Lake Illawarra entrance channel: data compilation

WRL TR 2022/25, November 2023

By T A Tucker, I R Coghlan and A J Harrison

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1 Introduction

1.1 Project Introduction

A specialist project team was engaged by Wollongong City Council (hereafter, “WCC”), on behalf of a project control group (hereafter, “PCG”) consisting of WCC, Shellharbour City Council (hereafter, “SCC”) and the NSW Department of Planning and Environment (hereafter, “DPE”), to undertake a two stage study of management options for the Lake Illawarra entrance channel. The Water Research Laboratory (hereafter, “WRL”) of the School of Civil and Environmental Engineering at UNSW Sydney partnered with Manly Hydraulics Laboratory (hereafter, “MHL”) to carry out the study at the direction of the PCG.

1.2 Background

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 lake entrance was intermittently connected to the ocean, 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 in 2007. 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. The entrance channel is presently hydraulically unstable and these changes are continuing to evolve.

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, the local councils (WCC and SCC), and state government asset managers.

This project has two aims:

1. To increase the understanding and interactions of the physical processes that drive changes within the entrance channel at Lake Illawarra. This information (documented in a separate report; Tucker et al., 2023) 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.
2. To develop long-term management options that address both present and potential future issues/threats/hazards to the Lake Illawarra system. The identification, development and assessment of preferred long-term management options will be undertaken in two stages (this report documents the first stage), with greater assessment efforts on a shortlist of options in the second stage.

Figure 1.1 Lake Illawarra location

1.3 Coastal Management Program (CMP)

The Lake Illawarra Coastal Management Program (CMP) was prepared in 2020 to guide the management of Lake Illawarra. In response to the negative changes which have occurred since the entrance was trained, addressing erosion within the entrance channel of Lake Illawarra was identified as action EC1 of the CMP (BMT, 2020a). Action EC1 is described in the CMP as: "*Investigate and Finalise Options to Manage Erosion and Accretion Changes in the Entrance Channel*". One of the tasks outlined within action EC1 is to prepare a "Lake entrance management options study". This scope of works addresses this task within action EC1.

1.4 Overview of project components

1.4.1 Preamble

The scope of works (currently agreed with WCC) is that three reports will be generated during the following two study stages:

- Stage 1: Options development and preliminary assessment
  - Report 1: Preliminary management options assessment (Coghlan et al., 2023)
  - Report 2: Data compilation (this report)

- Stage 2: Detailed assessment of preferred options
  - Report 3: Preferred management options assessment (report to be prepared following shortlist of options as agreed by the PCG).

All three reports for the study are described in the following sections 1.4.2 to 1.4.4.

1.4.2 Report 1: Preliminary management options assessment

The aim of this Stage 1 assessment was to produce a shortlist of preferred, long-term entrance management options to be assessed in detail during Stage 2. An initial list of 50 management options was developed by combining the outcomes from two ideas workshops with specialist staff from WCC, SCC, DPE, WRL and MHL. A high level multi criteria analysis (MCA) of each of these management options was then carried out. The criteria for the MCA, and their respective weightings, were facilitated by WRL and finalised by WCC, SCC and DPE. As a result of the MCA, the 50 management options were ranked in order of preference for the consideration of the PCG to establish an agreed shortlist of five options which will form the basis of Stage 2 of the study.

1.4.3 Report 2: Data compilation

This Stage 1 report summarises relevant literature to date, including data collection and process understanding. It captured the learnings from data collection carried out in 2018, 2021 and 2022 as well as work undertaken as part of the Windang Bridge protection works being implemented by Transport for NSW (hereafter, "TfNSW") following excessive erosion of sand beneath some of the bridge piers. This report includes valuable background/supporting information for the PCG to enable preliminary assessment of long-term entrance management options. A preliminary draft version of this Stage 1 report was used to inform the development of the initial list of 50 long-term entrance management options. This report also documents collected data that will be used to inform the detailed numerical modelling in the Stage 2 assessment.

1.4.4 Report 3: Preferred management options assessment

The Stage 2 assessment will begin with the agreed shortlist of long-term management options confirmed at the end of Stage 1. Further detailed analysis will be undertaken on this shortlist of options including:

- Numerical modelling using an updated, calibrated numerical model of Lake Illawarra estuary for a range of design conditions (to be confirmed with the PCG) including:
    - Present day tidal conditions
    - Flood impact assessment
    - Sea level rise horizons
    - Extreme ocean events
    - Co-incident events
- Multi criteria analysis

As a result of this report, the preferred long-term management option(s) will be selected in consultation with the PCG and other stakeholders.

2 Literature and data 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 a snapshot of some of the key literature and review of data from previous studies completed at Lake Illawarra which are relevant for the current investigation. Note, entrance management issues occurring at Lake Illawarra are similar to those at some other estuaries around the world. Subsequently, a discussion has also been provided reviewing similar case studies in NSW since these estuaries have comparable geomorphology, ecology, infrastructure and tidal range (at the ocean) to Lake Illawarra.

2.2 Literature review

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 PWD (1988) and Sloss et al*.* (2003 and 2005). With reference to Figure 2.1, a summary of the five geomorphological history stages presented in Sloss et al*.* (2005) is paraphrased below:

- Stage 1 (approximately 26,000 to 20,000 years ago): The valley in which Lake Illawarra is situated was first formed during a period of low sea levels, the “last glacial maximum” (LGM), when the action of rivers cut drainage paths through the continental shelf.
- Stage 2 (approximately 7,600 to 5,000 years ago): As sea levels began to rise, sediments began to infill into the valleys, mainly consisting of medium to coarse grained marine sand.
- Stage 3 (approximately 5,000 to 3,200 years ago): As sea levels began to stop rising (at 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. Note that the entrance to the lake at this time was located at Primbee (Korrongulla Swamp) rather than at Windang. As the back-barrier lagoon became a low-energy environment, fine grained catchment sediments were deposited into the lake forming estuarine muds.
- Stage 4 (approximately 3,200 to 2,500 years ago): The entrance to the lake moved from Primbee southward to Windang and became smaller in cross-sectional area as sea levels dropped 1 – 2 m (from level during Stage 3) towards the present day level. The drop in sea levels resulted in a system with comparatively little oceanic connection. Deposition of marine sediments into the lake were largely halted, and fluvial deposits (of finer grained sediments) dominated the sediment inputs into the lake.
- Stage 5 (approximately 2,500 years ago to the present [prior to entrance training]): The entrance to the lake at Windang become even smaller in cross-sectional area with the lower present day sea level. Fluvial deposition continued resulting in accretion of sediment adjacent to the western end of the entrance channel. 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 now classified as an open and trained wave dominated barrier estuary.

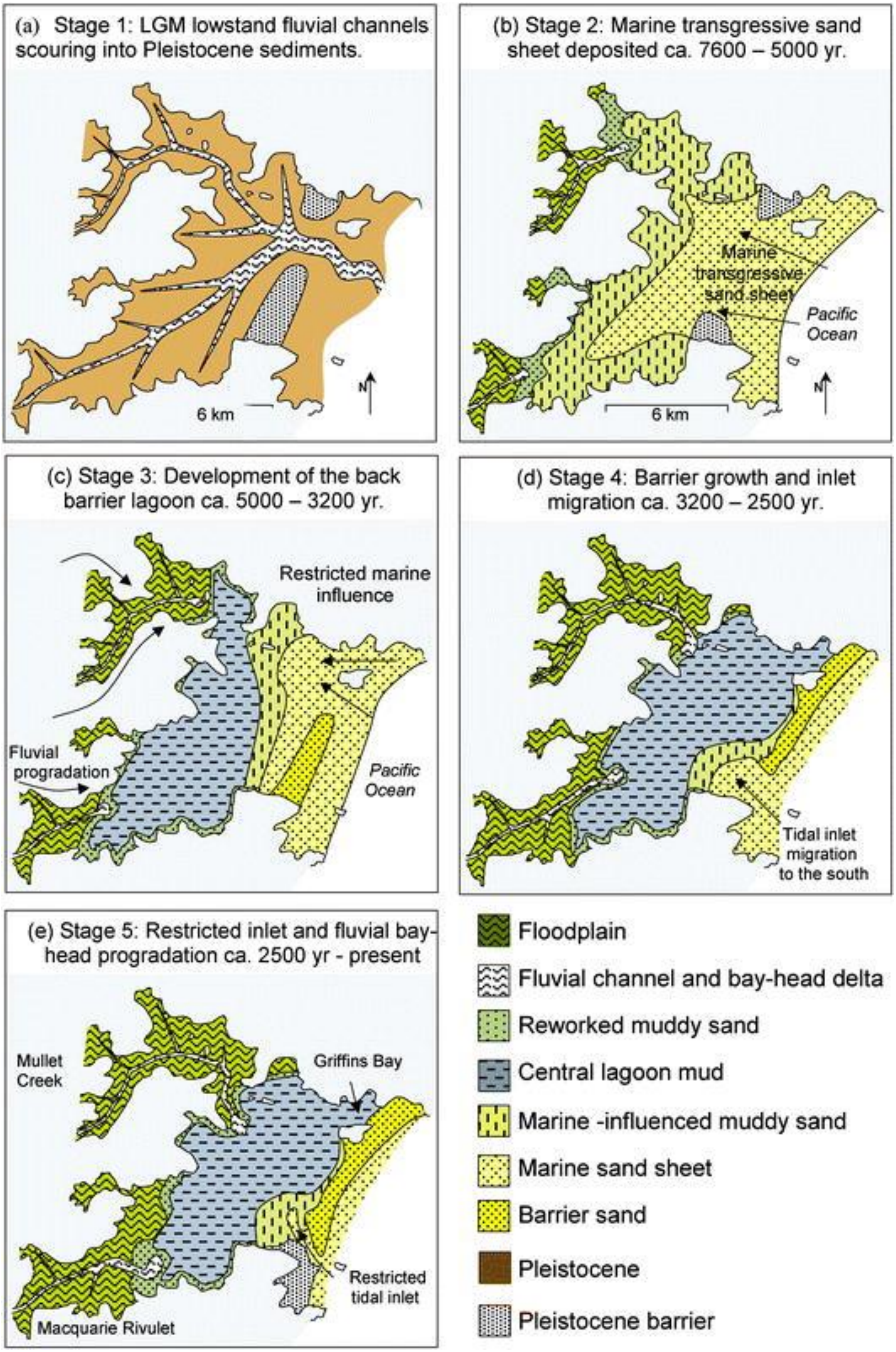

Figure 2.1 Geomorphological history of Lake Illawarra in five stages (Source: Sloss et al., 2005)

2.2.2 Early European history

European colonisation 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" (approximately 130 m) 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, 2006). 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, however, this development didn't become significant until the late 1940's (ERM Mitchell McCotter & Associates Pty Ltd, 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 the two local councils, WCC on the northern shoreline and SCC 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 (WCC and SCC) and consisted of 10 members from the relevant stakeholder communities (WCC, SCC, NSW Fisheries, Crown Lands, Southern Rivers Catchment Management Authority 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 m^3 with the aim of improving water circulation and water quality in Griffins Bay located in the north-eastern corner of the lake (LIA, 2011). The LIA coordinated the construction 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 was now a stronger legislative framework for estuary management that negated the need for a separate authority to manage the lake (Grant, 2013).

Table 2.1 Objectives of the LIA (LIA, 2013)

Area	Objective/Aim
Entrance management/condition	Create a stable entrance to the lake which is predominately open
Water quality	Improve the water quality of the lake to a standard that protects its ecological, recreational and aesthetic values
Algal blooms	Reduce the incidence of macroalgae and other forms of algae that degrade and dominate the natural ecological function of the lake
Organic wrack and ooze accumulation	Reduce ooze formation and malodorous conditions around the lake as a result of the accumulation and decay of seagrass and macroalgae
Erosion and sedimentation	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
Catchment inputs/management	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
Ecology and the fishery	Protect the abundance and diversity of native aquatic and terrestrial flora and fauna and restore habitats
Waterway usage	Permit appropriate recreational use of the estuary and foreshores compatible with ecosystem values
Riparian zones	To restore and protect foreshore vegetation and maximise public access to the lake without compromising ecosystem protection or visual amenity objectives
Flooding	To minimise the impact of flooding on public and private assets whilst adopting a policy of minimal intervention in natural processes wherever possible
Visual amenity	To preserve and enhance the visual quality of the lake, its foreshores and the catchment
Community involvement	To increase public awareness of the values and sensitive nature of the estuary in order to minimise activities that adversely impact on lake environments
Culture and heritage	To preserve cultural heritage values of the Lake and foreshores
Foreshore access	To maximise opportunities for public foreshore access to the lake
Commercial and tourism opportunities	To enhance the funding of environment protection and future management activities in the lake and foreshores through appropriate commercial use

2.2.4 Entrance training of Lake Illawarra

As identified 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 2.2 shows a summary of major construction works at the entrance since the 1960's. In the early 1960's, two walls were built at 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 (Wilson et al., 1991). Between 1963 to 1970 a concrete training wall was constructed by SCC along the southern bank of the entrance 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.

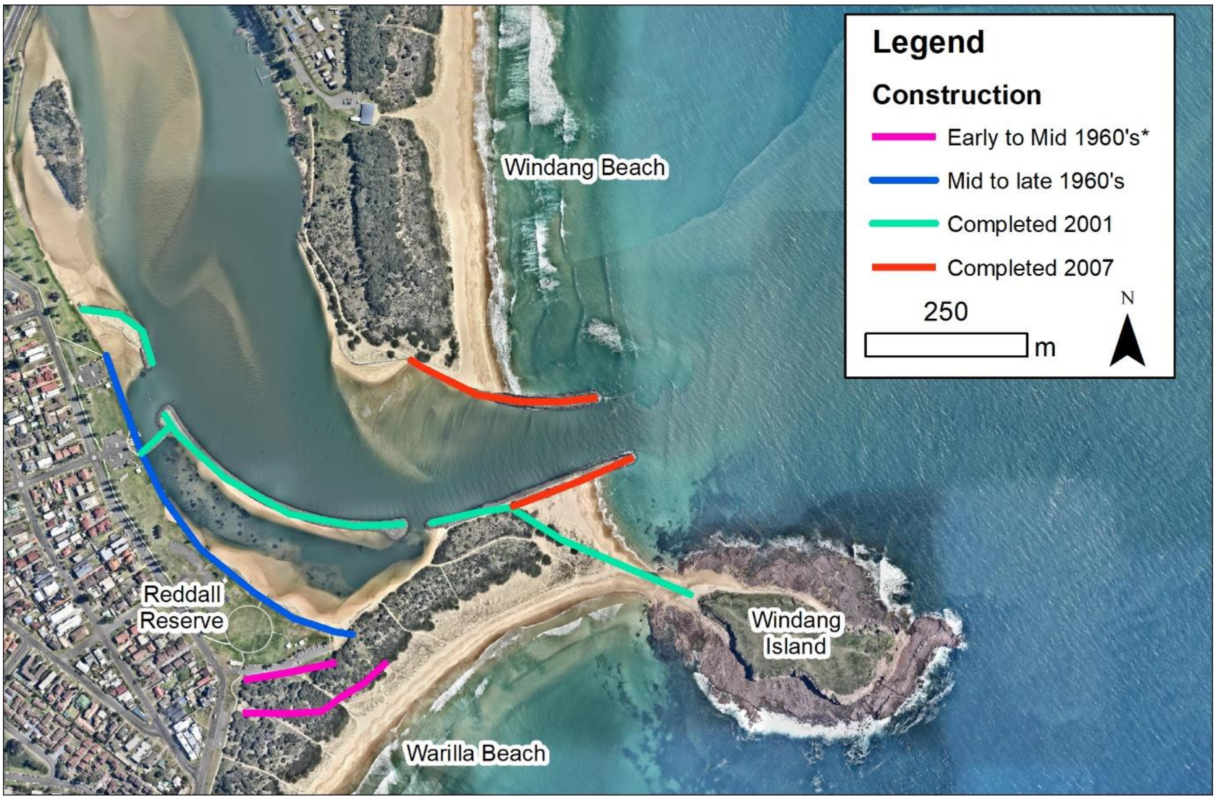

Figure 2.2 Indicative locations of construction works since the 1960s

* position and length of walls is indicative only and has been estimated from old aerial images

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 best 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
- Minimise sand transport from Warilla and Perkins Beach that resulted in entrance shoaling

Ultimately, Wilson et al. (1991) recommended eight 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 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 m^2 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 30 to 110 mm, and significantly increase the potential for tidal flushing to alleviate water quality issues.

