Lake Illawarra Entrance Channel Management Options Study
- Literature Review and Field Investigations

WRL TR 2018/44 | December 2018

By D S Rayner and A Harrison
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This preliminary report is provided to fulfil Stage 1 of the agreed study program. This issue of the report is provided as a preliminary draft and is subject to final Water Research Laboratory internal QA review. This report summaries the preliminary investigations undertaken during Stage 1 of the project program including; literature review, data compilation, field investigations and data analysis. Conceptual flow understanding and numerical model development are also summarised in this preliminary report.

Lake Illawarra is an estuary on the south coast of NSW, located 10 km south of Wollongong CBD with a catchment of 235 km$^2$. The main lake waterbody of 36 km$^2$ is connected to the ocean at Windang via a 2,000 m long entrance channel (Figure 1-1). Historically, the ocean entrance was intermittently connected, with sand building up before elevated lake levels resulted in a breach and scouring of the entrance sand berm. The entrance to the ocean would remain open until nearshore sediment processes infilled the entrance with sand again, limiting tidal interaction with the lake waterbody.

Following community action in the 1990s and early-2000s regarding poor lake water quality, the entrance was connected to the ocean with the construction of entrance training walls. These works resulted in a permanently open entrance condition on the northern side of Windang Island. Since the entrance was trained, significant changes have been observed within the connecting entrance channel and the wider Lake Illawarra waterbody including increased salinity, increased tidal range in the lake, and highly dynamic sediment processes within the entrance channel.

Changes within the entrance channel are driven by the large difference in tidal water levels between the lake and the ocean, resulting in fast flowing tidal currents through the entrance channel during daily flood and ebb tides. The high current velocities induce scouring of the entrance channel, foreshore erosion, ingress of sediments into the lake, and highly dynamic sand shoals. These changes are an ongoing issue for local stakeholders, local councils, and state government asset managers.

This project aims to increase the understanding and interactions of the physical processes that drive changes within the entrance channel at Lake Illawarra. This information can be used to develop a conceptual understanding of what changes might continue to occur into the future if the management of the entrance remains unchanged. To appreciate the risk that these changes may pose to the stakeholders and community, the present day uses and values also have to be
established. Ultimately, this information will be used to develop a range of management options that address both present and potential future issues/threats/hazards to the Lake Illawarra system. From these options, a preferred management pathway will be determined with the project working group for detailed analysis and consultation with the wider community and incorporation into a final management plan.

Figure 1-1: Lake Illawarra location
While a substantial amount of information has already been collected at Lake Illawarra since the entrance was trained in 2007, the rapid changes that are occurring necessitates the repetition of some data collection to quantify the rate and magnitude of change. In addition, further investigation is required to improve the understanding of the sediment transport processes, and the risk that they pose to the infrastructure in the region. This includes (but is not limited to):

- A bathymetry survey to be compared to previous surveys;
- Gauging of a spring tidal cycle flows, to be compared to data from 2008, 2012 and 2016;
- Spot measurements of bed transport velocities throughout the channel;
- A condition assessment of Council infrastructure, particularly to identify areas that are potentially at risk from eroding foreshore and future sea level rise; and
- Particle size distribution of the channel sediments.

Sediment transport in estuaries is driven by a range of complex processes that are occurring on varying spatial and temporal scales. Determining the direction and flux of sediment movement in an intricate system like Lake Illawarra is inherently difficult. For example, while erosion of the foreshore has been evident in the years since the entrance training, bathymetry surveys indicate that there is a net loss of sediment from the entrance channel. At present, it is challenging to assess whether this sediment eventually ends up in the lake, offshore, or some combination of the two. As there is a significant amount of infrastructure that will likely be at risk if the channel continues to erode, novel approaches to measuring sediment transport are required to provide a greater degree of certainty on the likely on-going evolution of the channel.

A sediment tracer study, whereby tracer particles are deployed at a range of locations and allowed to migrate under natural conditions with in-situ sediments, enables the magnitude and direction of sediment flux to be quantified. It can also provide an unambiguous marker of littoral movement over time and space. Undertaking this approach to studying the sediment transport at Lake Illawarra reduces the uncertainty and will improve the understanding of the processes that are occurring and the risks that they pose. In turn, this can substantially increase the confidence with which management options can be developed and assessed.

Using the field data collected, a 2D numerical hydrodynamic model will be developed for the project using the modelling suite RMA. The model allows for rapid visualisation of water levels and velocities and shear stress throughout the whole entrance channel, which assists in identifying erosive hot spots throughout the model domain. The model can also test a range of management scenarios to assess the impact of any engineering changes on shear stress, flushing, and flow.
velocities throughout study area. The results of the RMA hydrodynamic model, coupled with information collected as part of the sediment tracer study, will be used to establish a sediment dynamics conceptual model and mass balance. This will include information such as likely rates of change throughout the channel, net sediment transport and an identification of areas at risk of significant erosion or accretion.

In conjunction with data collection and modelling, consultation with the community and stakeholders is essential to understanding the value of Lake Illawarra. The major community consultation prior to the development of the management options will be in the form of a community survey with targeted questions to establish the primary uses and values of the lake. The survey also serves the purposes of increasing the awareness of the issues occurring in the lake and the ongoing effort to improve management.

Using all the available data and information, options for the ongoing management of the Lake Illawarra Entrance Channel will be developed, which will focus on addressing the key issues identified. A preferred management option will be established based on an analysis of the relative benefits and risks associated with each option and consultation with the project management group. Following a high level analysis of the preferred management option, an informal community workshop day will be undertaken, whereby members of the community can drop in and discuss the project in an informal setting with WRL and Council staff. In this session, the aims and outcomes of the project will be discussed with interested members of the public who can provide feedback and voice concerns as required. This feedback, along with feedback from the project working group, will be incorporated into the final management plan to be produced at the end of this project.

This preliminary report details the initial investigations into the history of the Lake Illawarra entrance channel, data collation, data collection, field investigations and numerical model development. The following sections of the report include:

- **Section 2** summaries the history and existing literature;
- **Section 3** details the field investigations undertaken in 2018 for this study;
- **Section 4** outlines the proposed methodology for the sediment tracer study;
- **Section 5** presents the analysis of the field investigations;
- **Section 6** details the conceptual understanding of entrance tidal flow dynamics; and
- **Section 7** presents the numerical model development and calibration.
2 Literature Review

2.1 Preamble

Lake Illawarra has been the subject of numerous studies, both prior to the entrance training in 2007 and since. Studies since the entrance training have largely focussed on assessing the changes occurring in the entrance and within the Lake as a result of the permanent connection with the ocean. This section provides an overview of the literature reviewed as part of this study.

2.2 History of Lake Illawarra

2.2.1 Geomorphological History

The development of Lake Illawarra is typical of the development of a barrier estuary on the NSW coast. The geomorphological history of the lake is discussed in detail in Sloss et al. (2003) and PWD (1988), and summarised in this section. The valley in which Lake Illawarra is situated was first formed during a period of low sea levels, when the action of rivers cut a drainage paths through the continental shelf. As sea levels began to rise, sediments began to infill into the valleys, mainly consisting of medium to coarse grained marine sand. As sea levels began to stop rising (to a level 1 – 2 m above the present day level), a sand barrier began to form at the seaward edge of the lake progressively restricting the connectivity with the ocean. As the back-barrier lagoon became a low-energy environment, fine grained catchment sediments were deposited into the lake forming estuarine muds.

When sea levels dropped to present day levels, which have been relatively stable for approximately 6,000 years, the inlet into Lake Illawarra stabilised into its current position. The drop in sea levels resulted in a system with little oceanic connection. Deposition of marine sediments into the lake were largely halted prior to the entrance training, and fluvial deposits (of finer grained sediments) dominated the sediment inputs into the lake. Increased sedimentation from upper catchments may have also resulted from the clearing and industrialisation of the greater Illawarra area. Based on the estuary classification developed by Roy et al. (2001) Lake Illawarra is classified as a wave dominated barrier estuary with an open, trained entrance.
2.2.2 Early European History

European settlement in the Illawarra region centred around Lake Illawarra, as the lake provided access to the water and the surrounding land was fertile. Land clearing begun in the early 1800s and development in the Illawarra region had begun in earnest by the 1840’s (Campbell, 2006). By the 1890s, the idea of transforming the lake into a port began to emerge in order to facilitate coal export from the region. It was envisaged that this work would require the channel to be dredged and two breakwaters to be built to form a channel 430 feet wide at the entrance of the lake (LIA, 2014). Rock breakwaters were built in the late 1800’s, however the project was abandoned as the rate of infill of the entrance with marine sediments was too fast to manage (LIA, 2014).

The first bridge crossing over the entrance of Lake Illawarra was built in 1938, connecting the northern and southern sides of the entrance for the first time (Campbell, 2003). Industry in the surrounding area was growing rapidly with the increased development of Port Kembla and the Tallawarra Power Station and correspondingly population around the lake began to increase. Residential development of the area started in the 1920s as Port Kembla developed, but more significant settlement did not begin until the late 1940’s (ERM, 1994).

2.2.3 Lake Illawarra Authority

With increased residential and industrial development, concerns over water quality in the lake were raised throughout the 20th century, with much of the attention focussed on the significance of the periodic opening of the entrance (ERM, 1994). Algal blooms began to occur in the 1970’s as catchment loads deposited more nutrients into the lake (CSIRO & UOW 2000) and there was a degradation of water quality observed. Management of Lake Illawarra was complicated as the responsibility was split between two (2) councils, Wollongong City Council on the northern shoreline and Shellharbour Council to the south, and several NSW Government agencies (Grant, 2013). In response to the environmental degradation of the lake, the Lake Illawarra Authority Act was established in 1988. The Lake Illawarra Authority (LIA) was funded largely by the NSW government and the two constituent councils, and consisted of 10 members from the relevant stakeholder communities (Wollongong Council, Shellharbour Council, NSW Fisheries, Crown Lands, Southern Rivers CMA and five members of the community). The LIA mission statement was (LIA, 2013):

“The Lake Illawarra Authority aims to achieve a healthy, attractive, well-managed amenity for the benefit of the community”.

