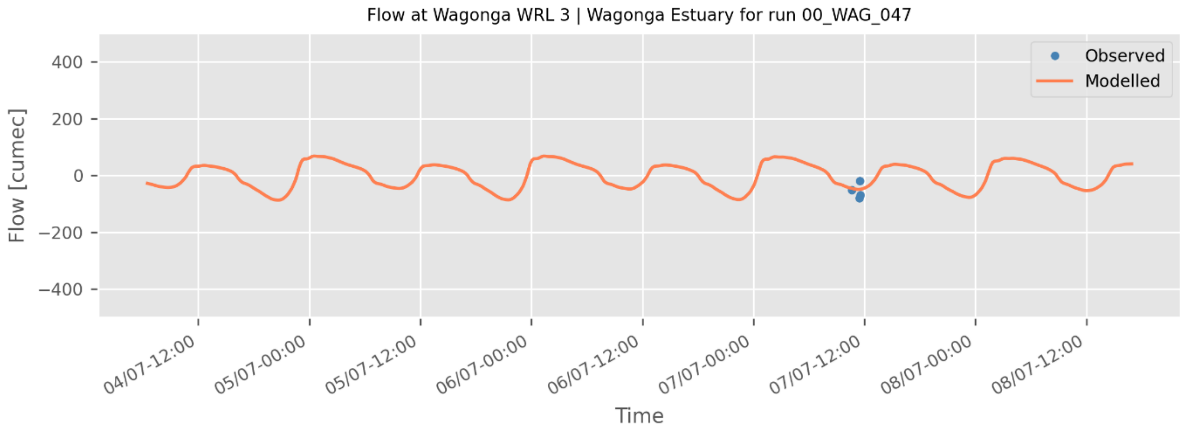


**Figure B-11 2023 tidal flow calibration – Location F – Honeymoon Bay**

## B1.4 Water level calibration – 2023

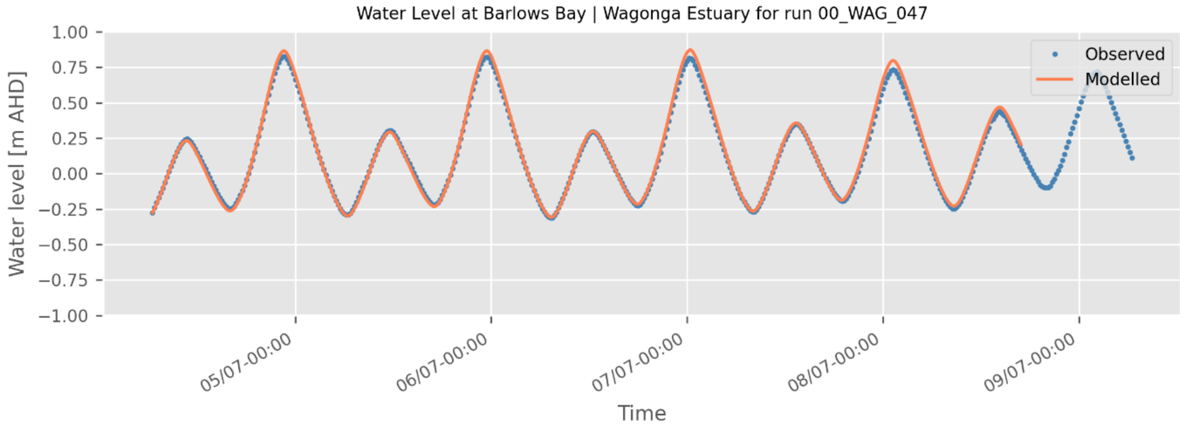


**Figure B-12 2023 water level calibration – Location 2 – Barlows Bay**

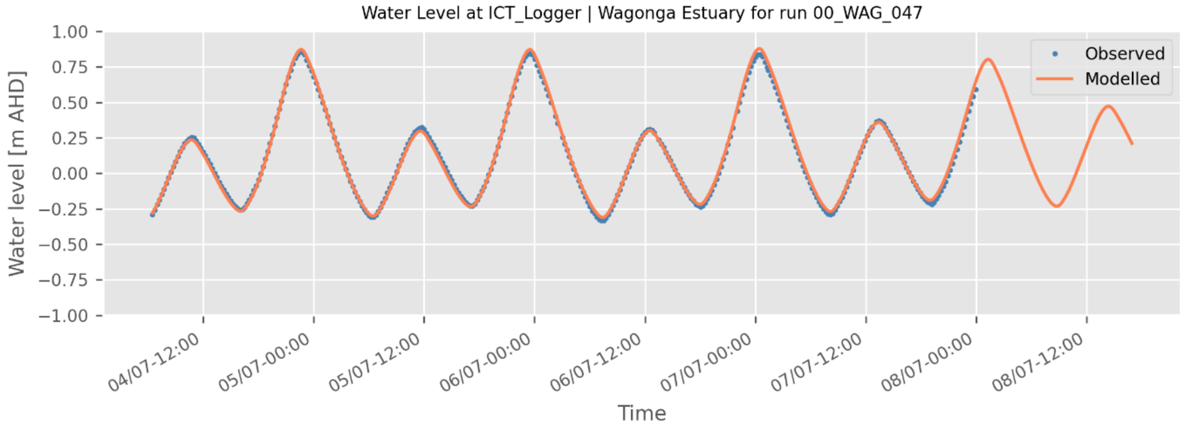