Based on this modelling, 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 in an attempt 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 would have assisted 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 (Save Lake Illawarra Action Group, 2018). 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 Murtagh and Chan (1992) study that explored options for opening the lake. Lawson and Treloar (2003) undertook modelling of nine 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
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 3 month model of geomorphological changes in the lagoon indicated that the entrance would evolve over time (Figure 2.3). 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).

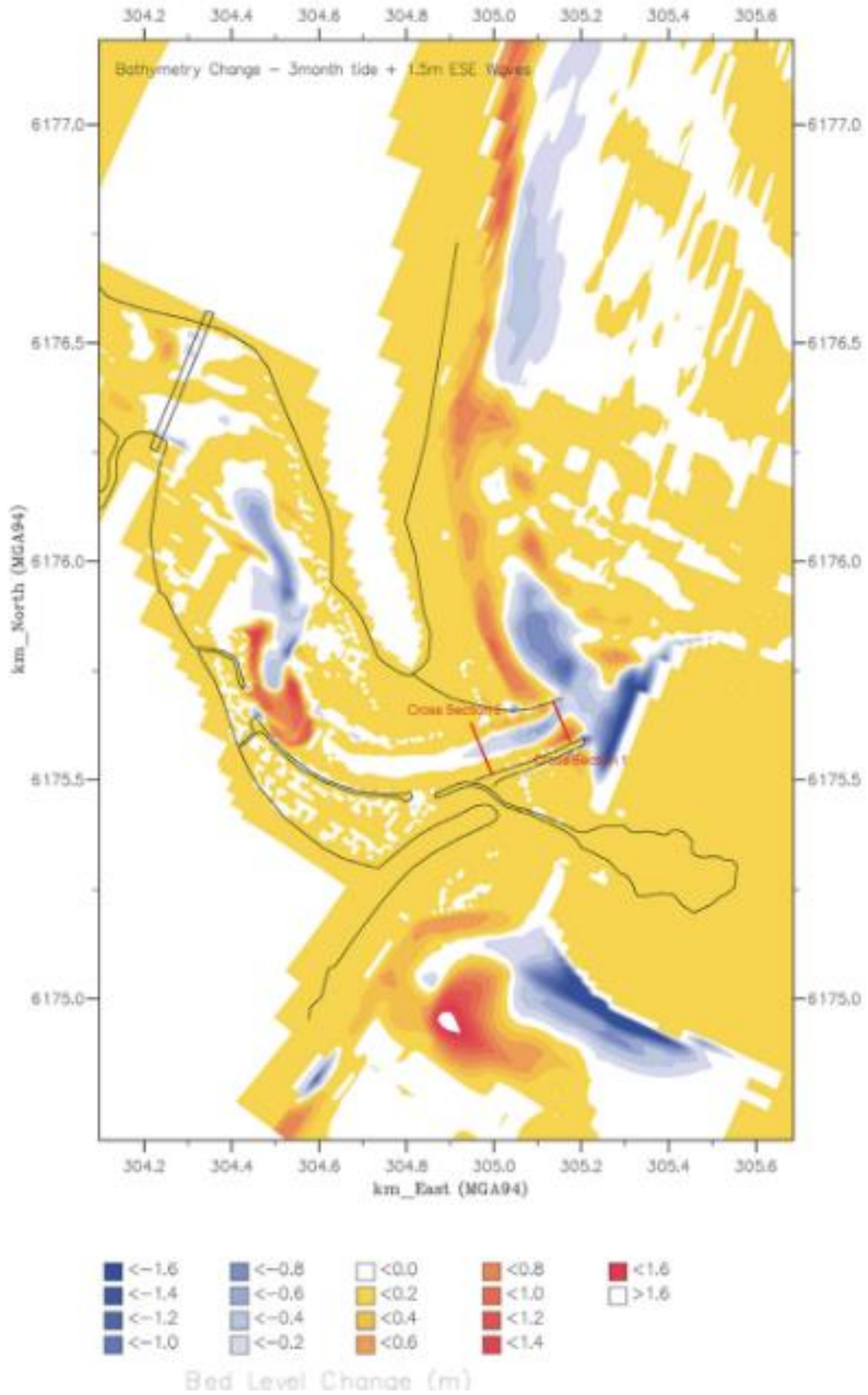

Figure 2.3 Modelled bathymetry changes over 3 months of tidal flows as a result of breakwater construction (Source: Lawson and Treloar, 2004)

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 Environmental Impact Statement (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 of sediment removed (WBM, 2006).

2.2.5 Influence of entrance training on Lake Illawarra

Overview of changes

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, morphodynamics, water quality and ecology. These changes have been summarised in the following sections.

Hydrodynamic changes

MHL has undertaken extensive monitoring of Lake Illawarra hydrodynamics both prior to and since the training of the entrance. This includes:

- Long-term water level gauges at
    - The entrance channel
    - Cudgeree Bay
    - Koonawarra Bay
- Tidal gauging (water levels, velocities and discharge) over a single tidal cycle in 2008, 2012, 2016, 2019, 2020 and 2022

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 2.4. Daily mean and minimum water levels dropped by approximately 0.20 m and 0.24 m respectively after the entrance works.

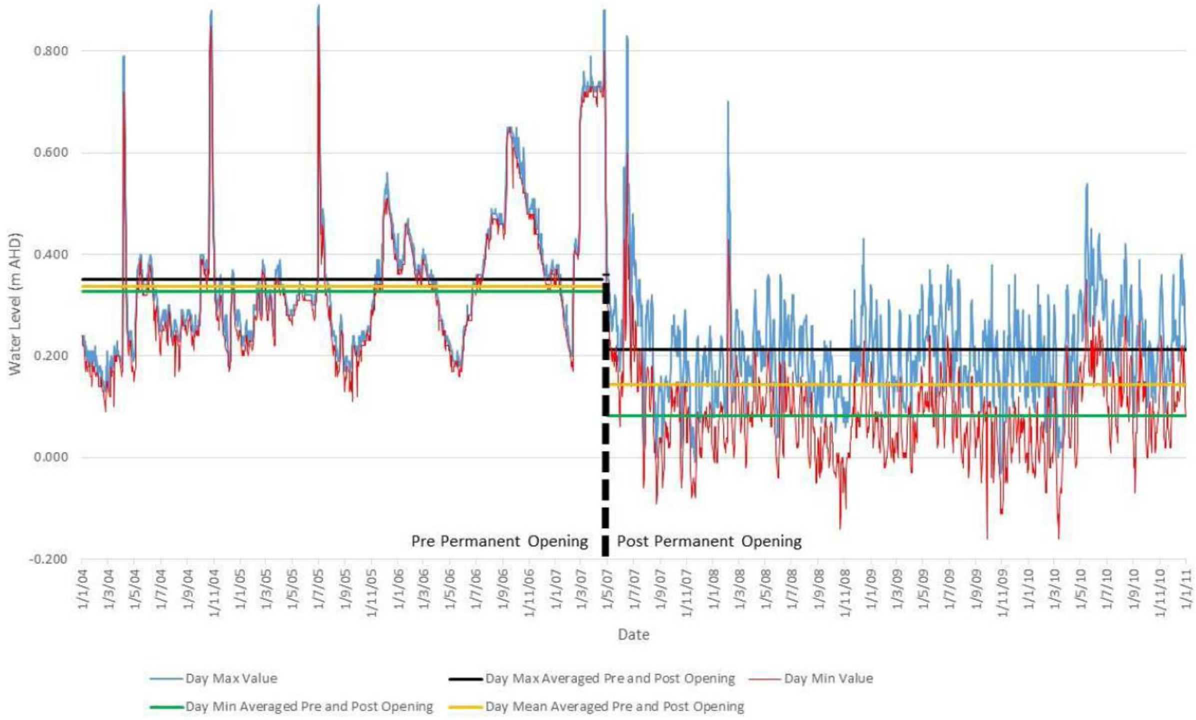

Figure 2.4 Analysis of mean daily maximum, mean and minimum water levels (Source: Wiecek et al., 2016)

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 (mean high water springs minus mean low water springs) had 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 median tidal range within the lake (considering a range of different entrance conditions) was 20 mm but that the tidal range when the entrance was scoured from a significant catchment runoff event was typically 70 mm (with a maximum value of 100 mm). In the year between July 2018 and June 2019, MHL (2023a) calculated the mean tidal range (mean high water minus mean low water) at Cudgeree Bay and Koonawarra Bay to be 161 mm and 141 mm respectively. As such, in the year ending 30 June 2019, the average tidal range in the lake was at least seven times what it was prior to the construction of the training walls in 2007.

Further analysis by MHL (2023b; reproduced in Appendix A) showed that the ratio of the lake to ocean spring tidal range has been increasing by approximately 0.007 per year since 2007 and was 0.14 in the year ending 30 June 2020 (Figure 2.5). There has also been a slight decrease in the phases of the principal lunar (M_2) and principal solar (S_2) tidal constituents in Lake Illawarra indicating that propagation of the tidal wave is becoming more efficient.

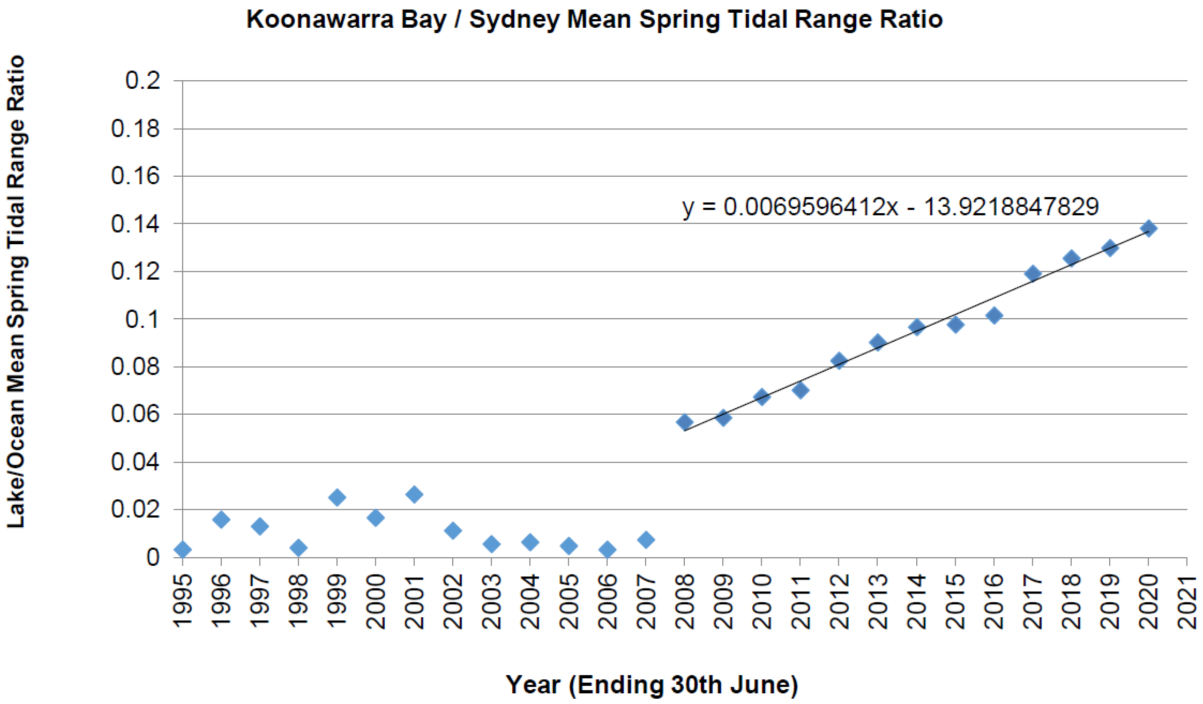

Figure 2.5 Lake Illawarra to Ocean Mean Spring Tidal Range Ratio (Source: MHL, 2023b)

Gauging of tidal flows at the entrance to Lake Illawarra has been undertaken seven 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 are summarised in Table 2.3. It is evident that the tidal prism, discharge and velocities generally have an increasing trend between 2008 and 2021. However, the two low tide water levels and high tide water level during each gauging event were not equal which had an influence on the measured tidal prism, maximum discharge and maximum tidal velocities. Analysis is presented later in Section 2.3.4 to demonstrate that, independent of ocean tide level variations between gauging events, the tidal prism within Lake Illawarra is increasing. Note, the 2012 experiment was undertaken in a slightly different location (i.e. further upstream) to the other six exercises which may mean that the measured tidal prism and maximum discharge was comparatively lower for that gauging exercise.