Under the Act, the LIA was responsible for overseeing development activities relating to the management of Lake Illawarra. The objectives of the LIA, as outlined in LIA (2013) are summarised...
in Table 2-1. The development works undertaken by the LIA were diverse, ranging from the installation of jetties and parks throughout the lake’s foreshore to dredging of 300,000 m³ for improving water circulation and water quality in Griffins Bay located in the north-eastern corner of the lake (LIA, 2011). The LIA coordinated the constructions of the breakwater training walls at Lake Illawarra, estimating the cost of that project at $11.6 million as of 2011 (LIA, 2011). Following a review of the LIA in 2013, the LIA was disbanded in 2014, as it was considered to have met its objectives and there is now a stronger legislative framework for estuary management that negates the need for a separate authority to manage the lake (Grant, 2013).

Table 2-1: Objectives of the LIA (LIA, 2013)

<table>
<thead>
<tr>
<th>Area</th>
<th>Objective/Aim</th>
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<tr>
<td>Entrance Management/Condition</td>
<td>Create a stable entrance to the lake which is predominately open</td>
</tr>
<tr>
<td>Water Quality</td>
<td>Improve the water quality of the lake to a standard that protects its ecological, recreational values</td>
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<tr>
<td>Algal Blooms</td>
<td>Reduce the incidence of macroalgae and other forms of algae that degrade and dominate the natural ecological function of the lake</td>
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<tr>
<td>Organic Wrack and Ooze Accumulation</td>
<td>Reduce ooze formation and malodorous conditions around the lake as a result of the accumulation and decay of seagrass and macroalgae</td>
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<tr>
<td>Erosion and Sedimentation</td>
<td>Reduce the rate of sedimentation in the lake to a pre-European level, restore areas of the lake degraded by excessive sedimentation and minimise further erosion around the lake</td>
</tr>
<tr>
<td>Catchment Inputs/Management</td>
<td>Seek to ensure that land usage decisions are made having regard to the quality and amenity of the environmental and recreational values of the lake</td>
</tr>
<tr>
<td>Ecology and the Fishery</td>
<td>Protect the abundance and diversity of native aquatic and terrestrial flora and fauna and restore habitats</td>
</tr>
<tr>
<td>Waterway Usage</td>
<td>Permit appropriate recreational use of the estuary and foreshores compatible with ecosystem values</td>
</tr>
<tr>
<td>Riparian Zones</td>
<td>To restore and protect foreshore vegetation and maximise public access to the lake without compromising ecosystem protection or visual amenity objectives</td>
</tr>
<tr>
<td>Flooding</td>
<td>To minimise the impact of flooding on public and private assets whilst adopting a policy of minimal intervention in natural processes wherever possible</td>
</tr>
<tr>
<td>Visual Amenity</td>
<td>To preserve and enhance the visual quality of the lake, its foreshores and the catchment</td>
</tr>
<tr>
<td>Community Involvement</td>
<td>To increase public awareness of the values and sensitive nature of the estuary in order to minimise activities that adversely impact on lake environments</td>
</tr>
<tr>
<td>Area</td>
<td>Objective/Aim</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Culture and Heritage</td>
<td>To preserve cultural heritage values of the Lake and foreshores</td>
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<tr>
<td>Foreshore Access</td>
<td>To maximise opportunities for public foreshore access to the lake</td>
</tr>
<tr>
<td>Commercial and Tourism</td>
<td>To enhance the funding of environment protection and future management activities in the lake and foreshores through appropriate commercial use</td>
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2.2.4 Entrance Training of Lake Illawarra

As mentioned in Section 2.2.2, attempts to permanently open the entrance of Lake Illawarra date back to the 1890’s, although these early works were abandoned relatively quickly and not much remains of those structures. Figure 2-1 shows a summary of major construction works at the entrance since the 1960’s. In the early 1960’s, two walls were built off the end of Reddall Parade to protect Warilla Beach from outbreaks of the entrance near dredging areas of the channel. These walls have been damaged and degraded by coastal processes since the construction, particularly in the big storms in the mid 1970’s (AWACS, 1991). Between 1963 to 1970 a concrete training wall was constructed by Shellharbour Municipal Council along the southern bank of the entrance, in order to protect the parkland on the Warilla foreshore. This structure prevented further southward migration of the entrance channel, but was not aimed at preventing the entrance from shoaling.
Water quality in the lake was a primary factor for the establishment of the LIA, particularly due to the frequent algal blooms occurring through the 1970’s and 1980’s. It is well recognised that catchment inputs are a major contributor to poor water quality in the lake and the LIA put in place measures to try and manage water quality of catchment inflows, however there was significant community pressure to increase tidal flushing of the lake by permanently opening the entrance as this was seen as the solution to improving water quality (Wilson et al., 1991).

In 1991, the Australian Water and Coastal Studies Pty Ltd (AWACS) undertook a study looking into conceptual structural solutions for improving the entrance to Lake Illawarra (Wilson et al. 1991). The primary aims of the designs were to:

- Permanently open the lake through a channel running north of Windang Island; and
- Minimise sand transport from Warilla and Perkins Beach that resulted in entrance shoaling.

Ultimately, Wilson et al. (1991) recommended eight (8) alternative designs, the majority of which involved a rock revetment tie wall along the southern bank of the entrance (near Reddall Reserve), backed by either parkland or a waterway. The alignment of the tie-wall was such that it would prevent the entrance from migrating south of Windang Island, allowing a stable dune barrier to form.
which minimised sand transport from Warilla Beach back into the entrance. However, the breakwaters were not designed to continue beyond the natural beach shoreline.

In 1994, Lawson and Treloar (1994) completed a numerical modelling project that assessed the impact of three (3) possible alignments of a southern tie wall, combined with dredging, on: mean lake levels, tidal prisms, and sediment transport conditions. This project concluded that by limiting the sand supply from littoral drift from Warilla Beach and increasing the tidal prism as a result of dredging works, the frequency of entrance closures could be significantly reduced. They suggested that maintaining a minimum cross-sectional area of 150 m² would minimise sediment transport from both catchment and tidal flows. The project also anticipated that undertaking these entrance works would increase the tidal range in the lake from 3 cm to 11 cm, and significantly increase the potential for tidal flushing to alleviate water quality issues.

Based on the modelling undertaken, the LIA completed the southern training wall in 2001, which forms the northern wall of the small protected waterway on the Reddall Reserve Foreshore. Dredging in the entrance was also undertaken to try and stabilise the entrance channel and increase the tidal prism, as per the modelling by Lawson and Treloar (1994). However, the entrance began to shoal quickly after the initial dredging and construction of the wall. By 2002, the entrance closed again as a result of drought conditions dampening the typical catchment flows into the lake that assist in scouring the entrance (Patterson Britton, 2005). The Save Lake Illawarra Action Group (SLIAG) was formed by the local community in 2001, voicing the public concern about the shoaling of the entrance and its perceived impact on lake water quality. In 2002, SLIAG organised over 1,000 local residents to manually open the lake to the ocean, in an effort to improve water quality in the lake and put public pressure on the LIA to undertake more permanent measures.

In 2003, Lawson and Treloar were commissioned by the LIA to expand on the AWACS (1992) study that explored options for opening the lake. Lawson and Treloar (2003) undertook modelling of nine (9) alternative options for permanently opening the lake, including several different arrangements of groynes and breakwaters. The options were assessed in terms of:

1. Structural Stability;
2. Improvements to the Perkins Beach alignment;
3. Improvements to tidal flows;
4. Conveyance during flood events;
5. Reduced periods of closure;
6. Navigability; and
7. Cost.
Ultimately, an independent review panel chaired by Bruce Thom (2003) provided support for one of the options presented in Lawson and Treloar (2003). The preferred option included the construction of the northern training wall at least 100 m from the existing wall, a southern spur wall, and extensive dredging. This option had obtained strong community support (Thom, 2003) and was reviewed as the most effective at improving the entrance and lake conditions (largely through maintenance of a permanent channel, lowering average water levels in the lake and increased tidal flushing). Prior to the construction, Lawson and Treloar (2003) and Patterson Britton and Lawson and Treloar (2004) undertook a study in the tidal hydrodynamics, flood behaviour and geomorphological behaviour of the proposed entrance works. A three (3) month model of geomorphological changes in the lagoon indicated that the entrance would evolve over time (Figure 2-2). The modelling indicated that there would be some shoaling of the entrance along the southern breakwater, but some sections of the channel would deepen. Initial modelling by Lawson and Treloar (2003) suggested that the entrance was unlikely to be self-scouring during extended periods of dry weather and it was estimated that dredging of the entrance would still be required every 5 to 10 years to prevent closure (WBM, 2006). The studies concluded that there would be no significant change to the tidal range compared to that predicted in the original modelling (Lawson and Treloar, 1994) undertaken for the southern training wall (which was constructed in 2001).

Modelling of the morphological changes of the entrance and adjacent beaches focussed on short-term changes immediately after construction, which was identified as a concern after the public exhibition of the EIS for the work (albeit largely due to a concern that the entrance would continue to infill). After the assessment of the EIS prepared for the works, the NSW Department of Planning stated “the agencies agree that as there is no identifiable or irreversible damage that could result from the proposed works, the project could be treated as a valuable experiment. The outcome would remain to be seen over time” (Department of Planning, 2005), indicating the unstable scouring regime that was created as a result of the works was an unforeseen issue. In the same report, it was suggested that monitoring the entrance and lake for a period of 5 years would be sufficient to assess the effectiveness of the works. In 2007, after significant community pressure, the LIA finished the construction of the northern training wall and the extension of the 2001 southern wall. In addition to the new structures, the channel was also dredged to facilitate the initial opening of the entrance with approximately 200,000 m$^3$ dredged (WBM, 2006).
Figure 2-2: Modelled bathymetry changes over 3 months of tidal flows as a result of breakwater construction (Lawson and Treloar, 2004)
2.2.5 Post 2007

After the construction of existing training walls at Lake Illawarra, significant effort has been made to monitor the changes in the entrance and the wider lake. The numerous studies have encompassed a broad range of aspects, including changes to the hydrodynamics, water quality and morphological changes.