**Figure B-13 2023 water level calibration – Location 3 – Lower Honeymoon Bay**

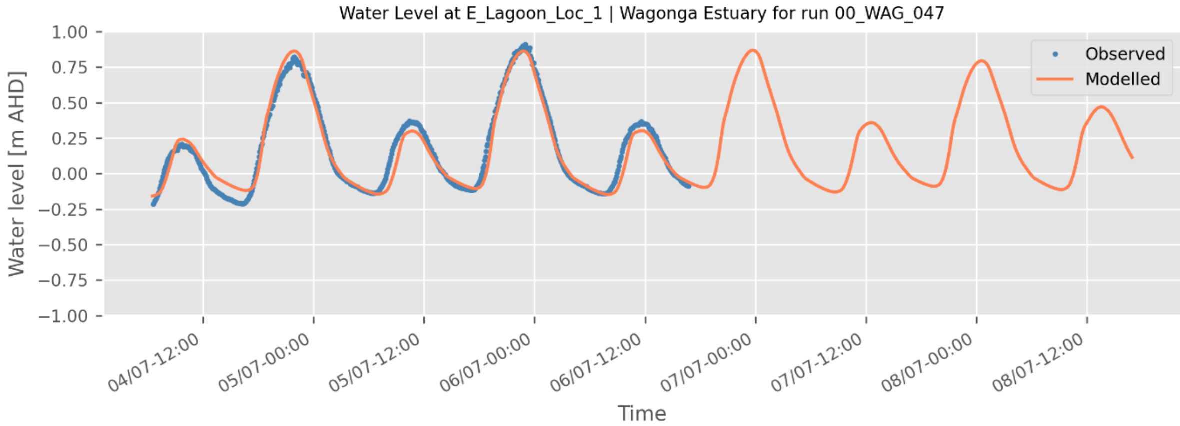


**Figure B-14 2023 water level calibration – Location 4 – Eastern Lagoon (South)**

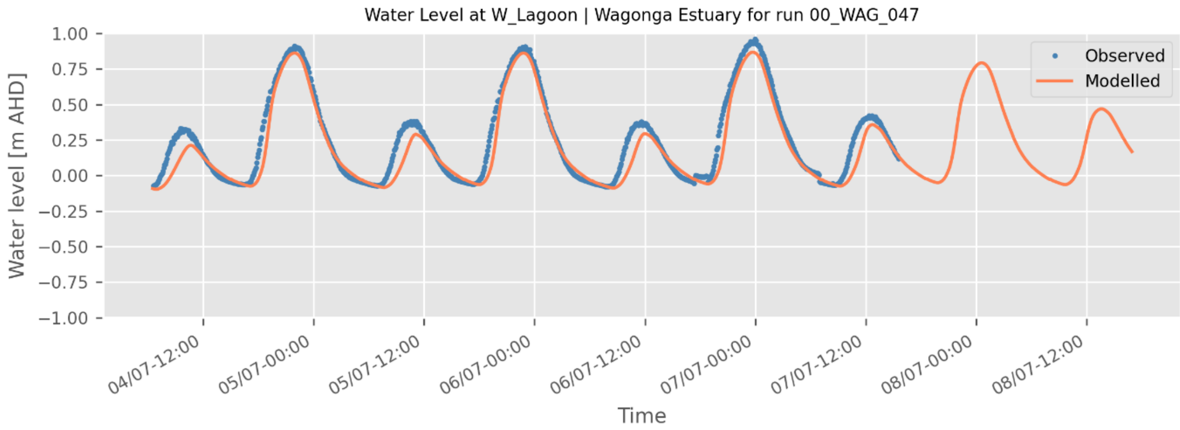