Table 2.2 Jervis Bay measured water levels during tidal gauging exercises (MHL, 2023c)

Date	Low tide (m AHD)	High tide (m AHD)	Low tide (m AHD)
10/03/2008	-0.60	0.71	-0.59
16/10/2012	-0.74	0.84	-0.69
11/03/2016	-0.70	0.82	-0.74
11/10/2018	-0.74	0.65	-0.77
2-3/09/2019	-0.66	0.77	-0.74
10/03/2020	-0.63	0.96	-0.89
6/12/2021	-0.40	1.11	-0.79

Table 2.3 Summary of tidal gauging results at Lake Illawarra (MHL, 2009, MHL, 2013, MHL, 2017, MHL, 2020a and MHL, 2023b)

Dates	Tidal prism Flood ($m^3 \times 10^6$)	Tidal prism Ebb ($m^3 \times 10^6$)	Maximum discharge Flood (m^3/s)	Maximum discharge Ebb (m^3/s)	Maximum tidal velocity Flood (m/s)	Maximum tidal velocity Ebb (m/s)
10/03/2008	2.70	2.14	222	131	0.72	0.84
16/10/2012*	4.85	4.09	320	205	1.08	1.05
11/03/2016	5.46	4.80	388	245	1.22	1.40
11/10/2018^	5.50	5.60	407	287	0.93	1.21
2-3/09/2019	7.37	6.81	518	357	1.06	1.00
10/03/2020	9.30	6.97	589	364	1.18	1.29
6/12/2021	12.98	10.30	778	462	1.35	1.44

*2012 tidal gauging was undertaken in a different location in the entrance channel, comparisons are indicative only

^ Gauging completed by WRL – see Appendix B

Morphological changes

The increasing tidal prism and maximum tidal velocities, accompanied with the gradually increasing tidal range within Lake Illawarra are an indicator that the entrance is presently hydraulically unstable. MHL first identified the unstable scour occurring in the entrance channel and increasing tidal range in the lake in a 2012 report (MHL, 2012) which informed a subsequent conference paper (Couriel et al., 2013). This paper included an analysis of the stability of Lake Illawarra using the available field data and the techniques described in O'Brien and Dean (1972) to produce an Escoffier diagram. This approach has been previously applied at three 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 factors (e.g. the depth of the lake and the depth of the ebb tide bar) or restrictions (e.g. the training walls and landform controls) that may 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.

Hydraulic instabilities within the Lake Illawarra entrance channel have caused erosion of sediment and the undermining of Windang Bridge. MHL (2019) used numerical modelling to assess how the placement of a rock surcharge under the Windang Bridge would influence entrance stability. For this work, a numerical model developed by WRL (2019) was used to assess options for a rock surcharge design and the likely influence designs would have on velocities within the Lake Illawarra entrance channel. Reviewing model results, MHL (2019) concluded that while the placement of a rock surcharge would offer localised protection, it could also exacerbate erosion at other locations within the entrance channel. Following this study, in 2019 to 2020 a rock surcharge was placed beneath a section of the northern end of Windang Bridge. Further, more detailed numerical modelling completed by MHL (2020b) assessed a range of options for increasing the scour protection along the full span length of the bridge. They identified that the elevation of the rock surcharge will influence the morphology within the entrance channel.

MHL (2019) also updated the entrance stability analysis completed by Couriel et al. (2013) as part of their investigation. However, this has been updated again by MHL (2023b) based on flow and bathymetry data collected in December 2021 with a rock surcharge structure in place underneath the northern end of Windang Bridge (Figure 2.6). Based on the December 2021 measurements, MHL (2023b) estimated that the entrance may continue to be unstable for another 120 years while the cross-sectional area of the channel increases from ~600 m^2 to ~4,500 m^2. When this stable equilibrium area is reached, the ratio of the lake to ocean spring tidal range would have increased from 0.14 (December 2021) to 0.97 (i.e. the lake tidal range would be approximately equal to the ocean tidal range).

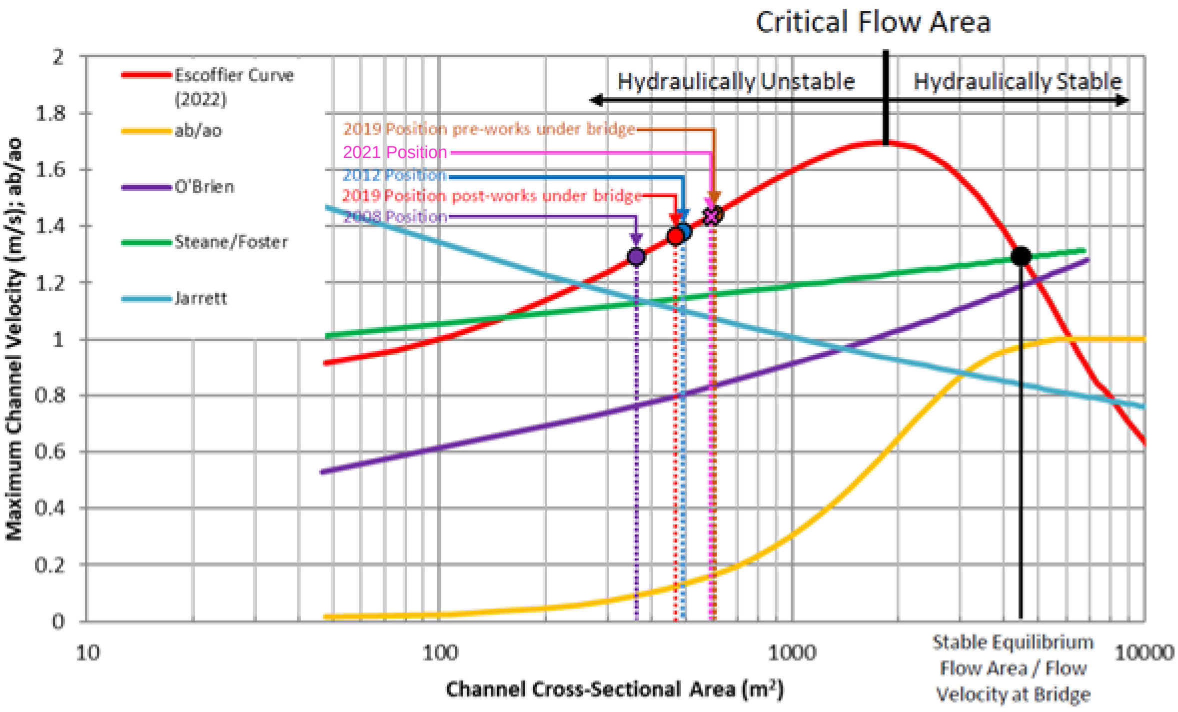

Figure 2.6 Lake Illawarra inlet stability curve at Windang Bridge (Adapted from MHL, 2023b)

Hydrographic surveys have been completed at the Lake Illawarra Entrance, since it was opened, to provide a better understand the bathymetric changes that are occurring. Regena (2016) and Wiecek et al. (2016) directly compared hydrographic surveys completed in 2008 and 2016 plotting the difference in bed elevations (Figure 2.7) and the movement of the deepest section of the channel (known as the thalweg, shown in Figure 2.8). Over this period, significant changes in the entrance channel were observed. There had been significant channel scouring (around 2 to 4 m deepening) along the Windang foreshore, while there had been complimentary accretion around Berageree Island (Figure 2.7) as a result of the deepest section of the channel moving.

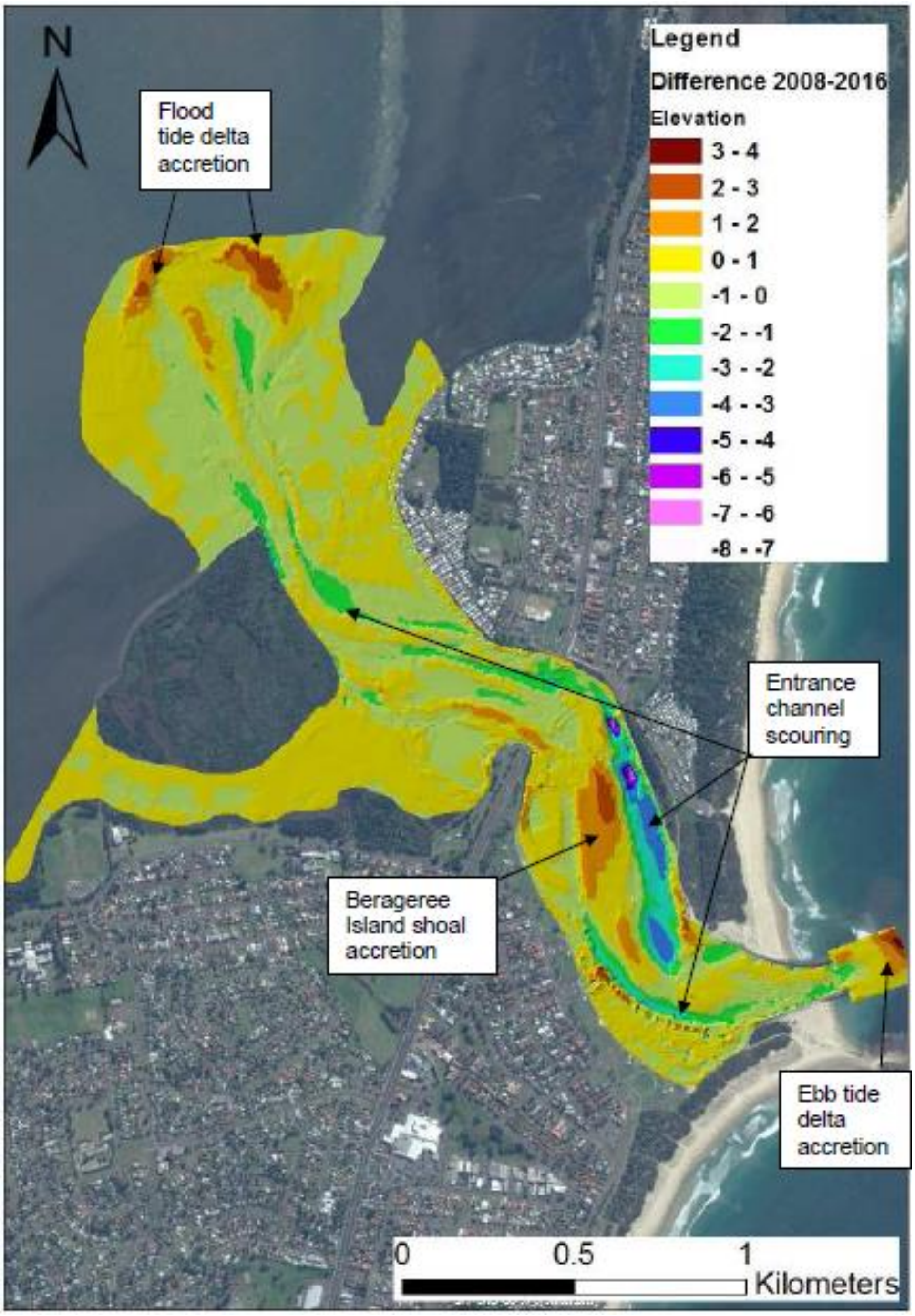

Figure 2.7 Comparison of 2008 and 2016 hydrographic surveys (Source: Wiecek et al., 2016, adapted from Regena, 2016)

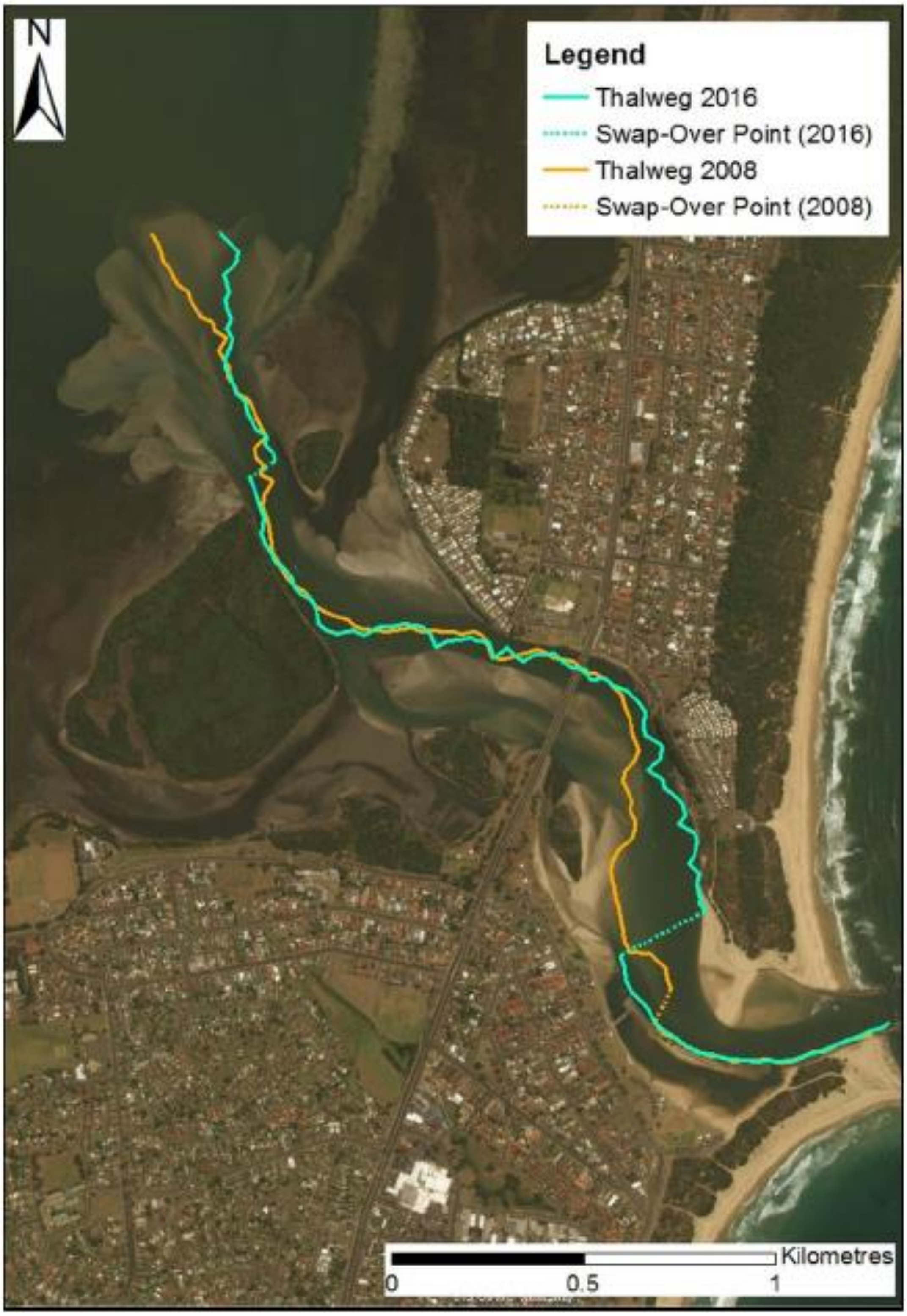

Figure 2.8 Position of the thalweg, based on 2008 and 2016 hydrographic surveys (Source: Regena, 2016)

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 WCC implemented protection works to limit the erosion, including adding additional piles to stabilise the Pine Tree Park boardwalk and construction of three 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.

Since 2012, due to high velocities in the channel caused by the alignment of the groynes, there were 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, had developed off the end of the structures, evident in Figure 2.7. Despite the additional piles installed at the Pine Tree Park boardwalk, the structure was significantly damaged in 2015 (Wiecek et al., 2016) and scouring continued 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.

Following further damage to the Pine Tree Park boardwalk at Windang between February and April 2022 another section was removed. Another section of the boardwalk then collapsed in October 2022 and the remaining sections of the boardwalk were completely removed in December 2022. A discussion regarding the scour associated with the Pine Tree Park boardwalk is presented in Tucker et al. (2023).

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 – the top of the flood tide delta was predominately poorly sorted marine sands, this was overlaying finer grained material with more organic matter.