Hydrodynamic Changes
Manly Hydraulics Laboratory (MHL) has undertaken extensive monitoring of Lake Illawarra both prior to and since the training of the entrance. This included:

- Long-term water level gauges at:
  - The entrance channel,
  - Cudgeree Bay; and
  - Koonawarra Bay.

MHL (2017) undertook a tidal analysis of the three long-term water level monitoring stations in Lake Illawarra, showing that the mean spring tidal range has been increasing at an average rate of 6 to 8 mm/year since the entrance was opened in 2007. Prior to the entrance works, WBM (2003) estimated that the tidal range within the lake varied between 0 m (when the entrance was closed) to a maximum range of 0.08 m after the lake was scoured from a significant catchment runoff event. Median tidal range was approximately 0.02 m (WBM, 2003). In the year between July 2015 and June 2016, MHL (2017) calculated the mean spring tidal range at Cudgeree Bay and Koonawarra Bay to be 0.14 and 0.13 m respectively, while at the entrance the tidal range had increased to 0.71 m.

Wiecek et al. (2016) used the MHL long-term water level gauge at Koonawarra Bay (data from 2004 to 2011) to investigate the impact of entrance training on long-term (3 year) average daily maximum, mean and minimum water levels in the lagoon before and after the training walls were constructed. The results of this analysis are shown in Figure 2-3. Daily mean and minimum water levels dropped by approximately 20 cm and 24 cm respectively after the entrance works.
Gauging of tidal flows at the entrance to Lake Illawarra has been undertaken three times to develop an understanding of the changing hydraulic processes in the entrance. Each gauging exercise has been conducted from low tide to low tide (measured tidal water levels in Jervis Bay are outlined in Table 2-2), measuring a full flood-ebb tide cycle. The resultant tidal prism, maximum discharge and maximum tidal velocities during each exercise is summarised in Table 2-3. It is evident that the tidal prism, discharge and velocities have all increased each time the gauging was repeated. However, it is difficult to establish how much the varying ocean tidal levels contributed to the differences in discharge (particularly as the 2008 tide was smaller than the 2012 and 2016 tidal cycles). In addition, the 2016 experiment was undertaken in a slightly different location to the previous two exercises which may have influenced the measurements.

Table 2-2: Jervis Bay measured water levels during tidal gauging exercises (MHL, 2008, MHL, 2012 and MHL, 2016)

<table>
<thead>
<tr>
<th>Date</th>
<th>Low Tide (m AHD)</th>
<th>High Tide (m AHD)</th>
<th>Low Tide (m AHD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/03/2008</td>
<td>-0.60</td>
<td>0.71</td>
<td>-0.59</td>
</tr>
<tr>
<td>16/10/2012</td>
<td>-0.74</td>
<td>0.84</td>
<td>-0.69</td>
</tr>
<tr>
<td>11/03/2016</td>
<td>-0.70</td>
<td>0.82</td>
<td>-0.74</td>
</tr>
</tbody>
</table>
Table 2-3: Summary of tidal gauging results at Lake Illawarra
(MHL, 2008, MHL, 2012 and MHL, 2016)

<table>
<thead>
<tr>
<th>Year</th>
<th>Tidal Prism (m$^3$ x 10$^6$)</th>
<th>Maximum Discharge (m$^3$/s)</th>
<th>Maximum Tidal Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flood</td>
<td>Ebb</td>
<td>Flood</td>
</tr>
<tr>
<td>2008</td>
<td>2.7</td>
<td>2.1</td>
<td>222</td>
</tr>
<tr>
<td>2012</td>
<td>4.9</td>
<td>4.1</td>
<td>320</td>
</tr>
<tr>
<td>2016*</td>
<td>5.5</td>
<td>4.8</td>
<td>388</td>
</tr>
</tbody>
</table>

*2016 tidal gauging was undertaken in a different location in the entrance channel, comparisons are indicative only

Morphological Changes

Increasing tidal prisms and maximum tidal velocities, accompanied with gradually increasing tidal range within Lake Illawarra are potentially an indicator that the entrance is presently hydraulically unstable. Couriel et al. (2013) undertook an analysis of the stability of Lake Illawarra using the available field data and using the techniques described in O’Brien and Dean (1972). This approach has been previously applied at three (3) other NSW estuaries by Nielson and Gordon (2008). This study concluded that if completely unconstrained, the entrance to Lake Illawarra would continue to scour until the cross-sectional area increases to approximately 4,500 m$^2$ over a period of 165 years, about 7.5 times larger than the measured cross section in 2012. While Couriel et al. (2013) acknowledged that there are other physical processes (e.g. the ebb tide bar) or restrictions (e.g. the presence of bed rock or non-erodible surfaces) that will prevent the entrance from reaching this theoretical cross-sectional area, it is an indicator that the entrance is likely to continue scouring in the near future.

Three (3) hydrographic surveys have been undertaken at the Lake Illawarra Entrance since it was opened to provide a better understand the bathymetric changes that are occurring. The surveys were undertaken in 2008, 2012 and 2016 by NSW Department of Environment, Climate Change and Water (DECCW), NSW Public Works Spatial Services, and the Office of Environment and Heritage (OEH) respectively. Regena (2016) and Wiecek et al. (2016) directly compared the 2008 and 2016 hydrographic surveys and plotted the difference in bed elevations (Figure 2-4) and the movement of the deepest section of the channel (known as the thalweg, shown in Figure 2-5). Significant changes have been observed in the entrance channel – there has been significant channel scouring (around 2 to 4 m deepening) along the Windang foreshore, while there has been complimentary accretion around Berageree Island (Figure 2-4) as a result of the deepest section of the channel moving.
As a result of the movement of the channel thalweg, significant erosion began to occur along the Windang foreshore near the boat ramp and Pine Tree Park boardwalk. In 2012, LIA, in conjunction with Wollongong Council implemented protection works to limit the erosion, including adding additional piles to stabilise the boardwalk and construction of three (3) rock groynes. The estimated cost of the rock groynes was approximately $150,000 (LIA, 2012). Cardno (2012) undertook basic hydrodynamic modelling that indicated that constructing the groynes would deflect high currents away from the shoreline which would reduce shoreline erosion. This report also attributed the erosion of the foreshore to an increase in catchment flows during a period of higher than average rainfall, rather than a function of increased tidal flows.

However, a result of the high velocities in the channel and the alignment of the 2012 groynes, there is now highly turbulent flows off the end of the groynes near the Windang boat ramp. Scour holes, up to 8 m deeper in 2016 than 2008, have developed off the end the structures, evident in Figure 2-4. Despite the additional piles installed at the boardwalk, the structure was significantly damaged in 2015 (Wiecek, 2016) and scouring continues to threaten public and private assets along the foreshore. Regena (2016) also noted that the flood tide delta had expanded further into the lake between 2008 and 2016.

In addition to the hydrographic surveys, Jones (2012) conducted 15 vibracores in the flood tide delta to assess the changes to the delta over time. Each core was approximately 2 m deep. Most of the cores indicated that there was a marked change in depositional environment – while presently areas of the flood tide delta are predominately poorly sorted marine sands, this is overlaying finer grained material with more organic matter.

**Water Quality Changes**

The LIA monitored water quality at six (6) sites along the edge of Lake Illawarra on a monthly basis. LIA (2010) concluded that there was no observable impact on water quality at these sites as a result of the entrance works. However, these sites were distributed along the banks of the lake where flushing is limited, sediment nutrient cycling, and catchment inflows are likely to dominate the water quality. Baxter and Daly (2010) analysed the continuous water quality data sets at Koonawarra Bay and Cudgeree Bay (operated by MHL, see section 2.3.5) between January 2005 and January 2009, as well as the LIA monthly data. Their results indicated:

- Salinity at both locations increased from 20 ppt to 30 ppt prior to the entrance works, to 35 ppt (similar to oceanic salinity) after the works. Salinity in the lake can still be influenced by large freshwater catchment events, but is generally less variable;
• Acidity at the two probes decreased slightly as a result of the entrance works, with typical pH of 8 indicating the influence of tidal exchange on lake acidity;
• Total nitrogen and total phosphorous decreased in variability and on average, but still regularly, exceeded the ANZECC (2001) water quality guidelines for total nitrogen (TN) and filterable reactive phosphorous (FRP);
• Turbidity remained highly variable, but largely remained below the ANZECC (2001) guidelines.

Baxter and Daly (2010) concluded that the entrance work had decreased the variability in water quality in the lake and had marginally improved water quality, however freshwater inflows can still cause a temporary reduction in water quality.

Wiecek et al. (2016) analysed the available OEH water quality data from 2007 to 2016, focusing on average values of chlorophyll-a and turbidity and compliance with water quality guidelines. This work concluded that there has been no improvement of water quality in that time. Instead a weak trend of decreasing water quality was identified. This may be a result of increased catchment loads rather than reduced flushing following the entrance training. Wiecek et al. (2016) also showed changes in total nitrogen, phosphorus and filterable reactive phosphorous compliance generally had improved on a yearly basis, however not at all locations in the Lake.
Figure 2-4: Comparison of 2008 and 2016 Hydrographic Surveys
(Source: Wiecek, 2016, adapted from Regena, 2016)
Figure 2-5: Position of the thalweg, based on 2008 and 2016 hydrographic surveys
(Source: Regena, 2016)
2.3 Existing Data

2.3.1 Hydrological Data

Water Levels
Water levels in Lake Illawarra are continuously monitored by MHL at three locations (shown in Figure 2-6):

- The entrance channel (Site 1);
- Cudgeree Bay (Site 2); and
- Koonawarra Bay (Site 3).

Each of these locations have been monitoring water levels since prior to the entrance training. Extensive analysis has been done by MHL (Couriel et al. 2013 and MHL, 2017) using these datasets which show the tidal range in the lake has been changing since the entrance training works were implemented in 2007. Each dataset has been obtained for use in calibration of the numerical model in this study. Additionally, the MHL tidal monitoring location in Jervis Bay has been obtained to understand the open coast tidal range over the same period.