**Figure B-15 2023 water level calibration – Location 5 – Western Lagoon**

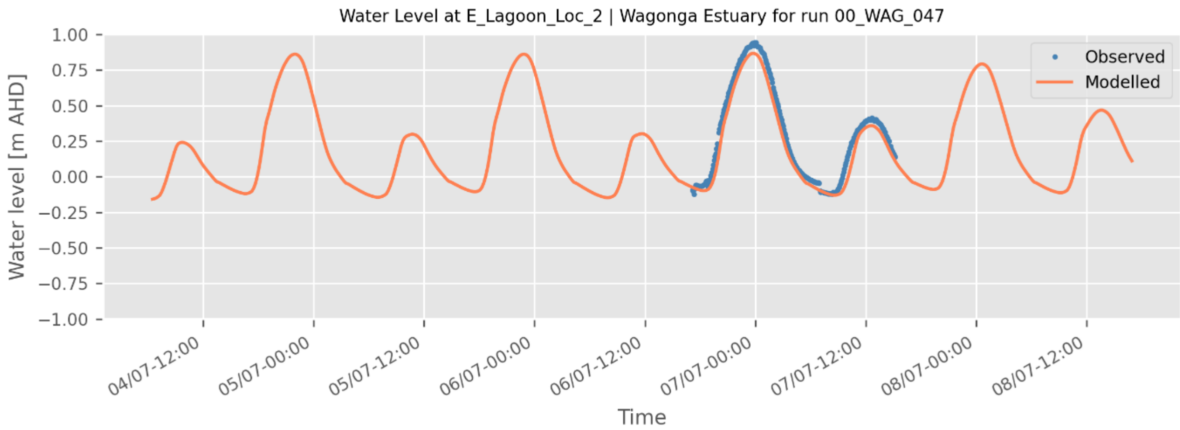


**Figure B-16 2023 water level calibration – Location 6 – Eastern Lagoon (North)**

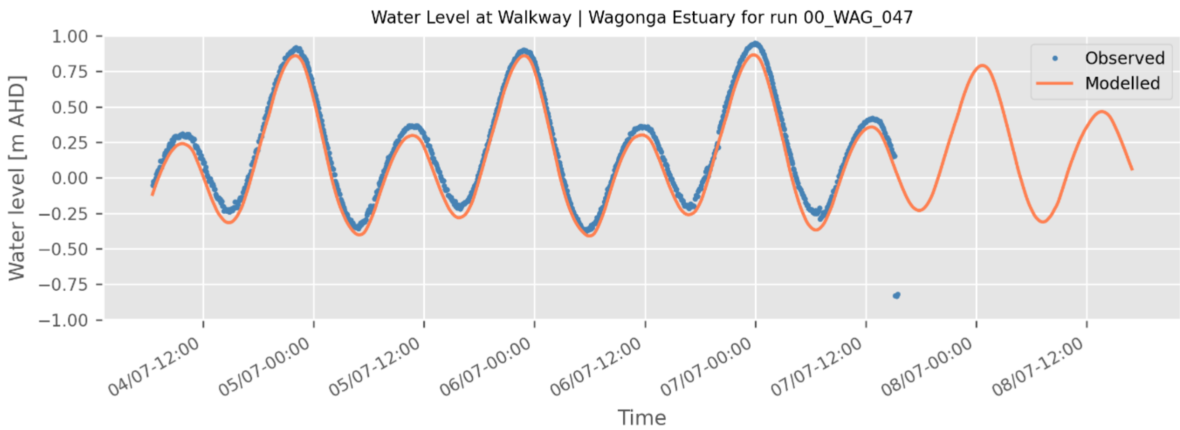


**Figure B-17 2023 water level calibration – Location 7 – Narooma Boat Ramp**