Works have also been completed on the northern bank of the Lake Illawarra entrance channel west of Windang Bridge. This includes approximately 750 m of foreshore protection along Oaklands Village which was constructed since the entrance opening. Review of the foreshore protection completed by WRL (2021) identified that approximately 115 m of the foreshore protection had failed and that other sections of wall were not compliant with contemporary coastal engineering standards. As part of their investigation, WRL (2021) also provided a recommended concept design for the long term protection of the foreshore at Oaklands Village that incorporated a rock apron which would allow for continued erosion of the channel in front of the structure.

Water quality changes

The LIA monitored water quality at six 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 2.3.6) 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 (2000) water quality guidelines for total nitrogen (TN) and filterable reactive phosphorous (FRP).
- Turbidity remained highly variable, but largely remained below the ANZECC (2000) guidelines.

Baxter and Daly (2010) concluded that the entrance works 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 had 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 within the lake.

Since October 2013, WCC and SCC have been monitoring the water quality within Lake Illawarra (WCC, 2015; WCC, 2016; WCC, 2017; WCC, 2018 and WCC, 2022). WCC (2022) completed an assessment of the water quality data that was collected from May 2021 to April 2022 at the locations shown in Figure 2.9. Monitoring included data to provide an assessment of ecosystem health (temperature, pH, dissolved oxygen, salinity, turbidity, nutrient and chlorophyll a) and recreational suitability (enterococci). It was noted that this monitoring period was significantly influenced by catchment rainfall events with a summer rainfall (1 November to 30 April) of 1425.5 mm more than double the average of the previous 12 years (619 mm).

Figure 2.9 WCC and SCC water quality monitoring locations (blue = ecosystem health, orange = recreational suitability) (Source: WCC, 2022)

Analysis of data completed by WCC (2022) provided the following conclusions:

- Rainfall events resulted in higher nutrient loading and a drop in salinity throughout Lake Illawarra
- Nutrient concentrations regularly increased above guideline values identified for Lake Illawarra
- When compared to previous years, with the exception of Site 3, levels of chlorophyll a, turbidity, nitrogen and phosphorus were found to either have either no trend or a decreasing trend
- Except for Site 5 and Site 6 (rated fair) all monitoring locations rated as good to very good estuarine health for the 2020/21 period as per the Monitoring, Evaluation and Reporting (MER) framework (OEH, 2016) – this indicated an overall improvement in estuarine health compared to previous years
- For the monitoring period (May 2021 to April 2022), compliance for primary recreation contact (e.g. swimming) ranged from 55% to 70% while compliance for secondary recreation contact (e.g. sailing) ranged from 70% to 80% as per the ANZECC (2000) guidelines for recreational use of waterways

Ecological changes

Wiecek et al. (2016) completed an assessment of how estuarine macrophytes (mangroves, saltmarsh, and seagrass) have been influenced by the entrance opening. They observed an increase in distribution of mangroves, a small loss of saltmarsh and a significant loss of seagrass habitat. Evidence of mangroves encroachment on saltmarsh habitat was limited to one location at the confluence of Duck Creek and Lake Illawarra. Analysis of seagrass mapping, which was completed on an annual basis from 2007 to 2016 by Aurecon (2016), showed that there was a net loss due to the entrance opening. Overall Zostera and Ruppia species declined, while an increase in the abundance of Halophila was observed (Figure 2.10).

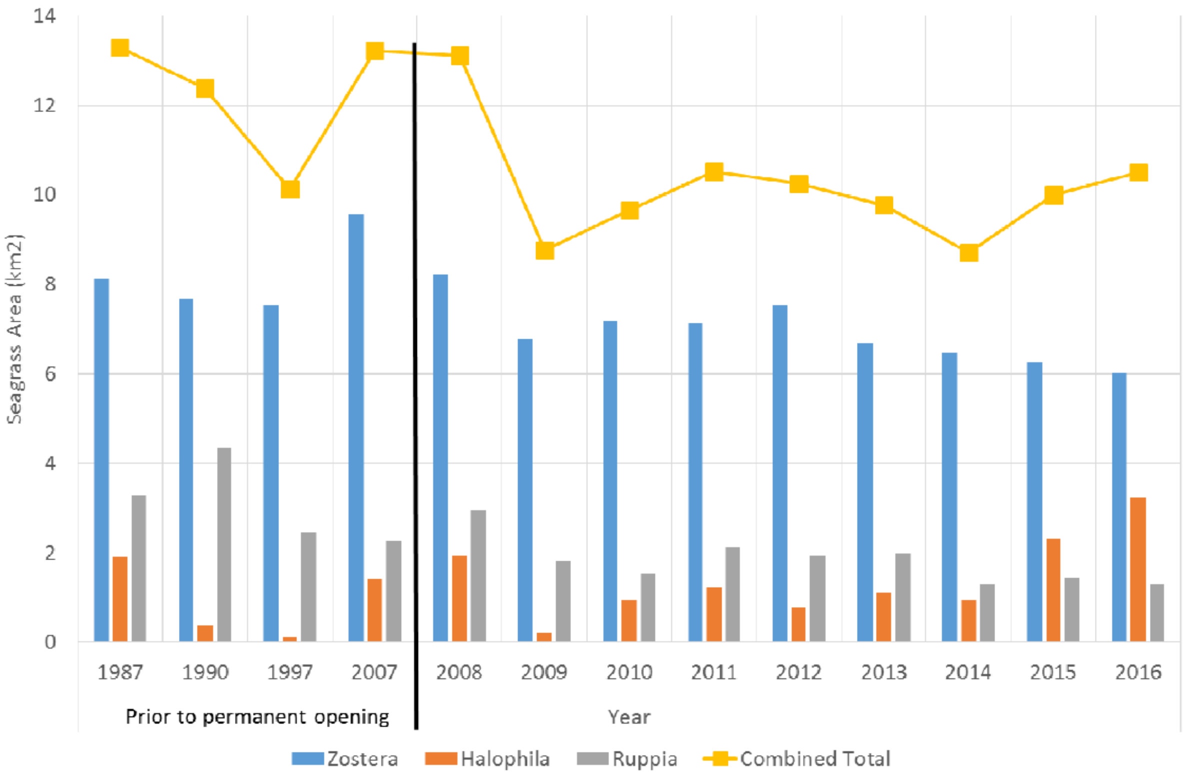

Figure 2.10 Seagrass distribution in Lake Illawarra pre and post the 2007 permanent opening (Source: Wiecek et al., 2016, data from: Aurecon, 2016)

Gaston et al. (2022) investigated the linkages between key species (i.e. bream, flathead, whiting, mullet, school prawn, blue swimmer crab) and their habitat (i.e. saltmarsh, mangrove, seagrass, and mudflats). They found that over 90% of the key species relied upon seagrass and saltmarsh habitat for food sources. Gaston et al. (2022) highlighted how targeted restoration of habitat, specifically saltmarsh and seagrass at Lake Illawarra, could be used to ensure the productivity of key species.

2.2.6 Coastal Management Program (CMP)

A CMP has been developed for Lake Illawarra in accordance with the Coastal Management Act 2016 (BMT, 2020). The purpose of the CMP is to provide a long-term strategy for the management of Lake Illawarra to maintain/improve the social, cultural, environmental, and economic value of the system (OEH, 2018; BMT, 2020). During the development of the CMP, threats and values provided by the estuary were assessed.

The top three values identified by over 80% of the Lake Illawarra community and stakeholders were:

1. Water quality (89% of survey respondents said this was highly valued)
2. Visual amenity of the lake (81% of survey respondents said this was highly valued)
3. Native wildlife (80% of survey respondents said this was highly valued)

Seventeen (17) threats were identified for Lake Illawarra with three posing a very high threat at present, in the near future (2040 to 2050), and in the far future (2070 to 2100):

- Water pollution
- Catchment development
- Changes due to the entrance channel opening

The CMP determined nine management strategies for the purpose of directly addressing all of the threats identified for Lake Illawarra. Forty-one (41) actions were identified to achieve each strategy and using a multi criteria cost benefit analysis their implementation was prioritised (note, only 39 actions were recommended for implementation). As mentioned earlier in Section 1.3, action EC1 is described as: "*Investigate and Finalise Options to Manage Erosion and Accretion Changes in the Entrance Channel*". This scope of works addresses one of the tasks outlined within action EC1 which is to prepare a "Lake entrance management options study".

As a final step, a business plan was developed to assist in the implementation of the CMP. This outlines a proposed schedule and expected costs from implementation of the CMP for the next 10 years. The goal is that this plan will assist in achieving the strategies and broader purpose of the CMP.

2.3 Data review

2.3.1 Overview of data

Lake Illawarra has been the focus of numerous data collection campaigns collecting various types of data which are useful to inform its management. The following section provides a summary of available data sources which have been identified as relevant for this current investigation. Note, due to its abundance, all of the raw data available has not been collated within this report but instead a reference to the data has been provided. Data identified in this section includes:

- Hydrological data
    - Water levels
    - Streamflow
    - Climate
    - Topography
- Tidal gauging data
- Hydrographic survey data
- Sediment data
- Water quality data

2.3.2 Hydrological data

Water levels
Water levels in Lake Illawarra are continuously monitored by MHL at three locations (shown in Figure 2.11):

- The entrance channel (Site 1; relocated from the Pine Tree Park following damage to the supporting boardwalk [last measurement 14 October 2022] to Windang Bridge [first measurement 12 April 2023])
- Cudgeree Bay (Site 2)
- 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 to inform the detailed numerical modelling in the Stage 2 assessment. Additionally, the MHL tidal monitoring location in Jervis Bay has been obtained to understand the open coast tidal range over the same period. A tide gauge in Port Kembla owned by the National Tidal Centre, administered via the Bureau of Meteorology (BOM), also records hourly open coast tide measurements as an alternative to the Jervis Bay gauge.

Figure 2.11 MHL long-term water level monitoring locations
Note: Site 1 was moved from Pine Tree Park to Windang Bridge in April 2023

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 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 1 m grid from LiDAR flown in 2016. This data will be used to inform the detailed numerical modelling in the Stage 2 assessment. Additionally, historical DEMs may be compared at the entrance to assess changes to the shoreline.

2.3.3 Tidal gauging data

MHL has undertaken detailed gauging of a tidal cycle on six occasions in; 2008, 2012, 2016, 2019, 2020 and 2022 (MHL, 2009, MHL, 2013, MHL, 2017, MHL, 2020a, MHL, 2023b) (Table 2.2). One round of tidal gauging was also complete by WRL in 2018 (see Appendix B). Each gauging exercise was undertaken from low tide to low tide to capture the entire tidal cycle. These exercises were timed to coincide with large spring tides when the low water levels either side of the high tide were 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 completed using a RD Instruments Workhorse Acoustic Doppler Current Profiler (ADCP) (gauging complete by MHL and WRL) and a Sontek RiverSurveyor-M9 (for gauging completed by WRL). These instruments measure velocities throughout the water column as a vessel moves perpendicular to the flow direction. By completing multiple transects across a water body, discharge throughout time can be measured. On each of the seven gauging exercises, between 30 to 45 transects throughout the tidal cycle were completed to reconstruct the discharge signal. While the measurements were taken at approximately the same location in 2008, 2016, 2018, 2019 and 2020 (Location 1 in Figure 2.12), the 2012 measurements were further upstream near Berageree Island (Location 2 in Figure 2.12). As shown in Table 2.2, there were also differences in the offshore tidal range during each of the seven exercises.

Figure 2.12 Approximate MHL tidal flow gauging transect locations

WRL analysed the results of the seven gauging exercises to assess changes to the tidal prism independent of ocean tide variations. The total volume of water passing through the entrance channel on each occasion is a function of several factors, including:

- The tide elevation
- Channel geometry
- Channel friction
- Previous tide cycles

This means that directly comparing total flow volume for each gauging event (i.e. the tidal prism) does not give a true indication of whether the actual tidal prism is changing. Assuming that the tide elevation is the largest influencing factor on the tidal prism and that other influencing factors are relatively negligible, the tidal prism measured for each gauging event has been normalised using Equation 2.1.

$$R = \frac{P_{Lake}}{A_{Lake}\Delta H}$$

Equation 2.1

Where:

R is the potential tide ratio, a non-dimensional ratio that accounts for losses through the Lake Illawarra entrance channel and represents ratio of the actual (P_{Lake}) versus potential water volume (i.e. full ocean tidal range $\Delta H \times A_{Lake}$) that makes it from the ocean into Lake Illawarra
P_{Lake} is the tidal prism within Lake Illawarra and measured during field experiments (m^3)
A_{Lake} is the surface area of Lake Illawarra (assumed to be constant) (35.2×10^6 m^2)
ΔH is the change in the ocean tide elevation over the tidal cycle during which flow measurements were collected – taken from the Jervis Bay gauge (MHL, 2023c) (m)

By solving Equation 2.1, each of the seven tidal gauging measurements can be compared (noting the assumptions used to develop the potential tide ratio). These results are presented in Figure 2.13.

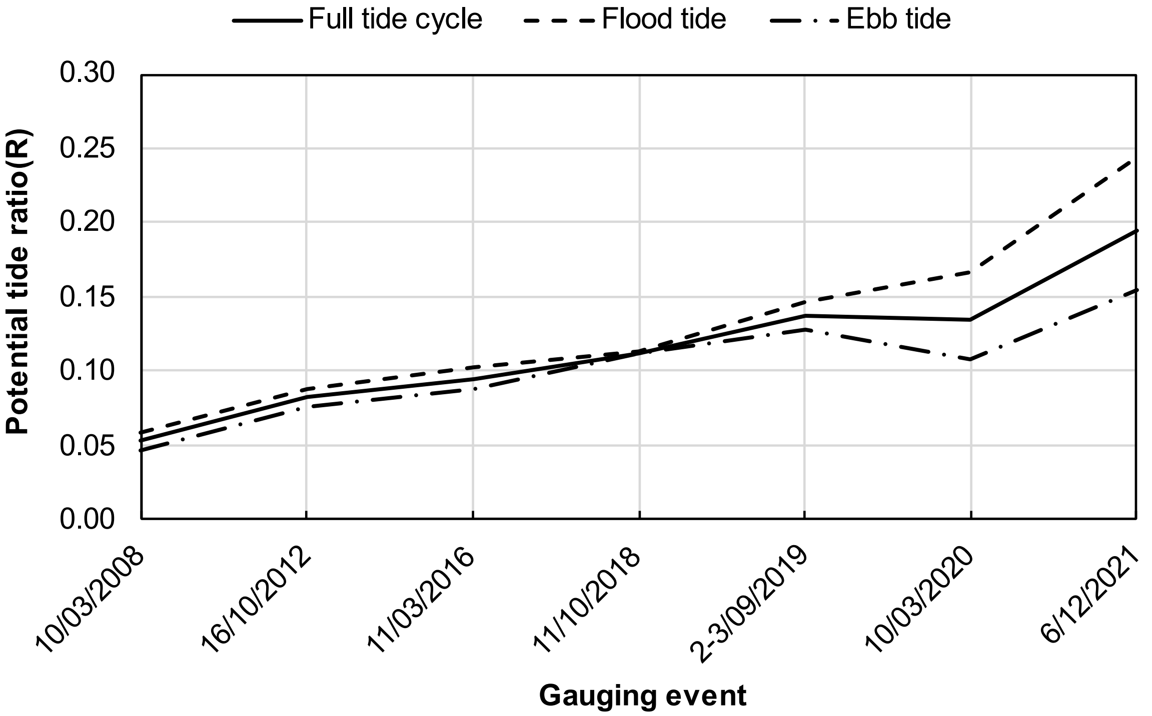

Figure 2.13 Change in the potential tidal ratio between tidal prism measurements

The results show that the tidal prism within Lake Illawarra has had an increasing trend between 2008 and 2021 due to increased conveyance through the entrance channel which has resulted from the permanent entrance opening. Where originally 5% of the potential water volume passed through the entrance channel, now almost 20% of the potential water volume passes through. Note, the potential tidal ratio decreased on a single occasion on the ebb tide for the 2020 gauging event. The decrease could be due to the assumptions underlying Equation 2.1, the time within the tidal cycle when tidal gauging was completed (i.e. spring/neap cycle), and/or the uncertainty related to data collection (±5% of the tidal prism).