Streamflow Data
WaterNSW maintain a streamflow gauge (level and discharge) on Macquarie Rivulet at Albion Park (Station Number 214003), approximately 9 km upstream of Lake Illawarra. This gauge has been operating since 1949 to the present and provides a significant dataset for understanding catchment inflows into Lake Illawarra.

Climate Data
Climate data (rainfall and evaporation) has been obtained from the Bureau of Meteorology (BOM). Daily rainfall and evaporation is available at Albion Park (Station 068241), and additional daily rainfall is also available at the Windang Bowling Club (Station 068123).

Topography
Digital Elevation Models (DEMs) of the catchments surrounding Lake Illawarra are available from Geosciences Australia and the NSW Government Spatial Services divisions. DEMs are typically derived from LiDAR (Light Detection and Ranging) data collected by an aircraft, which has subsequently been gridded. The most recent data available is a 1m grid from LiDAR flown in 2016. This data will be used in any catchment modelling required as part of this study. Additionally, historical DEMs may be compared at the entrance to assess changes to the shoreline.
2.3.2 Tidal Gauging

Manly Hydraulics Laboratory (MHL) has undertaken detailed gauging of a tidal cycle on three (3) occasions in: 2008, 2012 and 2016 (MHL, 2009, MHL, 2013, MHL, 2017) (Table 2-2). Each gauging exercise was undertaken from low tide to low tide to capture the entire tidal cycle. These exercises have been timed to coincide with large spring tides when the low water levels either side of the high tide is approximately equal. This ensures that velocities measured during the exercise are representative of the maximum velocities in the entrance on both the flood and the ebb tide.

Tidal gauging was undertaken with a RD Instruments Workhorse Acoustic Doppler Current Profiler (ADCP). The ADCP measures velocities throughout the water column as a vessel moves perpendicular to the flow direction. By completing multiple transects across a water body, the ADCP is able to measure discharge throughout time. On each of the three (3) gauging exercises, MHL completed 30 to 45 transects throughout the tidal cycle to reconstruct the discharge signal. While the measurements were taken at approximately the same location in 2008 and 2016 (Location 1 in Figure 2-7), the 2012 measurements were further upstream near Berageree Island (Location 2 in Figure 2-7). As shown in Table 2-2, there were also differences in the offshore tidal
range during each of the three (3) exercises. Direct comparisons of the discharges and velocities are therefore indicative only.

![Figure 2-7: Approximate MHL tidal flow gauging transect locations](image)

### 2.3.3 Hydrographic Surveys

Three (3) hydrographic surveys have been undertaken in the entrance of Lake Illawarra since the entrance was trained in 2007, coinciding with each of the tidal gauging exercises undertaken by MHL (Section 2.3.2). The dates of the available surveys are listed below:

- February 2008 – undertaken by NSW Department of Environment, Climate Change and Water;
- October to November 2012 – undertaken by NSW Public Works Department, Survey and Spatial Information Services; and
- March 2016 – undertaken by the NSW Office of Environment and Heritage.

Where possible, raw data from each of these surveys has been obtained for direct comparison with data collected as a part of this study.
2.3.4 Sediment Analysis

Regena (2016) collected 72 sediment samples as part of her research at the locations shown in Figure 2-8. Particle size distribution for 18 of the samples were presented, all from locations in and around the entrance. Samples from the flood tide delta and the main entrance channel showed that sediments were poorly distributed with a typical particle size of 200 to 400 μm (Figure 2-9). On the secondary entrance channels, south of Bevans Island and near Judbowley Point, sediments were shown to be better sorted, with a higher percentage of silt with some sands (Figure 2-10). This indicates that the main entrance channel and flood tide delta has a higher energy which results in greater marine deposition. The lower energy of the secondary channel allows for the deposition of some finer materials (Regena, 2016).

Figure 2-8: Sediment sample locations (adapted from Regena 2016, locations are approximately only)
Figure 2-9: Particle size distribution (a - f) (Regena, 2016)
2.3.5 Water Quality

There has been extensive water quality monitoring undertaken in Lake Illawarra. Pacific Power, who operated the Tallawarra power station prior to 2003, then LIA from 2005 – 2013 and continued...
to the present by Wollongong and Shellharbour City Councils. Currently, 15 sites are monitored on a monthly basis, as shown in Figure 2-11 and summarised in Table 2-4. Water quality constituents measured at these sites include:

- pH;
- temperature;
- dissolved oxygen;
- salinity;
- turbidity;
- total nitrogen;
- total phosphorous; and
- chlorophyll-a.

In addition to these monthly measurements across the lake, MHL operate two water quality meters that collected data continuous at 15 minutes at Cudgeree Bay and Koonawarra Bay (locations shown in Figure 2-6). These stations measure pH, temperature, salinity, chlorophyll a (from November 2014 onwards) and dissolved oxygen (Koonawarra only).

![Figure 2-11: WCC Water quality monitoring sites (WCC, 2017)]
### Table 2-4: Summary of WCC water quality locations

<table>
<thead>
<tr>
<th>Site Location</th>
<th>ID</th>
<th>Lake Zone</th>
<th>Monitoring Commenced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entrance Channel at the south training wall</td>
<td>Site 1</td>
<td>Lake Entrance</td>
<td>2005 (LIA)</td>
</tr>
<tr>
<td>Boat ramp at Windang Peninsula</td>
<td>Site 2</td>
<td>Lake Entrance</td>
<td>2005 (LIA)</td>
</tr>
<tr>
<td>Bridge to Picnic Island</td>
<td>Site 3</td>
<td>Lake Entrance</td>
<td>2005 (LIA)</td>
</tr>
<tr>
<td>Jetty at Boonerah Point Reserve</td>
<td>Site 3A</td>
<td>Lake Edge</td>
<td>Jan 2014</td>
</tr>
<tr>
<td>Jetty at Sailing Club at Burroo Bay</td>
<td>Site 4</td>
<td>Lake Edge</td>
<td>2005 (LIA)</td>
</tr>
<tr>
<td>Jetty at Tallawarra Power Station</td>
<td>Site 4A</td>
<td>Lake Edge</td>
<td>Jan 2014</td>
</tr>
<tr>
<td>Boat ramp and jetty at Kanahooka</td>
<td>Site 5</td>
<td>Lake Edge</td>
<td>2005 (LIA)</td>
</tr>
<tr>
<td>Jetty at Holborn Park Reserve</td>
<td>Site 5A</td>
<td>Lake Edge</td>
<td>Jan 2014</td>
</tr>
<tr>
<td>Jetty at Griffins Bay Wharf</td>
<td>Site 6</td>
<td>Lake Edge</td>
<td>2005 (LIA)</td>
</tr>
<tr>
<td>Jetty at Purry Burry Reserve</td>
<td>Site 6A</td>
<td>Lake Edge</td>
<td>Jan 2014</td>
</tr>
<tr>
<td>North along a north-south transect</td>
<td>NS1</td>
<td>In-lake</td>
<td>March 2014</td>
</tr>
<tr>
<td>Middle along a north-south transect</td>
<td>NS2</td>
<td>In-lake</td>
<td>March 2014</td>
</tr>
<tr>
<td>South along a north-south transect</td>
<td>NS3</td>
<td>In-lake</td>
<td>March 2014</td>
</tr>
<tr>
<td>East along an east-west transect</td>
<td>EW1</td>
<td>In-lake</td>
<td>March 2014</td>
</tr>
<tr>
<td>West along an east-west transect</td>
<td>EW2</td>
<td>In-lake</td>
<td>March 2014</td>
</tr>
</tbody>
</table>

### 2.4 Similar Case Studies

There have been several estuaries that have been artificially trained along the NSW coast. The motivation for entrance training varies, however it is often related to reducing the impact of flooding, providing safe navigation, or to improve water quality (or a combination). Nielsen and Gordon (2016) state that such practices often have unintended consequences, including:

- Increasing tidal range as the entrance enters an unstable scouring mode;
- Scouring causing damage to infrastructure;
- Increasing tidal velocities, inhibiting recreational and navigation activities;
- Loss of seagrass and saltmarsh habitat;
- Altering littoral drift patterns either side of the entrance; and
- Changing long-term beach alignments.

This section examines case studies of two NSW estuaries that were trained prior to Lake Illawarra, and provides a summary of morphological changes experiences and the management of the two systems.
2.4.1 Wallis Lake

Wallis Lake separates the towns of Forster and Tuncurry, approximately 215 km north of Sydney. The lake has a surface area of 100 km$^2$ and is connected to the ocean through a 400 m trained channel. Prior to any entrance works, the entrance to the lake was meandering and shoaled due to the littoral drift along the coast (Nielsen and Gordon, 1980).

The first entrance works at Wallis Lake included the construction of a southern breakwater in 1898, with the intention of improving navigation. However, in 1966, this was deemed insufficient and the southern breakwater was extended by 90 m and a 460 m northern breakwater was constructed. Nielsen and Gordon (2008) estimated that the tidal range prior to the construction of the northern breakwater was approximately 4% of the ocean tide, but had increased 17% by 2004. This equates to an average increase in tidal range 2.4 mm/yr between 1966 and 2004. This increase in tidal range has been accompanied with significant scouring of the seaward 3 kilometres of the estuary and increasing tidal velocities in the entrance channel. The increasing tidal velocities, tidal prism and channel scouring is continuing to occur. Nielsen and Gordon (2008) estimate that the channel will continue to scour, if left unabated, until the tidal range in the lake is around 85% of the ocean tide and the cross sectional area of the tidal entrance channel increases to 5,000 m$^3$.

Unexpected increases in tidal velocities and the tidal range has had significant impact on the ecology of the lake, as well as impact on man-made structures. An increase in the area of the flood tide delta has smothered endangered seagrasses and sedimentation as a result of mobilisation from fast tidal currents has impacted navigability. To manage these impacts, dredging and re-distribution of sediments has been required (GLC, 2014).