2.3.4 Hydrographic survey data

Hydrographic surveys of the Lake Illawarra entrance channel have regularly occurred since the entrance was trained in 2007. A summary of the available surveys has been provided in Table 2.4. Where possible, raw data from each of these surveys has been obtained for direct comparison with data collected as a part of this study.

Table 2.4 Summary of bathymetric surveys within the Lake Illawarra entrance channel from 2008 to 2022

Survey date	Responsible entity	Extent
01/04/2008	**NSW OEH**	**Lake Illawarra and entrance channel**
19/10/2012	NSW DFS	Main entrance channel (excluding the ebb and flood tide deltas)
08-11/03/2016	**NSW OEH**	**Entire entrance channel**
2018	Fugro Hydrographic Services Service Line	Entrance channel from east of Windang Bridge
08-12/10/2018	**WRL**	**Entire entrance channel (see Appendix B)**
09/05/2019	NSW OEH	Windang Bridge
05-08/08/2019	**NSW OEH**	**Entire entrance channel**
15/10/2019	NSW OEH	Windang Bridge
16/12/2019	NSW OEH	Windang Bridge
31/01/2020/ 20/02/2020	NSW OEH	Windang Bridge
19/08/2020	North Coast Surveys	Windang Bridge
02/09/2020	**North Coast Surveys**	**Main entrance channel**
17-18/09/2020	NSW DPIE	Windang Bridge
04/12/2020	TfNSW	Windang Bridge
17/07/2021	**North Coast Surveys**	**Main entrance channel**
16/12/2021	**North Coast Surveys**	**Main entrance channel**
19/10/2022	**North Coast Surveys**	**Main entrance channel**

Note: The eight surveys shown in bold at least cover the main entrance channel and are used in analysis presented in Figure 2.13, Table 2.5, Figure 2.16 and Appendix D

The ongoing sediment erosion/accretion within the Lake Illawarra entrance channel has been assessed by comparing the eight bathymetry surveys completed from 2008 to 2022 which at least cover the main entrance channel (these surveys are shown in bold in Table 2.4). Comparison of entrance channel surveys shows that there has been a continuing trend of erosion. Since 2008, almost 900,000 m^3 of sediment has been displaced from within the entrance channel (Figure 2.14). It is inferred that the majority of the sediment has been transported outside of the analysis domain shown in Figure 2.14 into either the lake or offshore beyond the ebb tide delta to the littoral zone.

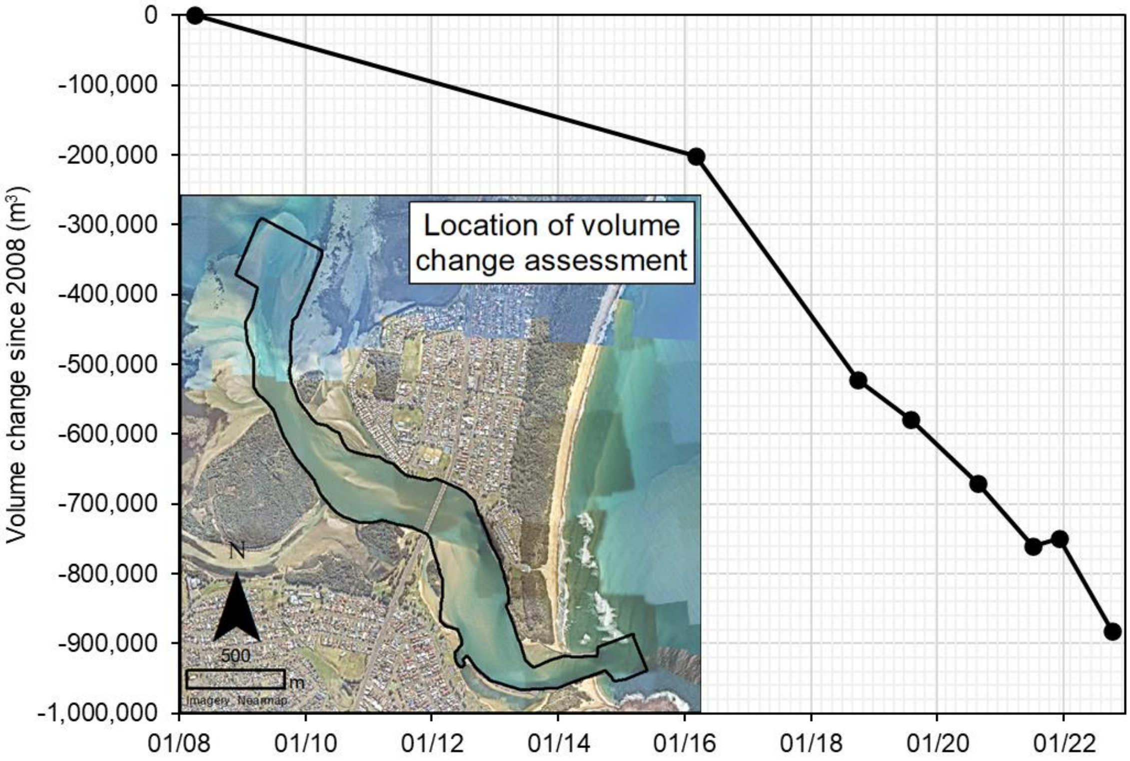

Figure 2.14 Volume change within the Lake Illawarra entrance channel from 2008 to 2022

A comparison between 2008 and 2021 bathymetry (i.e. the first and last time full entrance channel surveys, including the flood and ebb tide deltas, were completed) has also been provided in Figure 2.15. This clearly shows areas where erosion and accretion have occurred in the entrance channel.

To identify erosion "hot spots" an analysis was completed where the Lake Illawarra entrance channel was divided into 16 sediment compartments (Figure 2.16). Results of this analysis showed that the rate of erosion across the entrance channel varies significantly (see Table 2.5 and Figure 2.17). Some areas experienced significantly higher rates of erosion (sediment compartments 2, 4 and 11) while other areas experienced accretion (sediment compartments 6 and 16). Sediment compartment 2, along the Windang foreshore, had the highest rate of sediment change with average erosion of more than 0.2 m per year between 2008 and 2022. While WRL considers that wave-driven marine sediments are still likely being transported into the entrance channel, the net negative sediment change rates for compartments 1 to 5 near the entrance indicate that scour from tidal velocities is the dominant process. Note, the rate of change during the 14 year period during which the entrance bathymetry has been monitored is variable over time and between compartments. For reference, the volume change over time for each individual sediment compartment shown in Figure 2.16 has been provided within Appendix D.

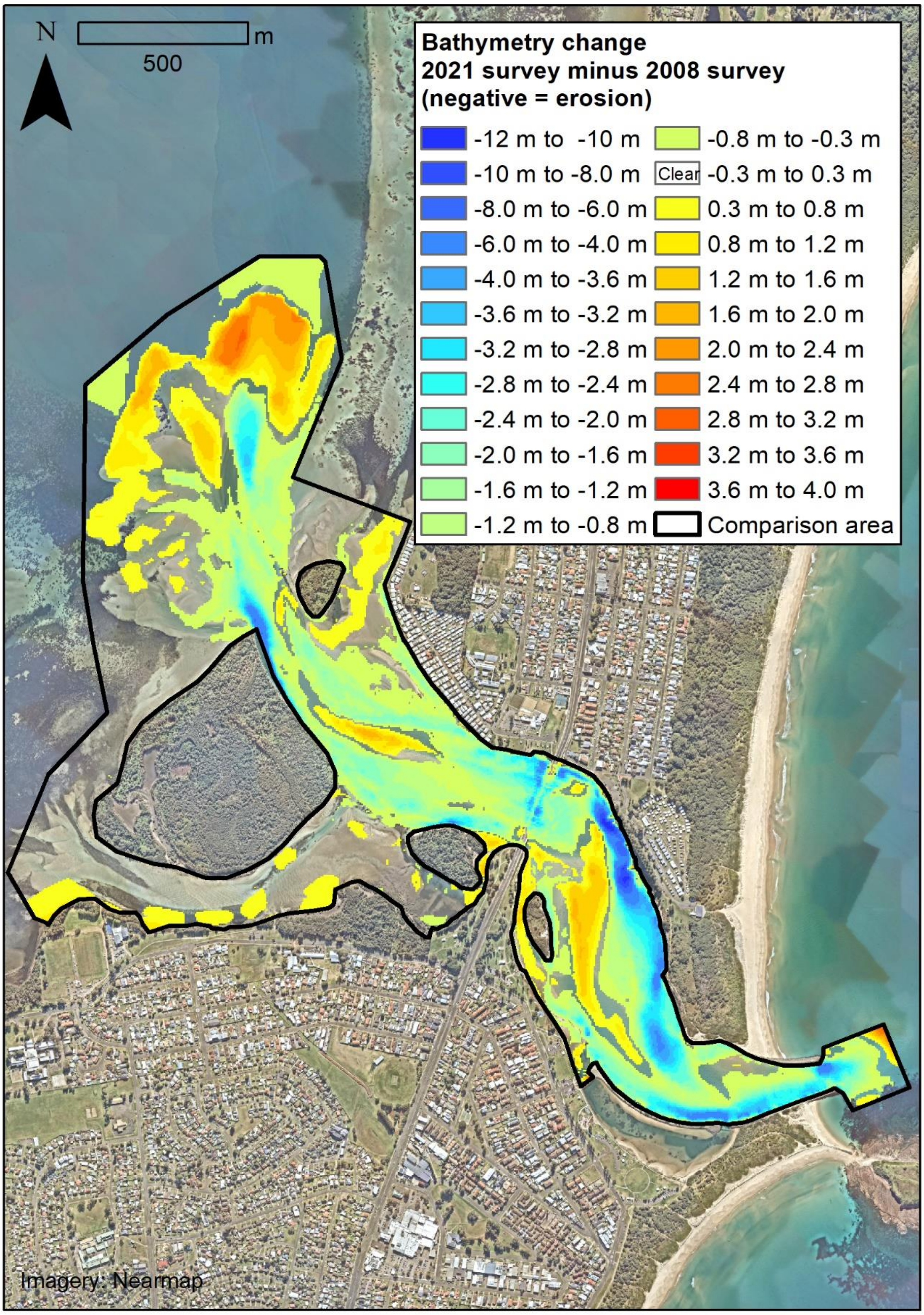

Figure 2.15 Change in bathymetry from 2008 to 2021

Figure 2.16 Lake Illawarra entrance channel sediment compartments for erosion analysis

Table 2.5 Erosion within different sediment compartments

Sediment compartment	Compartment area (m^2)	Total volume change within compartment 2008 – 2022 (m^3)	Compartment average sediment change rate (m/year)
1	37,675	-40,724	-0.074
2	43,150	-103,966	-0.165
3	28,900	-28,501	-0.068
4	85,350	-279,570	-0.225
5	62,250	-39,408	-0.043
6	65,450	10,134	0.011
7	29,975	-25,373	-0.058
8	7,975	-11,662	-0.100
9	48,650	-73,339	-0.104
10	58,050	-24,671	-0.029
11	95,525	-132,018	-0.095
12	20,725	-20,080	-0.067
13	106,175	-63,103	-0.041
14	17,225	-14,370	-0.057
15	66,275	-3,561	-0.004
16	30,750	19,698	0.044

Figure 2.17 Average annual sediment change rate within each sediment compartment of the Lake Illawarra entrance channel

2.3.5 Sediment data

Regena (2016) collected 72 sediment samples from locations in and around the entrance channel and presented particle size distributions for 18 of the samples. The locations of 14 of these samples of particular relevance are shown in Figure 2.18. 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 2.19). 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 2.20). This indicated that the main entrance channel and flood tide delta had a higher energy which resulted in greater marine deposition. The lower energy of the secondary channel allowed for the deposition of some finer materials (Regena, 2016).

Sediment analysis was also completed by WRL in 2018. Findings from this analysis are provided in Appendix B. The dominate sediment classification from this analysis was medium sand (250 to 500 µm), consistent with the results of Regena (2016).