As well as issues of sedimentation, mitigation of the effects of erosion and scour has also been required. Scouring eventually resulted in damage to the foundations of the Forster-Tuncurry Bridge, resulting in extensive repairs being required (Nielsen and Gordon, 2016).

2.4.2 Lake Macquarie

Lake Macquarie is located 130 km north of Sydney and is connected to the ocean by the 4.5 km long Swansea Channel with a lake surface area of approximately 110 km$^2$. The entrance of the lake was trained between 1878 to 1887 and since that time there has been significant issues related to channel scour and bank erosion. Nielsen and Gordon (2008) estimated that the spring tidal range was increasing at a rate of 1.3 mm/year (between 1992 and 2008). An Escoffier analysis suggests that the channel will continue to scour (subject to morphological constraints) until the tidal range in the lake is 77% of the ocean tide.
There have been a significant number of issues associated with the increasing tidal range in Lake Macquarie. The high tidal velocities have caused significant amounts of scouring, foreshore erosion and flood tide delta sedimentation which has resulted in damage to infrastructure and loss of ecological habitat. Similar to the Forrester Tuncurry Bridge, there has been significant scour around the foundations of the Pacific Highway bridge that crosses the Swansea Channel. Scour holes underneath the bridge are up to 11 m deep (WBM, 1996).

The issues associated with the training of the Swansea Channel have necessitated on-going management of the area by the Council. To manage sedimentation and maintain navigability through the flood-tide delta, periodic dredging is required in some parts of the entrance. In 2014, a $1.5 million contract was awarded to undertake a ‘once off’ large scale dredge campaign to establish a channel that was 60 m wide and 3.5 m deep, with the dredge spoil being piped to a nearby beach (Neuman Contractors, 2014). This contract also involved smaller scale subsequent maintenance dredging. Managing the impact of foreshore erosion has also been an ongoing issue. WBM (2014) assessed various options for managing the risks posed to the community by the entrance, stating that existing revetments and groynes will likely need to be maintained and/or extended into the future to halt foreshore erosion. The report also stated that as the channel evolved, new development controls may become the most feasible way to minimise long term risk posed by the rapidly changing geomorphology of the site.
3 Investigations

3.1 Preamble

Lake Illawarra is a dynamic system undergoing rapid changes in bathymetry and hydrodynamics. WRL completed detailed field investigations as part of this study to collect present day bathymetry, flow, water level, and sediment transport rate data. This field dataset was utilised to develop conceptual models of the site, as well as to calibrate the hydrodynamic model. This section outlines the methods and extent of the data collection program.

3.2 Hydrographic Survey

A detailed hydrographic survey was undertaken from the 8th to 12th October 2018. Sub-aerial data was primarily collected using a jetski equipped with a CEEDUCER pro RTK hydrographic survey system mounted on-board with a 200kHz transducer interfaced with the HYPACK hydrographic survey software (Figure 3-1). This system is capable of working in depths as shallow as approximately 30 cm, which was appropriate for most parts of the main channel, the ebb tide delta and the flood tide delta. In sections where high tide levels were too shallow for using the jetski, the estuary was surveyed on foot using an Trimble RTK GPS. Surveys have a nominal accuracy of ±10 cm. Figure 3-2 outlines the coverage of the WRL’s October 2018 hydrographic survey.

Figure 3-1: Jetski hydrosurvey setup
In addition to the jetski hydrosurvey and survey undertaken on foot, WRL also undertook a
aerial survey with an eBee RTK survey grade drone. Due to the size of the area, flights were undertaken
on successive days on the 3rd and 4th of December. The drone uses an advanced photogrammetry
technique called “structure through motion” to develop a detailed, three dimensional surface from
the images taken during the flight. This system provides a high accuracy dataset for textured and
stationary surfaces, but cannot capture accurate data below the water surface, in the swash zone or
beneath vegetation. Data from the drone flights has been used to infill data in areas that were too
shallow to cover with the jetski, particularly near Berageree Island and east of Cudgeree Island
where there are significant areas of sand shoals that remain dry. By combining the jetski and drone
data, there is sufficient coverage of the entire entrance channel to undertake sediment analysis and
to use the data for numerical modelling of the site and compare to previous hydrographic survey
datasets.

3.3 Intertidal Drone Survey

Figure 3-2: October 2018 hydrographic survey coverage
3.4 Tidal Gauging

Flow gauging over a spring tidal cycle was undertaken on the 11th October 2018. Discharge was measured using Sontek RiverSurveyor-M9 (M9) and RDI Workhorse Acoustic Doppler Current Profiler (ADCP) and an external Trimble R10 RTK GPS to record position. Note that the ADCP was only used for the final two (2) hours of gauging after the M9 ceased working due to an internal memory issue. Both instruments measure velocities through the water column, which is integrated over the cross section to provide an estimate of flow. In both cases, the instrument was mounted to the boat as per Figure 3-3. Flow was gauged near the mouth of the estuary, as shown in Figure 3-4. Observed flows are shown in Figure 3-4.

Figure 3-3: Sontek M9 mounted to the boat for gauging
**Figure 3-4: Flow gauging location**

**Figure 3-5: Observed flows (smoothed) on 11th October 2018 (not corrected for bed movement)**
3.5 Water Level Loggers and Velocity Meters

Over the period of the intensive field campaign (8\(^{\text{th}}\) – 12\(^{\text{th}}\) October), three (3) Marotte HS drag-tilt current meters (to measure velocity) and six (6) Heron water level loggers were installed at strategic locations throughout the channel, shown in Figure 3-6. Four (4) of the water levels were left in place as long-term (3 – 6 month) loggers in order to undertake a tidal plane analysis on the data over a longer period.

![Figure 3-6: Locations of water level loggers and velocity meters](image-url)
High water velocities were observed throughout the entrance during both flood and ebb tides. The currents are sufficient to mobilise the bed sediments, which accounts for the morphological changes that have been observed since the training walls were built. To understand the rates of change and how sediment transport varies throughout the entrance channel, bed transport rates were measured at various locations using an RDI ADCP (Acoustic Doppler Current Profiler) coupled with a Trimble RTK GPS. The ADCP measures movement using the bed as a reference point (bottom tracking, or BT). If the boat remains stationary, but the bed is moving the ADCP registers movement along a track in the opposite direction to the sediment transport. This can then be compared to the GPS track (see Figure 3-8) and the difference between the two tracks over time provides a measurement of the bed transport rate.

As current velocities vary throughout the tidal cycle, measurements were repeated at different stages of the cycle at most locations. The locations of bed transport measurement are shown in Figure 3-9, and a summary of the bed transport rates is provided in Figure 3-10. Figure 3-10 also shows the modelled tidal flows out the entrance to illustrate the part of the tidal cycle that was captured during that measurement. The fastest sediment transport rates were observed at the entrance to the estuary in the channel that runs adjacent to the southern breakwater.
Figure 3-8: Example of bottom track (BT) versus GPS track

Figure 3-9: Location of bed transport measurements
Figure 3-10: Bed transport rates, water velocity and modelled flows
3.7 Background Sediment Samples

On the 28th of August, background sediment samples were taken throughout the entrance channel and on Windang and Warilla Beach using a petite Ponar grab sampler (see Figure 3-11). The locations of the samples were distributed to represent the different sections of the estuary and are shown in Figure 3-12. The particle size distribution was analysed by Environmental Tracing Pty Ltd and is summarised in Table 3-1. Note that the volume collected at location 7 was too small to analyse. For all samples except location 8, the dominate sediment classification was medium sand (250 – 500 μm), consistent with the results of Regena (2016) within the main channel. At all locations, more than 90% of the sediments were greater than 160 μm. Only samples within the lake and side channels (locations 20, 24, 25, 27, 28 and 31) had significant amounts (>1%) of silt present. The largest grain sizes were typically observed within the deeper sections of the main channel where velocities are generally higher.

Figure 3-11: Background sampling of lake and entrance channel sediments (28/08/2018)
Figure 3-12: Locations of background samples
Table 3-1: Summary of particle size distribution
(two dominate bands are highlighted in green)

<table>
<thead>
<tr>
<th>Sample</th>
<th>&gt;1000 um</th>
<th>&gt;500 um</th>
<th>&gt;250 um</th>
<th>&gt;180 um</th>
<th>&gt;160 um</th>
<th>&gt;125 um</th>
<th>&gt;90 um</th>
<th>&gt;63 um</th>
<th>&lt; 63 um</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.20%</td>
<td>12.55%</td>
<td>70.65%</td>
<td>15.99%</td>
<td>0.03%</td>
<td>0.35%</td>
<td>0.19%</td>
<td>0.02%</td>
<td>0.02%</td>
</tr>
<tr>
<td>2</td>
<td>0.03%</td>
<td>1.73%</td>
<td>57.71%</td>
<td>37.79%</td>
<td>1.93%</td>
<td>0.71%</td>
<td>0.06%</td>
<td>0.02%</td>
<td>0.02%</td>
</tr>
<tr>
<td>3</td>
<td>1.63%</td>
<td>16.27%</td>
<td>66.80%</td>
<td>14.80%</td>
<td>0.32%</td>
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</table>
Figure 3-13: Bed sediment particle size distribution
4 Sediment Tracer Field Investigation

4.1 Preamble

A sediment tracer field investigation involves the deployment of purpose made tracer particles at strategic locations that are allowed to migrate under natural conditions with in-situ sediments. Following deployment, sediment samples can be collected throughout the study area and analysed for tracer particle concentration. This enables the magnitude and direction of sediment flux to be quantified, and can provide an unambiguous marker of littoral transport over time and space.

EcoTrace, the tracer proposed for use in this study, contains a fluorescent pigment which is bound to a naturally occurring mineral (Barium Sulfate) using a polyester resin. The tracer particles are approximately 85% by weight Barium Sulfate. However, the small percentage of fluorescent pigment remains readily measurable when analysed under the appropriate frequency light. This allows the tracer to have similar physical properties to the local sediments (particle size distribution and density) and be identifiable at very low concentrations as the sediments naturally disperse.

This section provides a brief justification for the need for the sediment tracer field investigation to support the aims of this project and an overview of methodology proposed for the investigation.