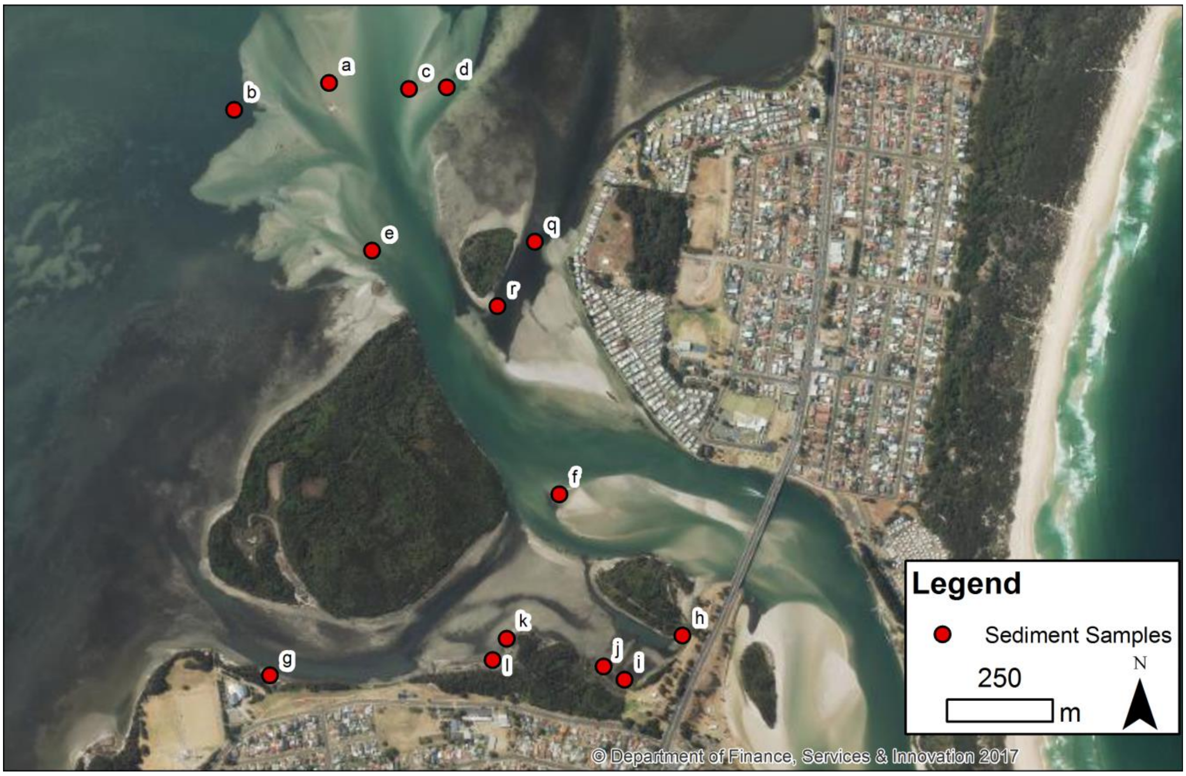

Figure 2.18 Sediment sample locations where particle size analysis was undertaken (adapted from Regena 2016, locations are approximate only)

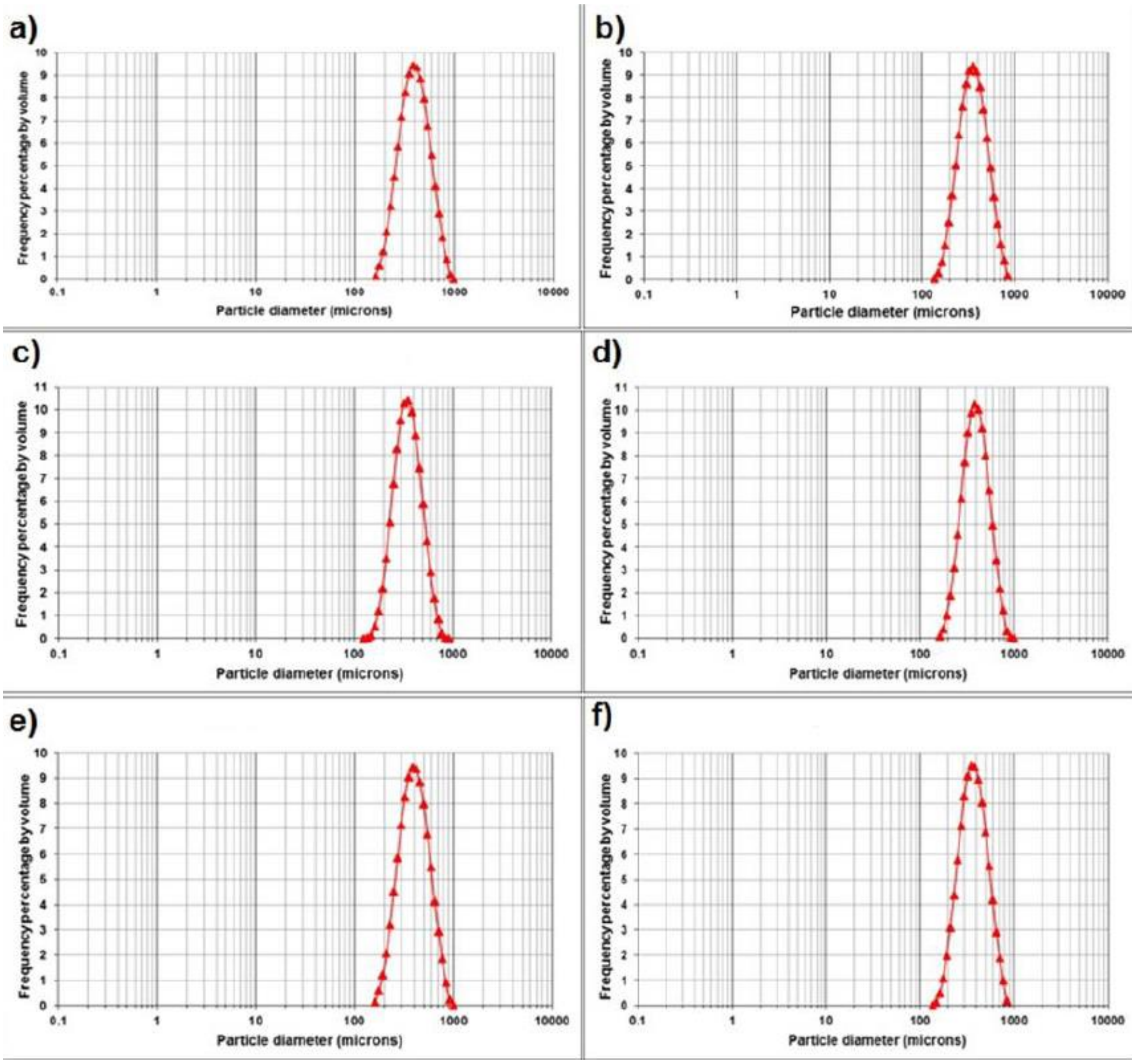

Figure 2.19 Particle size distribution (a – f) (Source: Regena, 2016)

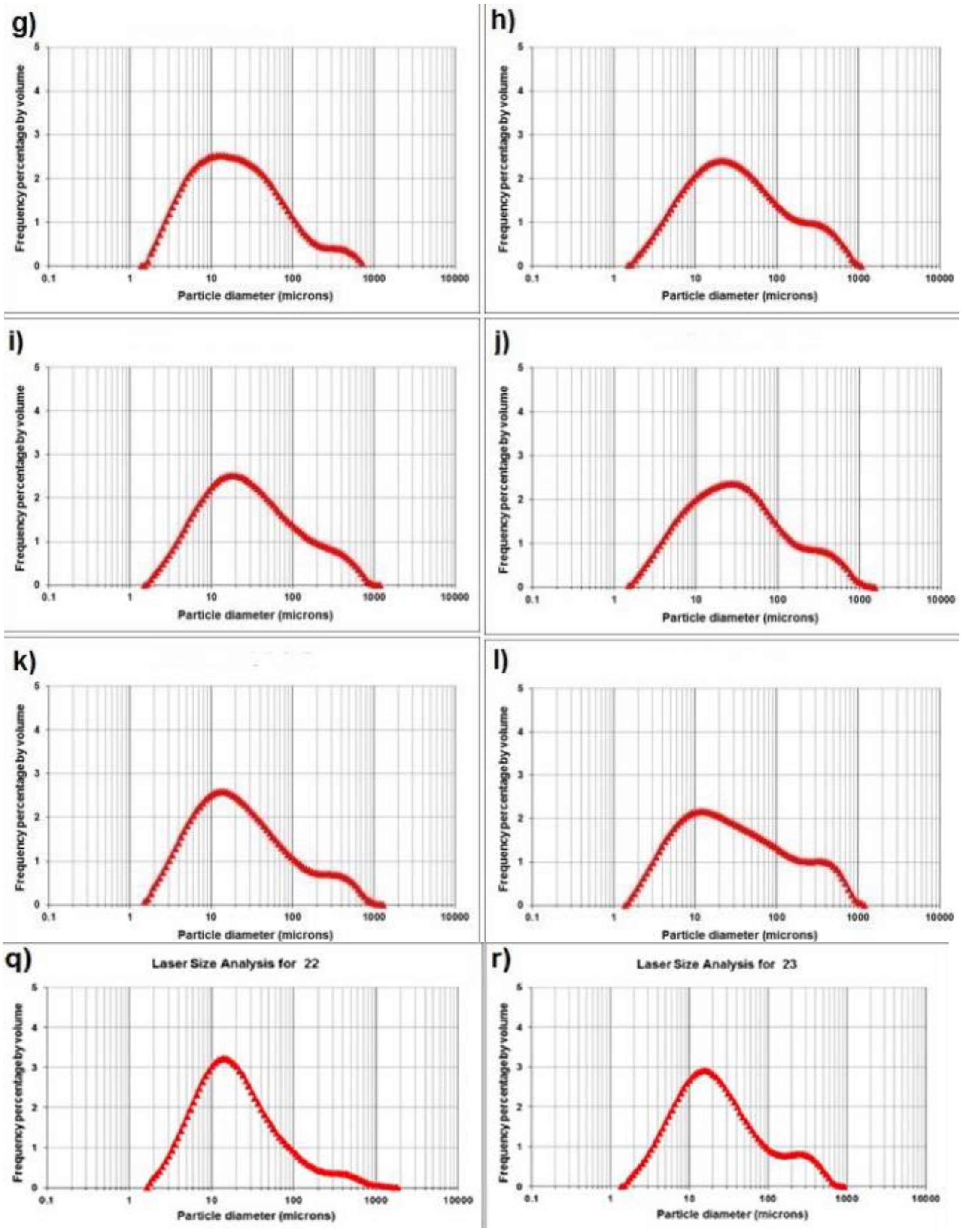

Figure 2.20 Particle size distribution (g – l and q – r) (Source: Regena 2016)

2.3.6 Water quality data

Monitoring of water quality within Lake Illawarra has occurred since 1987 by several organisations. Initially Pacific Power (the predecessor of Energy Australia who operate Tallawarra power station) monitored water quality at a number of locations from 1987 to 1991 and from 1996 to 2000 (WCC, 2018). In 2005 LIA continued water quality monitoring until it was taken on jointly by WCC and SCC in 2013 (WCC, 2018). Water quality has historically been monitored on a monthly basis by WCC and SCC at 15 locations within Lake Illawarra to assess the ecosystem health of the lagoon (WCC, 2016) (see

Figure 2.21 and Table 2.6). WCC and SCC stopped collecting data at Site 1 after December 2017 because of safety considerations, as access to Site 1 required climbing down over training wall rocks which had become unstable (WCC, 2018). However, WCC and SCC concluded that this was not a major drawback for the water quality monitoring program, as Site 2 was considered to have similar water quality to Site 1 (WCC, 2018). Since the 2018/19 summer, water quality is assessed for recreation at three new sites (previously shown in Figure 2.9; WCC, 2022). A summary of water quality data collected by WCC and SCC is provided in Table 2.7.

Figure 2.21 WCC and SCC water quality monitoring sites (WCC, 2017)

Table 2.6 Summary of WCC and SCC water quality locations

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

Table 2.7 Water quality parameters regularly collected at Lake Illawarra

Site type	Parameters
Ecosystem health	Temperature, pH, dissolved oxygen, salinity, turbidity, nitrogen, phosphorus, and chlorophyll a
Recreation suitability	Enterococci

Long-term continuous water quality data within Lake Illawarra has historically been collected by MHL. They operated two water quality meters that collected data continuous at 15 minutes at Cudgeree Bay and Koonawarra Bay from 1993 to 2018 (locations previously shown in Figure 2.11). These stations measured pH, temperature, salinity, chlorophyll a (from November 2014 onwards) and dissolved oxygen (Koonawarra only) (MHL, 2018).

2.4 Similar case studies

There have been many 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
- Changing long-term beach alignments

This section examines case studies of three NSW estuaries (Wallis Lake, Lake Macquarie and Wagonga Inlet) that were trained prior to Lake Illawarra, and provides a summary of morphological changes, experiences, and management of the three systems. At the time of writing, WRL understands that measures for controlling tidal conveyance at these three estuaries are not being actively explored by the local councils (MidCoast Council, Lake Macquarie City Council and Eurobodalla Shire Council, respectively).

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 to 17% by 2004. This equates to an average increase in tidal range of 2.4 mm/year between 1966 and 2004. This increase in tidal range has been accompanied with significant scouring of the first 3 km of the seaward end 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 have 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 seagrasses. As a result of sediment mobilisation from fast tidal currents, sediment deposition has impacted navigability and oyster farming. To manage these impacts, dredging and re-distribution of sediments has been required (GLC, 2014). At the time of writing, a study commissioned by TfNSW is underway to investigate short- and long-term solutions for the management of sand shoaling at the entrance to the lake (MidCoast Council, 2022).

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, is connected to the ocean by the 4.5 km long Swansea Channel, and has 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. Gordon and Nielsen (2022) estimated that the spring tidal range is increasing at a rate of 1.6 mm/year (between 1992 and 2021). An Escoffier diagram 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 Forster-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 have been measured up to 11 m deep (WBM, 1996). In 2004, it was found that up to 8 m of sand had scoured below part of the Swansea Bridge, lowering a section of the bridge by 0.14 m which required emergency works to support the undermined piles and jack the bridge to its original levels (Jenkins and Tilley, 2011). In 2006, 7,000 tonnes of rock ballast were placed under Swansea Bridge to increase the frictional resistance of the piles and provide scour protection (Jenkins and Tilley, 2011).

The issues associated with the training of the Swansea Channel have necessitated on-going management of the area by Lake Macquarie City Council (LMCC). 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 (Neumann Contractors, 2015) rather than to eroded sections of Swansea Channel. This contract also involved smaller scale subsequent maintenance dredging. Managing the impact of foreshore erosion has 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. They 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. The CMP for the area (LMCC, 2023) includes site-specific scour/erosion protection structures, monitoring of the ongoing evolution of Swansea Channel and planning to adapt to an increasing tidal range within Lake Macquarie.

2.4.3 Wagonga Inlet

Wagonga Inlet is located at Narooma (approximately 280 km south of Sydney), is connected to the ocean by a 3.3 km long channel with rock armoured intertidal training walls downstream of Narooma Bridge, and has a lake surface area of approximately 7 km^2. The entrance of the lake was trained between 1976 and 1978 primarily to improve entrance navigability for the commercial fishing fleet (MHL, 1994). Gordon and Nielsen (2022) estimated that the spring tidal range is increasing at a rate of 2.7 mm/year (between 1997 and 2021). An Escoffier diagram suggests that the channel will continue to scour (subject to morphological constraints) until the cross-sectional area of the channel is approximately tripled (Nielsen and Gordon, 2017).

Unlike the bridges at Lake Illawarra, Wallis Lake and Lake Macquarie, Narooma Bridge has not yet been threatened by erosion. While the channel is deeply scoured in places, erosion of the foreshore is comparatively limited (Gordon and Nielsen, 2022); likely because of the presence of the intertidal training walls. It is acknowledged that, at the time of writing, a failed seawall at Ken Rose Park (located immediately downstream of Narooma Bridge in the lee of an intertidal training wall) was in the process of being replaced with a “living seawall” (ESC, 2023).

The most acute impacts of the permanent opening of Wagonga Inlet have been on estuarine flora. Seagrass abundance in the estuary entrance channel was reduced by 57% between 1985 and 2005 Duchatel et al. (2014). Nielsen and Gordon (2017) attributed this loss of seagrass primarily to increased tidal velocities linked with scour of the channel which stressed flora located in the channel or deposition of eroded sand on the flood tide delta which smothered seagrass located there. Burrell (2012) found that since the completion of the training walls in 1978, the rate of the loss of saltmarsh and the rate of the growth of mangroves both approximately tripled. Nielsen and Gordon (2017) attributed some of the loss of saltmarsh communities in Wagonga Inlet to up-slope incursion of mangroves in response to the increasing tidal regime.

3 Conceptual overview of Lake Illawarra entrance channel processes (hydrodynamics and sediment transport)

3.1 Preamble

Developing a conceptual understanding of the Lake Illawarra entrance channel hydrodynamics and sediment transport processes is important in informing its future management. Considerable efforts have resulted in an extensive set of literature and data which is available for the site (Section 2). Continued collection and analysis of data within the Lake Illawarra entrance channel into the future will inform its ongoing management.

As part of this investigation, additional datasets were collected which add to the body of evidence showing that the entrance channel is in a state of change and is continuing to scour. These datasets will also be used to inform the detailed numerical modelling in the Stage 2 assessment. MHL (2023b) collected valuable water level and flow data within the entrance channel which supports their entrance stability analysis that, without implementation of a mitigation measure, scouring of the entrance channel is estimated to continue for a further 120 years (see Appendix A). Other datasets collected by WRL are detailed in Appendix B (data collected during a 2018 field campaign) and Appendix C (data collected during a field campaign spanning 2021 and 2022).

The following section provides a summary of the conceptual processes within the Lake Illawarra entrance channel based on the findings from the data compilation of this investigation. It discusses the present, and potential future, hydrodynamics and sediment transport (bathymetric change) to show how:

- Erosion in the entrance channel is likely to continue
- The tidal regime within the lake is likely to continue increasing

3.2 Hydrodynamics

Figure 3.1 presents an idealised sketch of a lake connected to the ocean by a single, relatively short and regular, entrance channel where the lake water level rises and falls uniformly across the entire lake area but with a smaller tidal range than the ocean. This is analogous to the environment of Lake Illawarra and its estuary channel. The estuary channel is effectively a flow constriction, acting like a valve, controlling tidal flows into and out of the main lake.

For most large estuary entrances in New South Wales, in the absence of freshwater flooding, maximum tidal flows occur near mid-tide at the ocean and tidal flows cease (reversing direction) at high and low tide (see example for Hunter River estuary entrance in Figure 3.2). However, the opposite occurs in the Lake Illawarra entrance channel (see Figure 3.3), maximum tidal flows occur at approximately high and low tide at the ocean and tidal flows cease (reversing direction) near mid-tide. The smaller tidal range in the lake (Koonawarra Bay) with later (lagging) high and low tide times compared to the ocean can also be seen in Figure 3.3. Further to this, the measured tidal range along the Lake Illawarra entrance channel gradually reduces from the ocean entrance to the lake (Figure 3.4) which indicates a frictional loss over the whole length of the entrance channel and not a specific site loss, such as for a weir, etc.

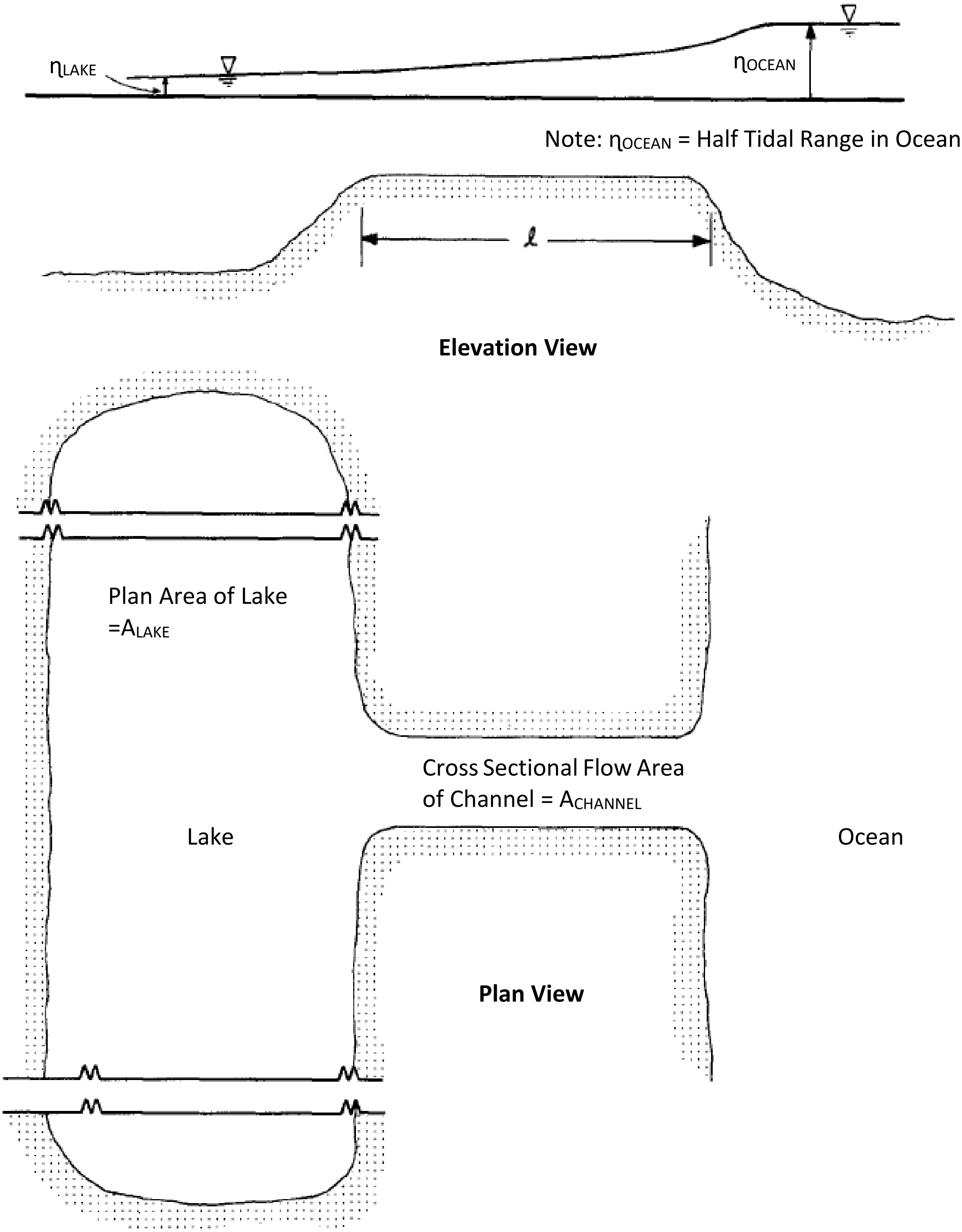

Figure 3.1 Idealised sketch of a lake connected to the ocean
(Adapted from O'Brien and Dean, 1972)

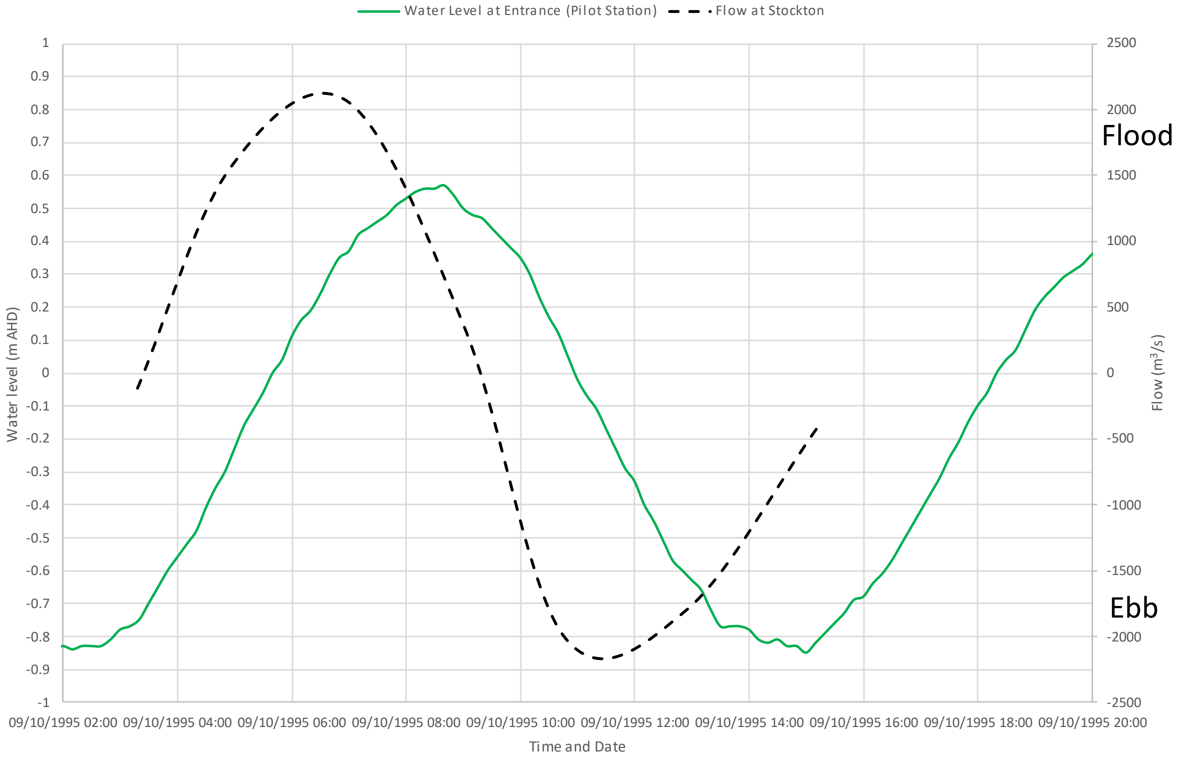

Figure 3.2 Hunter River estuary – comparison of gauged tidal flow with measured ocean water level 9 October 1995 (Adapted from MHL, 1996) – upstream flow (flood tide) is positive

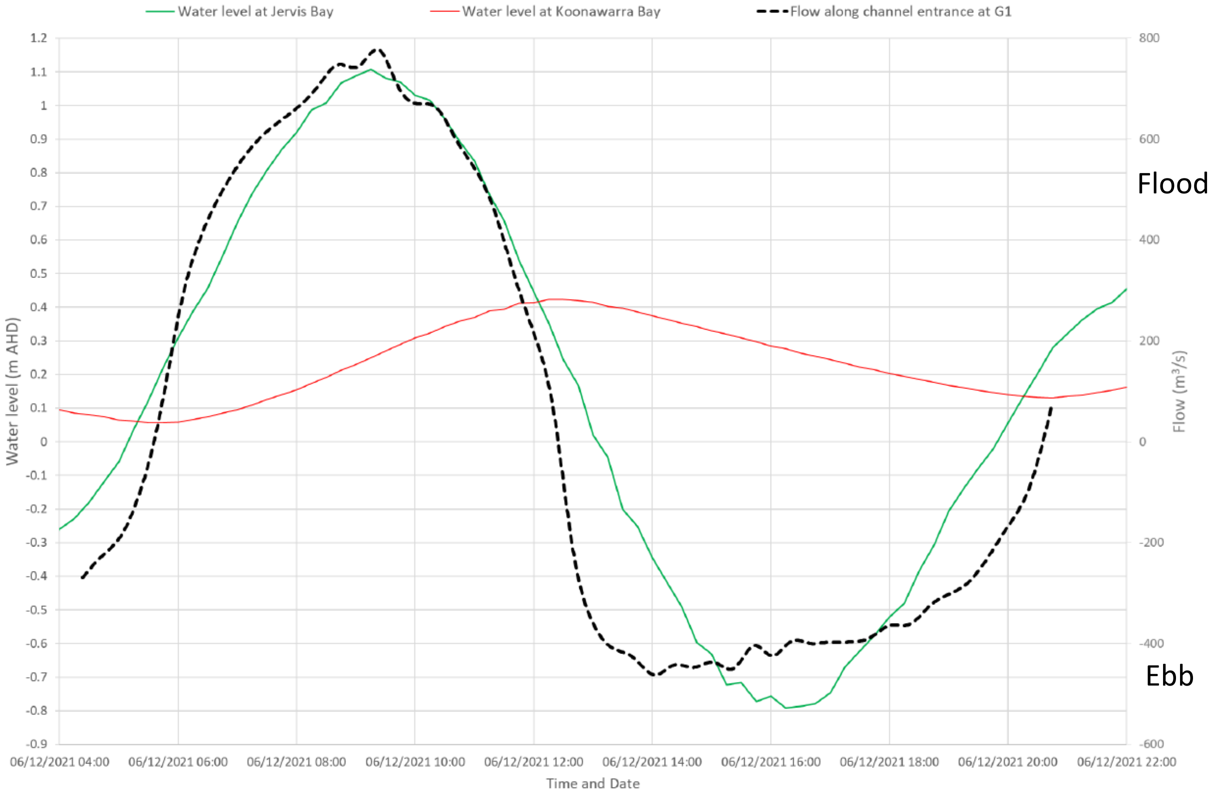

Figure 3.3 Lake Illawarra estuary – comparison of gauged tidal flow with measured ocean and lake water levels 6 December 2021 (Source: MHL, 2023b) – upstream flow (flood tide) is positive

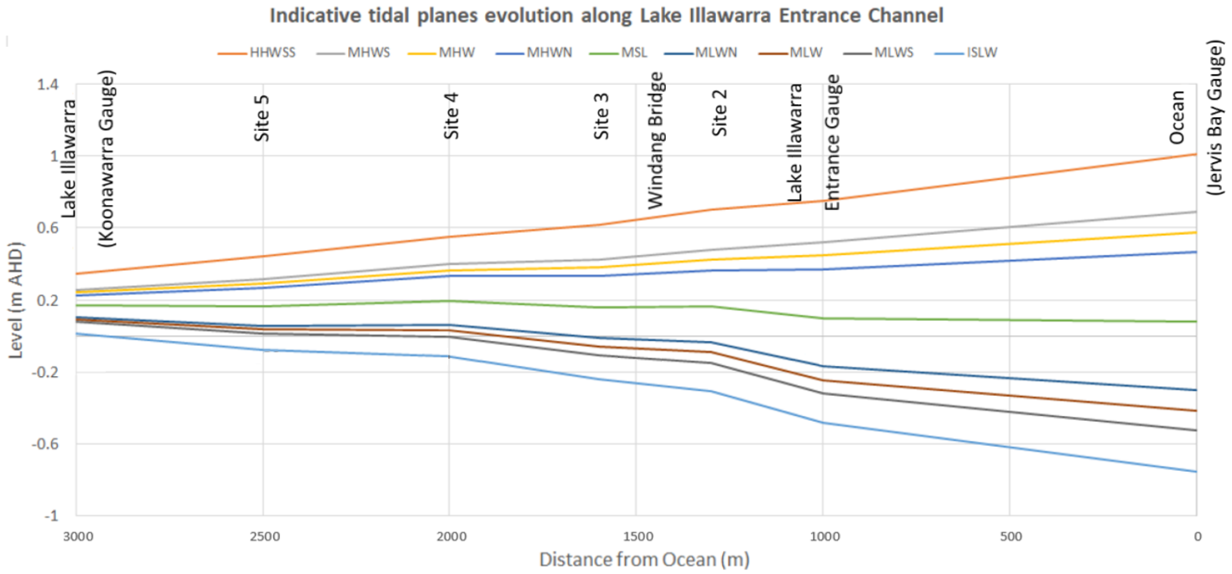

Figure 3.4 Indicative tidal planes evolution along Lake Illawarra estuary channel (Adapted from MHL, 2023b)

Concept sketches of the tidal level and flow regime in the Lake Illawarra entrance channel are shown in Figure 3.5 (high to low ocean tide) and Figure 3.6 (low to high ocean tide).