4.2 Justification

Using traditional field data collection methods, such as those described in Section 3, only provides a certain degree of certainty on the sediment dynamics in a rapidly evolving system like Lake Illawarra. While bathymetry surveys can show where areas of erosion and accretion exist and whether there is a net loss or gain of sediment throughout the channel, it is difficult to use this information to determine the source/sink processes that drive the changes. It is, for example, presently unclear whether offshore marine sediments enter the channel on a flood tide and contribute to a slow infilling of the lake (through progradation of the flood tide delta), or if sediment from the entrance is being lost offshore from the system during ebb tides. As sediment transport processes occur due to a complex combination of regular tidal currents, and longer-term transport from processes such as catchment flooding, ocean swell events, and Aeolian (wind) transport, spot measurements of bed transport velocities are limited to understanding bed transport at a certain moment in time.
Initial sediment dynamics numerical models of the entrance training (Lawson and Treloar, 2004) prior to the construction of the walls failed to predict the unstable scouring mode that the permanent entrance opening initiated. Sediment transport is a complicated process to model due to a number of factors including the presence of bed forms, subtle changes in sediment grain size and sensitivity to the model boundary conditions. Raw survey data shows that there are significant bed forms in the Lake Illawarra (shown in Figure 4-1) which are not typically able to be represented in numerical models due to the survey data, fine grid size and associated computing power required. Analysis of the sediments in the channel shows that grain size sometimes varies over a small spatial scale (such as background sample locations 11 and 12 in Table 3-1, which were both taken from inside the pool), which are unlikely to be adequately represented in a model. These difficulties, and the inability of previous models to adequately predicted realised erosion, make numerical modelling of the sediment dynamics on this site unreliable and unsuitable for the purpose of this study.

Figure 4-1: Presence of significant bed forms near the mouth of the entrance channel
As sediment transport modelling is not considered feasible to support the aims of this project, to confidently provide a reasonable estimate of the magnitude and direction of sediment flux throughout the entrance channel requires field measurements. Spot measurements of bed transport rates with the ADCP with sufficient spatial and temporal coverage to understand net sediment transport rate and directions is considered infeasible. Sediment traps have been traditionally used to measure sediment transport rates and while this method is capable of measuring sediment transport over a longer time frame (e.g. a whole tidal cycle) than the ADCP at a single location (as it does not need to be constantly manned), it is still limited in the spatial domain.

Sediment tracer studies have been undertaken across the world, and are considered a flexible and effective tool for measuring sediment transport in estuaries (Uncles and Mitchell, 2017). Undertaking a well-designed field sediment tracer study allows for the direct quantification of sediment flux/rates and characterisation of the source/sink processes occurring in the entrance. This would otherwise only be estimated with a low degree of certainty based on gross sediment loss over a two year period and point measurements of bed transport using an ADCP. This information can significantly increase the confidence of stakeholders and the community in the assessment of different engineering approaches and operational strategies to be adopted for the ongoing management of the Lake Illawarra entrance channel. Given that the potential risks associated with the continuing scour of the entrance have possibly substantial financial and social consequences (e.g. undermining of the Windang Bridge, damage public recreational space and existing protective structures), it is considered necessary to undertake more extensive and comprehensive field investigations at early stages of the project to assist in well informed management of the lake into the future.

4.3 Methodology

4.3.1 Tracer Deployment Locations

The proposed deployment locations for the sediment tracer are shown Figure 4-2. A total of 450 kg, or 0.17 m$^3$ by volume, is proposed to be deployed. The locations of the deployment have been strategically placed to assist in the determination of key questions about the sediment transport throughout the entrance channel. A brief justification of each of the locations is provided in Table 4-1.
Figure 4-2: Proposed sediment tracer deployment locations

Table 4-1: Short justification of possible tracer deployments

<table>
<thead>
<tr>
<th>Location</th>
<th>Primary Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>A – Ebb Tide Delta</td>
<td>It is presently uncertain whether marine sand from offshore is a source of additional sediments coming into the entrance channel or whether sediments that are deposited on the ebb tide delta re-enter the system on the flood tide or are essentially lost from the system. Location A will identify whether there is any sediment flux from outside the breakwaters into the channel through flood tide processes or transport from waves. This will assist in understanding sediment sources into the system. As the ebb tide delta is in the active coastal zone with significant wave action, Site A has the largest volume of tracer proposed. This decreases the risk of the sediment being rapidly lost due to moderate coastal wave events prior to any sampling.</td>
</tr>
<tr>
<td>B – Entrance Shoal</td>
<td>Analysis of available aerial imagery shows that the entrance shoal, off the northern bank 400 m downstream of the head of the breakwaters, is a persistent feature of the entrance channel. This site will identify whether sand from this location is in a</td>
</tr>
<tr>
<td>Location</td>
<td>Primary Justification</td>
</tr>
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<tr>
<td>closed loop within the entrance channel – sediment may be pushed into the flood tide channel (along the southern breakwater) on an incoming tide and be moved upstream, only to be brought back to the spit on the ebb tide. Alternatively, the shoal may just be a temporary trap for sediments that are constantly being eroded from upstream that ultimately leave the system on large tides. This location will assist in understanding the nett sediment transport downstream of the bridge.</td>
<td></td>
</tr>
</tbody>
</table>

| C – Just Downstream of Berageree Island | Observations in the field and preliminary modelling shows that the channel adjacent to Berageree Island is most active on the flood tide. Surveys have also indicated that this channel is currently eroding, although some of the nearby shoals are accreting. This site will show whether the sediments from here are ultimately ending up on the flood tide delta, are part of a circulatory system that eventually ends up on the entrance spit, or are simply supplying sand to the nearby shoals. |

| D – Immediately Upstream of Windang Bridge | Both observations during spring tides and the pilot model of the estuary shows that upstream of the bridge experiences high velocities during both ebb and flood tides, and the shoals around this area appear to be actively changing from observations on aerial images. This area will help to identify whether there is a significant flood tide transport towards the lake or whether the ebb tide is transporting sand towards the entrance from upstream of the bridge. |

| E – Channel between Bevans Island and Cudgeree Island | Preliminary analysis of bathymetry data shows that while the flood tide delta is changing and expanding in surface area, the total volume of sand does not appear to be increasing significantly. Tracer deployment at Location E will assist in understanding whether the flood delta is reshaping or if there is a net transport of sediments into the lake. |

### 4.3.2 Particle Size Distribution

The particle size distribution within the entrance channel showed that the dominate grain size throughout almost all of the samples was between 250 – 500 μm. While the grain size does vary, the variations are often subtle and can vary over a relatively small spatial scale. It was therefore decided to compare the tracer to the average grain size throughout the channel. The comparison of the distribution of the five (5) tracer colours and the average observed sediment is shown in Figure 4-3. The five (5) colours all have a relatively uniform particle size distribution, with the same dominant grain size of that observed in the estuary. The particle size of the tracer observed in each of the samples collected can be measured; this will allow an understanding of how grain size influences sediment transport throughout the system. There is still sufficient tracer that is the same size as the in-situ sediment to understand true sediment flux through the system.
Figure 4-3: Average observed particle size distribution compared to the distribution of the five tracer colours

4.3.3 Sampling Locations

The sampling locations are proposed to be distributed throughout the entrance channel study domain, including the flood and ebb tide delta, side channels and the beaches either side of the entrance. Indicative sampling locations are shown in Figure 4-4. The locations for sampling are designed to provide a good spatial coverage of the active areas of the sediment transport system and to assist in providing information to address the present gaps in knowledge (discussed in Table 4-1).

Samples will be collected using a Van Veen style grab sampler or similar from a small vessel. In shallow areas (depths < 1 m), samples will be collected by hand using a grab sampler with the equivalent sampling area and volume to the Van Veen grab sampler. RTK GPS will be used to record the location of each sample. Coring in shallow water will be conducted by hand using an auger. Coring samples in deeper waters will be collected using a Vibracoring system (or similar) from a small vessel at the conclusion of the sampling program. Coring will enable the rate of accretion to be determined.

Samples will be analysed by Environmental Tracing (ET) Pty Ltd at a specialised laboratory in the UK. Measurements will provide the concentration and particle size distribution of the tracer observed in each of the samples, which will subsequently be used to quantify sediment flux and
inform a conceptual understanding of sediment transport throughout the channel. Particle detection limits are 1 tracer particle per 10 million natural sand grains or 2 µg/kg.

Figure 4-4: Indicative sampling locations

4.3.4 Sampling Schedule

Sediment transport processes in Lake Illawarra are likely to be caused by a complex combination of daily tides, spring and neap tidal cycles, catchment flows and coastal processes. It is important that the temporal resolution of the sampling reflects the different processes that are occurring. A summary of the proposed sampling schedule, and the target process is provided in Table 4-2. Event driven processes, such as catchment flows and wave processes cannot be predicted prior to deployment, and will also impact the results. Interpretation of the sediment transport observed will include an assessment of the environmental conditions since the deployment of the tracer.
<table>
<thead>
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<td>Spring tidal cycle</td>
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<tr>
<td>1 month</td>
<td>Surface Only</td>
<td>Full 28 day tidal cycle</td>
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<tr>
<td>6 months</td>
<td>Surface and Core</td>
<td>Long-term accumulation of processes and net impact on the sediment transport</td>
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</table>
5 Analysis of Field Data

5.1 Preamble

This section provides an overview of the analysis and interpretation of the field data collected to date at Lake Illawarra. This section includes comparisons of the 2018 field data with the previously collected data within the estuary and details observed of changes in the area.

5.2 Bathymetry

Using the data collected from the jetski survey, drone survey and survey on foot, a Digital Elevation Model (DEM) of the entrance channel was constructed (Figure 5-1). The bathymetry data collected indicates that the entrance is channelised and there are significant scour holes off the groynes adjacent to the left bank (left looking downstream) (Figure 5-2) that are more than 10 m deep.