With reference to the panels in Figure 3.5, tidal flow into the channel is highest at the ocean high tide (panel 1), and inflows continue even as the ocean level is falling (panel 2), until the lake high tide occurs (panel 3). At this point, the water level in the entrance channel is approximately constant and tidal inflows from the ocean cease. As the ocean level falls below the lake level, the lake begins to drain with tidal flow reversed and directed toward the ocean (panel 4). Tidal outflows from the lake are then highest at the ocean low tide (panel 5).

With reference to the panels in Figure 3.6 (panel 5 is repeated from Figure 3.5), outflows from the lake continue as the ocean level is rising (panel 6), until the lake low tide occurs (panel 7). At this point, the water level in the entrance channel is again near constant and tidal outflows from the lake stop. As the ocean level rises above the lake level, the channel begins to fill again with tidal flow turned around and directed toward the lake (panel 8). The tidal cycle is completed when the ocean high tide occurs again (panel 9).

While Lake Illawarra begins filling after lake low tide, the following lake high tide level, occurring approximately 6.2 hours later, is much lower than the ocean high tide level. This is because there is not enough time for a sufficient volume of marine water (to fill Lake Illawarra to the ocean high tide level) to pass through the flow constricting entrance channel before inflows cease. Similarly, the lake low tide level is much higher than the ocean low tide level because there is not sufficient time to drain Lake Illawarra to the ocean low tide level before tidal infilling recommences.

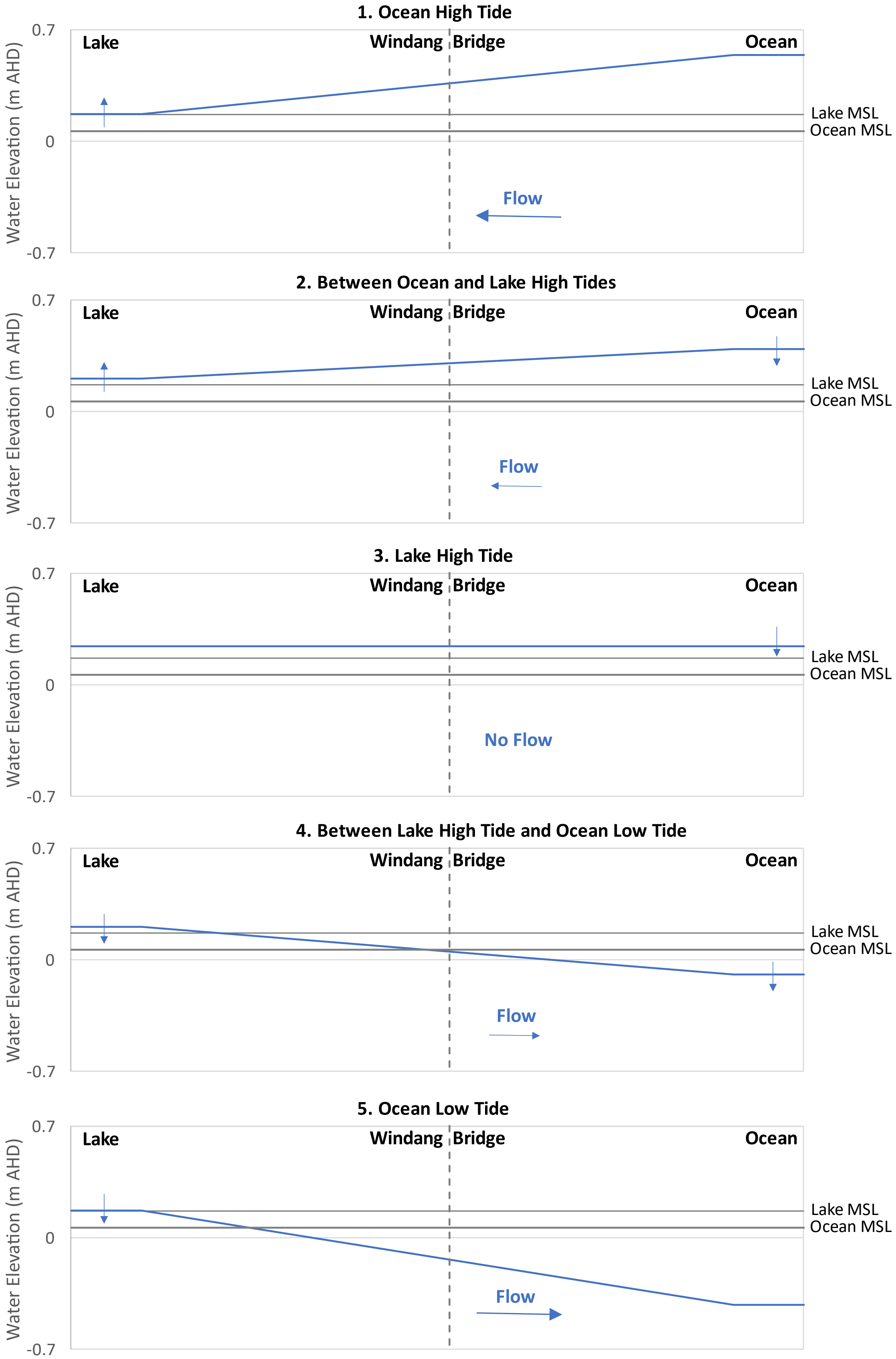

Figure 3.5 Concept sketches of water levels along the entrance channel (high to low ocean tide)

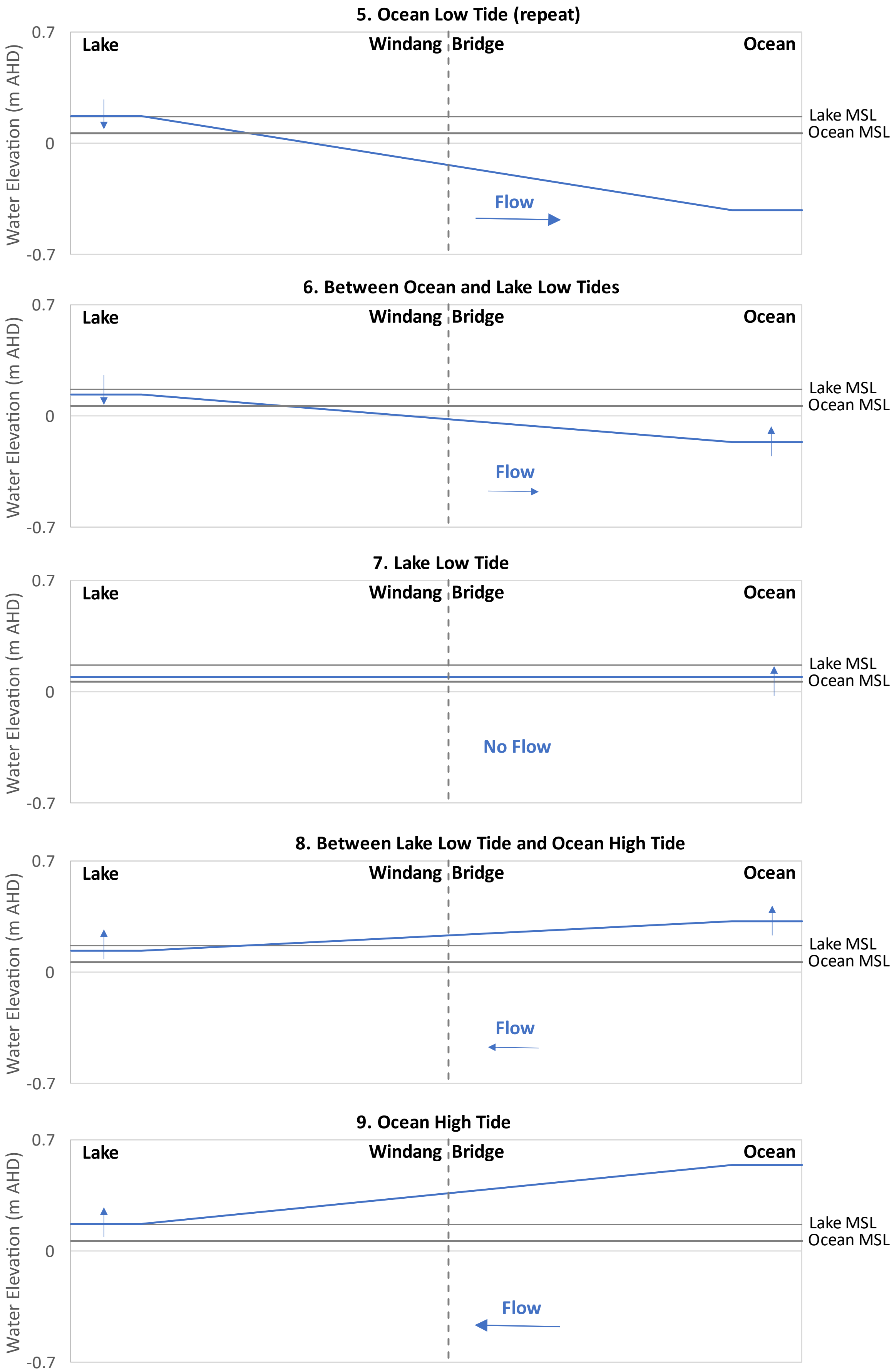

Figure 3.6 Concept sketches of water levels along the entrance channel (low to high ocean tide)

Hypothetically, if the plan area of Lake Illawarra (A_{LAKE}) was smaller, the lake tidal range would be larger because each cubic metre of inflow/outflow would result in a larger change in lake water level. Likewise, if the plan area of the lake was larger, the lake tidal range would be smaller.

Further, if the average cross-sectional area of the entrance channel ($A_{CHANNEL}$) was larger, so that flow constriction was reduced, the lake tidal range would be larger because a greater volume of marine water could inflow/outflow every 6.2 hours. If $A_{CHANNEL}$ was smaller (as it was in 2008 after the training walls were completed), so that flow constriction was increased, the lake tidal range would be smaller.

In combination with the entrance channel geometry (width, depth and length), friction at the channel bed and banks is responsible for resisting tidal flows and gradually reducing the tidal range from the ocean entrance to the lake. The change in the water surface elevation (potential energy) along the entrance channel due to frictional resistance results in high velocities (kinetic energy) – this process is called head loss.

3.3 Sediment transport

While the bed and banks of the Lake Illawarra estuary channel act to modify the hydrodynamics between the ocean and the lake, the water is also modifying the bed and banks. When the shear velocity (u_* which is proportional to tidal velocity) exceeds the critical shear velocity (u_{*c}) for sediment (typically medium sand; see Section 2.3.5) in the entrance channel, erosion is expected to occur. Similarly, when the shear velocity falls below the siltation shear velocity (u_{*s}), sediment accretion is expected. In between these two values, neither accretion nor erosion occurs. This estuarine process is shown over a tidal cycle in the idealised sketch in Figure 3.7, indicating that there is potential for eroded sediment to be both transported toward the lake and back toward the ocean.

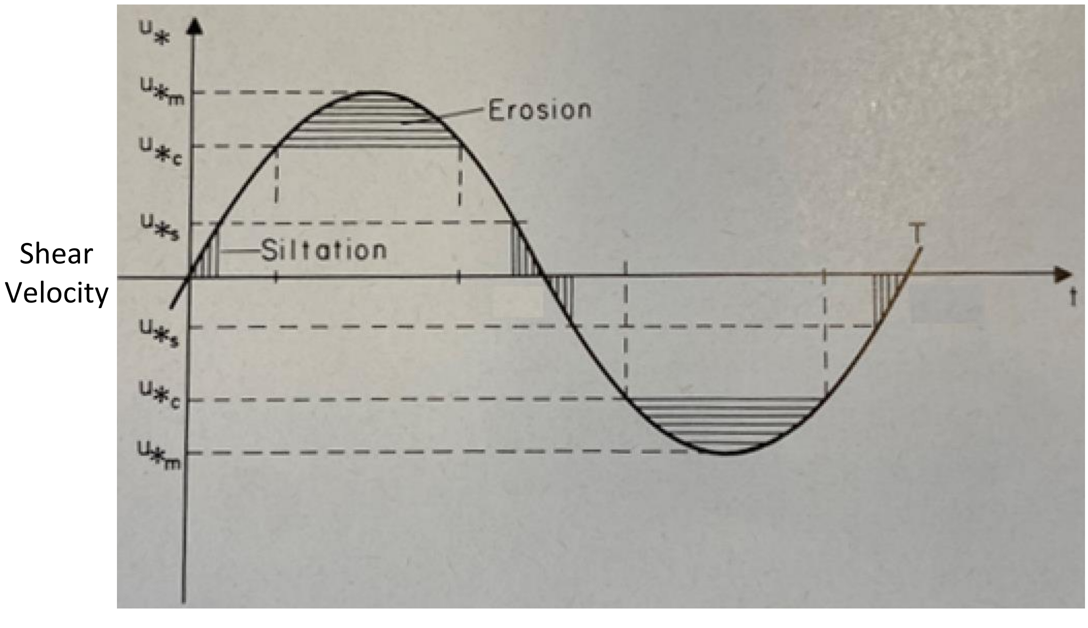

Figure 3.7 Sequence of erosion and siltation/accretion during a tidal cycle (Adapted from Raudkivi, 1976)

In the Lake Illawarra entrance channel, the erosion and accretion sequences are not in balance resulting in a positive feedback loop between the hydrodynamics and sediment transport. Due to the stress on the bed and banks from the high tidal velocities, net erosion is occurring in almost all compartments of the entrance channel (as discussed in Section 2.3.4). As a result of this ongoing erosion, the cross-sectional area of the entrance channel is increasing, reducing its flow constricting properties and allowing greater tidal flows (with higher tidal velocities) through it. The increasing tidal velocities are then further exacerbating the erosion/accretion imbalance in the channel. With reference to the inlet stability curve shown in Figure 2.6, this process of the entrance channel cross-sectional area increasing in proportion to the maximum tidal velocity is expected to continue from the 2021 position towards the right (along the red curve) until it reaches the peak of the curve (the critical flow area). To the right of this peak, the cross-sectional area will continue to increase but with a reducing maximum tidal velocity (i.e. an inverse relationship) until a stable equilibrium area is reached. At this point, tidal velocities will have reduced such that the erosion/accretion processes are in balance.

4 Afterword

Review of the data compiled in this report demonstrates that management of tidal conveyance is necessary to reduce foreshore and bed erosion and mitigate the increasing tidal regime in Lake Illawarra. The preliminary management options assessment (Coghlan et al., 2023) considered a range of measures for controlling tidal conveyance which can broadly be classified as providing increased head loss:

- via friction along part, or the whole length, of the entrance channel (e.g. sand nourishment) or
- at a specific site (or sites) in the entrance channel (e.g. a weir, groynes).

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