![Figure 5-1: DEM of Lake Illawarra 2018 bathymetry](image)
It is important to understand how the estuary has continued to change since 2016, when the last hydrographic survey was undertaken by OEH. The 2018 survey was compared to the 2016 dataset and the result is shown in Figure 5-3, where blues and greens indicate erosion and yellows and reds indicate accretion. The comparison shows that there has been a net loss of sediment from inside the entrance channel of approximately 370,000 m$^3$. Note that this sediment loss may have been transported offshore beyond the ebb tide delta, or into the lake. This analysis is not sufficient to determine the net sediment transport direction.

Overall, this comparison shows that the main channel through the entrance has continued to erode since 2016 and the scour holes off the end of the groynes have become substantially deeper. The channel that runs adjacent to Judbowley Point has eroded and conveys flow efficiently around the edge of the point. While there is a net erosion throughout the entrance channel, the flood tide delta is prograding into the lake, evidenced by the accretion off the north-eastern edge of the delta.
Some of the shoals, particularly immediately downstream of Windang Bridge and around the south east corner of Picnic Island, have also reshaped, moved or accreted. The channel between Bevans Island and Reddall Parade has remained relatively consistent between the two surveys.

Figure 5-3: Comparison of 2018 and 2016 DEMs

5.2.2 Flood-Tide Delta

Consistent with the observations of Regena (2016), the flood tide delta area is increasing as shown in Figure 5-4. Based on an analysis of aerial images by Regena (2016) and the most recent bathymetry survey, since 2014 the flood tide delta is largely only prograding into the lake in the northern areas, suggesting the majority of the flood tide flows through this area. As shown in Figure 5-4, this is supported by increasing channelisation of the flood tide delta. It is likely that the flood
tide flow acts more like a jet, with most of the flow being conveyed by the most efficient channel, while ebb tide flow is distributed more evenly across the full width of the entrance channel.

Figure 5-4: Change in the flood tide delta - 2016 to 2018

5.2.3 Windang Bridge to Bevans Island

The area upstream of Windang Bridge has undergone some substantial changes since the 2016 bathymetry survey, shown in Figure 5-5. There has been erosion of the main channel that runs adjacent to Bevans Island, leading to a gradual undermining of the north eastern banks of Bevans Island. Similarly, the scouring of the ebb tide channel that runs off the northern bank of Picnic Island has also caused undermining, shown in Figure 5-6 and consistent with the observations by
Wiecek (2018). There has also been a significant deepening of the channel that runs along the bank of Judbowley Point, which conveys a substantial amount of flow on the incoming flood tide.

The alignment of the main channel in this region has changed since the 2016 survey, with a nett migration in a southerly direction, as depicted in Figure 5-5. The channel has widened since 2016 and extends along the entire north eastern bank of Bevans Island.

While there has been a nett erosion of sediment in this region, there are a number of shoals that have accreted. On the eastern side of Picnic Island, sediment has accreted, limiting flow through the small channel that runs between the Island and the reserve on the southern side of Windang Bridge. Through observations from aerial imagery, it appears that this sand is being deposited on the flood tide from downstream, rather than a deposition from the eroding ebb tide channel to the east.
Figure 5-5: Area upstream of Windang Bridge, comparison of 2016 and 2018 surveys
5.2.4 Downstream of Windang Bridge

The area downstream of Windang Bridge is characterised by channelised flow on both the ebb and the flood tide. As shown in Figure 5-7, this region has also experienced a net loss of sediment between 2016 and 2018. The scour holes off the groynes (constructed in 2012) near the Windang caravan park have continued to deepen a further 4 metres in the two years between the surveys. Ultimately, continued scouring of these holes are a threat to the stability of groyne structures, which could fail if the holes continues to scour. There has also been significant scouring underneath Windang Bridge on the northern side, which is a concern for the on-going longevity of the bridge pylons.

The channel that runs on the eastern side of Berageree Island has continued to erode since 2016 and is now a defined channel that conveys significant flows, particularly on the flood tide. It appears that the sand from this channel may be the source of accreted sand on the south-eastern side of Picnic Island, a process that could be confirmed with the sediment tracer study. The shoal north
east of this channel appears to have accreted, however the dynamic nature of these shoals makes it difficult to assess whether the same shoal is just migrating and reshaping, or if there is a true nett accretion.

The main flood and ebb tide channels between the entrance and the bridge have also continued to erode. As the area between the two training walls is the most constricted section of the entrance channel, erosion here is consistent with the increasing tidal prism observed during the gauging exercise. The channel is becoming more efficient to facilitate a smaller hydraulic gradient between the lake and the ocean during peak tides, and as it cannot grow wider between the walls, the channel has continued to deepen.

![Figure 5-7: Area downstream of Windang Bridge, comparison of 2016 and 2018 surveys](image)
5.3 Bed Transport Measurements

Theoretical estimates of bed transport velocities can be made based on the water column velocity, depth and observed grain size using the methods described in Van Rijn (1984). Assuming a uniform median grain size ($D_{50}$) of 300 μm, Table 5-1 shows a comparison of measured and theoretical bed load velocity. This indicates that the theoretical bed load velocity is at least an order of magnitude larger than measured bed load at each location. While Nielsen and Williams (2017) have previously shown that van Rijn’s (1984) empirical formulas overestimate bed load, their results showed an overestimation of a factor of 3, significantly less than what has been observed at Lake Illawarra. Nielsen and Williams (2017) also demonstrated that there was a large scatter for observed bed load velocities, despite similar environmental conditions, which is consistent with the field measurements collected at Lake Illawarra.

<table>
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<tr>
<th>Location</th>
<th>Average Water Speed (m/s)</th>
<th>Depth (m)</th>
<th>Measured Bed Load Velocity (m/s)</th>
<th>Theoretical Bed Load Velocity (m/s)</th>
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<td>5.9</td>
<td>0.032</td>
<td>0.24</td>
</tr>
<tr>
<td>2</td>
<td>1.049</td>
<td>2.9</td>
<td>0.013</td>
<td>0.35</td>
</tr>
<tr>
<td>3</td>
<td>0.692</td>
<td>4.0</td>
<td>0.001</td>
<td>0.18</td>
</tr>
<tr>
<td>3</td>
<td>0.967</td>
<td>3.7</td>
<td>0.011</td>
<td>0.31</td>
</tr>
<tr>
<td>3</td>
<td>0.806</td>
<td>3.1</td>
<td>0.001</td>
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</tr>
<tr>
<td>4</td>
<td>0.733</td>
<td>10.0</td>
<td>0.010</td>
<td>0.17</td>
</tr>
<tr>
<td>4</td>
<td>0.888</td>
<td>3.5</td>
<td>0.016</td>
<td>0.27</td>
</tr>
<tr>
<td>5</td>
<td>0.801</td>
<td>4.5</td>
<td>0.002</td>
<td>0.23</td>
</tr>
<tr>
<td>5</td>
<td>0.871</td>
<td>3.9</td>
<td>0.002</td>
<td>0.26</td>
</tr>
<tr>
<td>6</td>
<td>0.447</td>
<td>3.5</td>
<td>0.001</td>
<td>0.07</td>
</tr>
<tr>
<td>6</td>
<td>1.085</td>
<td>4.0</td>
<td>0.004</td>
<td>0.36</td>
</tr>
<tr>
<td>7</td>
<td>0.283</td>
<td>3.0</td>
<td>0.003</td>
<td>0.00</td>
</tr>
<tr>
<td>7</td>
<td>1.108</td>
<td>2.4</td>
<td>0.001</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Overestimation of bed load velocity through empirical estimates may be a result of a number of factors, including generalised estimates of grain size, impact of bed forms on sediment velocity, bed slope, or other site specific conditions. Overall, this highlights the degree of certainty that can be achieved using theoretical bed transport equations and shows the need for further field measurements of sediment transport using the sediment tracer study.
5.4 Flow Gauging

Direct comparison of the four (4) flow gauging exercises undertaken in 2008, 2012, 2016 (by MHL) and 2018 (by WRL) is difficult due to the differences in offshore tides during each of the gauging exercises. Table 5-2 shows the open coast tidal water levels for each of the four (4) tidal cycles measured. While each measurement was undertaken during spring tides, high tide level in 2018 was lower than the 2016 and 2012 tides. Despite this, Table 5-3 shows that maximum discharge and tidal prism was larger in 2018 than any of the previous years (except the flood tidal prism, which was equal to the 2016 measurement). This indicates that there has been an increased efficiency of the channel and that the day to day tidal prism of the estuary is increasing on comparable tides. This is consistent with previous observations by MHL (2016), Wiecek et al. (2016) and Nielsen and Gordon (2016) who showed that the tidal range within the lake has been constantly increasing since the training walls were constructed in 2007. Increasing tidal flows are a direct result of erosion of the entrance channel and the subsequent larger channel cross-sectional area.

Table 5-2: Jervis Bay measured water levels during tidal gauging exercises

<table>
<thead>
<tr>
<th>Date</th>
<th>Low Tide (m AHD)</th>
<th>High Tide (m AHD)</th>
<th>Low Tide (m AHD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/03/2008</td>
<td>-0.60</td>
<td>0.71</td>
<td>-0.59</td>
</tr>
<tr>
<td>16/10/2012</td>
<td>-0.74</td>
<td>0.84</td>
<td>-0.69</td>
</tr>
<tr>
<td>11/03/2016</td>
<td>-0.70</td>
<td>0.82</td>
<td>-0.74</td>
</tr>
<tr>
<td>11/10/2018</td>
<td>-0.74</td>
<td>0.65</td>
<td>-0.72</td>
</tr>
</tbody>
</table>

Table 5-3: Tidal Prism and maximum discharge for the four gauging exercises

<table>
<thead>
<tr>
<th>Year</th>
<th>Tidal Prism</th>
<th>Maximum Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flood (m³ x 10⁶)</td>
<td>Ebb (m³ x 10⁶)</td>
</tr>
<tr>
<td>2008</td>
<td>2.7</td>
<td>2.1</td>
</tr>
<tr>
<td>2012</td>
<td>4.9</td>
<td>4.1</td>
</tr>
<tr>
<td>2016</td>
<td>5.5</td>
<td>4.8</td>
</tr>
<tr>
<td>2018</td>
<td>5.5</td>
<td>5.6</td>
</tr>
</tbody>
</table>

5.4.1 Impact of Bed Transport on Flow Measurement

All the measurements provided in Table 5-2 were taken using a method called “bottom tracking”. Bottom tracking calculates the velocity of the water relative to the bed, which allows flows to be
measured from a moving vessel. When the bed is stationary, this is a true measure of water velocity. However, if there is bed load transport, this method will underestimate the velocity and discharge, due to the movement of the bed in the direction of flow.

To assess the potential impact of bed transport on the flow measurements, the bed transport rates measured the day before the tidal gauging (see Section 3.6) were analysed. Bed transport rates between 0.001 – 0.079 m/s were measured throughout the channel, when average measured water velocities were between 0.28 – 1.21 m/s. A site specific linear relationship was developed between the water velocity and the bed transport rate, which is shown in Figure 5-8. This relationship implies water velocity for initiation of movement of approximately 0.52 m/s and shows that bed transport speeds are typically 1 – 2 % of the water velocity.

![Figure 5-8: Observed water speeds and bed transport rates](image)

Using this information, flows during the tidal gauging exercise were adjusted based on the observed velocities in the water column, the results of which are shown in Figure 5-9. The changes to the flows are small, typically 1 – 2 % during the peak of the flood and ebb tide and do not significantly change the tidal prism or discharge.
Figure 5-9: Adjustment of flows for bed transport, showing only minor changes in the flow at the peak of the tide.
6 Conceptual Understanding of Flow

6.1 Preamble

Using the field data and analysis, a conceptual understanding of tidal flows through the Lake Illawarra entrance channel has been developed. This section summarises the major flow paths during the peak of the ebb and flood tide. This information will be used to assist in the development of a conceptual sediment transport model in a later stage of the project.

6.2 Flood Tide

A diagram of the flood tide flows is shown in Figure 6-1, where the size of the arrow is indicative of the relative flow volume in that direction. Flood tide flows hug the south-western (right) bank of the channel until just south of Berageree Island, where the channel switches to the northern-eastern bank. Increasingly, greater flood tide flows are continuing to flow adjacent to the right bank immediately east of Berageree Island, evidenced by the continuing scour in this location; however, this volume is still comparatively small.

Upstream of the Windang Bridge, a portion of the flow is conveyed through the narrow channel immediately adjacent to Judbowlery Point, however, the majority flows through the two main channels that run north-west towards Bevans Island. Once the flow reaches the north-western corner of Bevans Island, the flow continues to jet through the efficient channel that has continued to scour through the flood tide delta that runs to the north/north-north-east.

6.3 Ebb Tide

A diagram of the ebb tide flows is shown in Figure 6-1, where the size of the arrow is indicative of the relative flow volume in that direction. Whilst flows during the flood tide delta are somewhat distributed across the channel, flows during the ebb tide are increasingly constrained as shallow shoals become increasing emergent.

Similar to the flood tide, ebb tide flows are conveyed via the same channel adjacent to Bevans Island, but continues along the right bank along the north-western face of Picnic Island. The channel switches banks just upstream of the Windang Bridge, and continues to follow the northern
bank until it crosses over approximately 350 m upstream of the ocean entrance. The final stretch of the outgoing tide is along the southern breakwater, as per the flood tide.

Figure 6-1: Conceptual understanding of flood tide flow paths
Figure 6-2: Conceptual understanding of ebb tide flow paths
7 Numerical Modelling

7.1 Preamble

Numerical modelling of the Lake Illawarra entrance channel assists in the understanding of the system through extensive temporal and spatial resolution which is typically not feasible to measure in the field. Coupled with targeted data collection, numerical modelling can be driven by, and calibrated to, real world data. WRL has developed a hydrodynamic model of the estuary using the modelling package RMA. RMA-2 is a two dimensional, depth averaged finite element hydrodynamic model which computes finite element solutions for water surface elevations and horizontal velocity components. This section provides an overview of the model development.

7.2 Model Development

7.2.1 Model Extent and Mesh Generation

The hydrodynamic model extends from an ocean boundary and includes the entire surface area of the lake. While catchment inflow channels (such as Macquarie Rivulet, Duck Creek, Brooks Creek and Mullet Creek) are tidal to some extent, the volumes of these channels are insignificant compared to the lake and were therefore considered unnecessary to include in the model. This model has been developed to simulate dry weather conditions where freshwater inflows are small compared to the tidal prism. Currently, this model is not intended as a flood model.

The model extent and mesh are shown in Figure 7-1. As tidal flows in the lake are very small, the majority of the lake is represented by a very coarse numerical grid. However, in the entrance channel the model resolution is significantly increased to represent the complex bathymetry and tidal flow dynamics.
Figure 7-1: Numerical model extent and mesh
7.3 Bathymetry

Two versions of the model have been developed; one using the 2016 bathymetry collected by OEH, and the other using the 2018 bathymetry collected by WRL. The 2018 bathymetry is shown in Figure 5-1. For the sections of the lake beyond the surveyed region, a flat bathymetry of –2 m AHD has been assumed. Within the entrance channel, flood tide delta and ebb tide delta, bathymetry was directly extracted at each node from the appropriate DEM. Minor changes to the mesh configuration were made between the two model versions to better represent the shoals and channels within the entrance.

7.4 Boundary Conditions

7.4.1 Offshore Tide

The downstream boundary of the model is the full ocean tide immediately offshore of the breakwaters. These boundary conditions are the primary driver of the model, determining the tidal flows through the entrance channel. There are several coastal tidal level monitoring stations that could be used as the oceanic boundary condition at Lake Illawarra, including:

- Jervis Bay (operated by MHL on behalf of OEH);
- Port Kembla (operated by National Tidal Centre/BOM); or
- HMAS Penguin, Sydney (operated by MHL on behalf of OEH).

While all of these locations have a similar signal (shown in Figure 7-2), initial results indicate that the model is sensitive to downstream boundary conditions with lake water levels responding to minor differences in ocean boundary water levels. The differences in the model results from using the three different boundary conditions are shown in Figure 7-3 (water levels extracted at Koonawarra within the lake). It is likely that there are local environmental factors (such as wind, surge or barometric pressure) that cause differences in observed water level at each of the tidal monitoring stations. The Port Kembla gauge was adopted as it is the closest location geographically and resulted in the most consistent fit with the observed water levels.
Calibration of the model is essential to understand the accuracy of the results. Calibration was undertaken for both the 2016 model bathymetry and the 2018 model. The model was calibrated to water levels and flows in both cases. Calibration is achieved by varying the model parameters.
including conducting sensitivity testing to determine the influence on key factors, such as bed roughness, on model predictions.

### 7.5.1 2016 Calibration

MHL undertook a tidal gauging exercise on the 11th March 2016 when tidal flows were gauged over a spring tidal cycle. In addition, MHL routinely monitor water levels at three locations (Figure 2-6):

- Cudgeree Bay;
- Koonawarra; and
- Entrance Channel.

To calibrate the model, predicted water levels were extracted at each location and compared to the observed levels. The results were typically within 3 cm of the observed levels are shown in Figure 7-4, Figure 7-5 and Figure 7-6. The model typically replicates observed water levels during some periods, and deviates from observed levels during other periods. As the model was shown to be highly sensitive to the boundary condition applied at the ocean entrance, it is likely that environmental conditions influenced local water levels.

![Figure 7-4: 2016 model calibration at the entrance channel](image-url)
In addition to calibration of observed water levels, the model was also calibrated to the 2016 observed flows on the 11th March. The results are shown in Figure 7-7. The model is able to...
replicate the timing and magnitude of the tidal flows well using a Manning’s n roughness value of 0.022.

**Figure 7-7: 2016 flow calibration**

7.5.2 2018 Calibration

Since there have been significant bathymetric changes in the estuary since 2016, the model bathymetry has been updated and the performance of the model has been verified against the new data collected. Calibration data available is summarised in Table 7-1.

Calibration of the 2018 numerical model is presently underway and will be completed in early 2019.
<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Location</th>
<th>Time Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cudgeree Bay</td>
<td>MHL Water Level</td>
<td>See Figure 2-6</td>
<td>Continuous</td>
</tr>
<tr>
<td>Koonawarra</td>
<td>MHL Water Level</td>
<td>See Figure 2-6</td>
<td>Continuous</td>
</tr>
<tr>
<td>Entrance Channel</td>
<td>MHL Water Level</td>
<td>See Figure 2-6</td>
<td>Continuous</td>
</tr>
<tr>
<td>Main Channel at Pools</td>
<td>WRL Water Level</td>
<td>See Figure 3-6</td>
<td>8/10/18 – 12/10/18</td>
</tr>
<tr>
<td>Main Channel at Boat Ramp</td>
<td>WRL Water Level</td>
<td>See Figure 3-6</td>
<td>8/10/18 – 12/10/18</td>
</tr>
<tr>
<td>Main Channel at Picnic Is</td>
<td>WRL Water Level</td>
<td>See Figure 3-6</td>
<td>8/10/18 – 12/10/18</td>
</tr>
<tr>
<td>Main Channel at Bevans Is</td>
<td>WRL Water Level</td>
<td>See Figure 3-6</td>
<td>8/10/18 – 12/10/18</td>
</tr>
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<td>Channel between Picnic Is and Bevans Is</td>
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<td>See Figure 3-6</td>
<td>8/10/18 – 12/10/18</td>
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<td>Channel between Cudgeree Is and Judbewley Pt</td>
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<td>See Figure 3-6</td>
<td>8/10/18 – 12/10/18</td>
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<td>Channel between Picnic Is and Bevans Is</td>
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<td>See Figure 3-6</td>
<td>8/10/18 – 12/10/18</td>
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<tr>
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<td>WRL Velocity</td>
<td>See Figure 3-6</td>
<td>8/10/18 – 12/10/18</td>
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<tr>
<td>Upstream of Bridge, southern side</td>
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<td>See Figure 3-6</td>
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<td>Entrance</td>
<td>WRL Flow Gauging</td>
<td>See Figure 3-4</td>
<td>11/10/2018</td>
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8 References


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