Quantifying change and impacts to Lake Illawarra from a permanent opening

D Wiecek[1], C Regena[2], R Laine[1], RJ Williams[3]
[1]Office of Environment and Heritage, Wollongong, NSW
[2]University of Wollongong, Wollongong, NSW
[3]Department of Primary Industries, NSW Fisheries, Sydney (retired)

Abstract

Lake Illawarra is a large coastal lake located on the NSW south coast, 85km south of Sydney. A number of changes have occurred to Lake Illawarra since the finalisation of works to create a permanent entrance opening in 2007 through training walls/breakwaters and associated entrance dredging. Lake Illawarra previously functioned as an ICOLL, and during drought would close off to the ocean for extended periods. Significant community pressure regarding concerns with poor water quality and estuary health during periods of closure culminated in the NSW Government (the now disbanded Lake Illawarra Authority) implementing a staged process of construction to create the permanently opened entrance.

Since the completion of the training walls/breakwaters and dredging, a number of hydrodynamic, physical, and biological changes to the Lake have been observed. These include changes to the tidal regime, entrance channel morphology, water quality and estuarine vegetation. Extensive data collection exercises to quantify these changes have included three separate hydrosurveys and tidal gauging exercises post 2007, ongoing water quality monitoring, and mapping of estuarine vegetation. This paper summarises the major changes that have occurred in Lake Illawarra since 2007 and highlight key impacts that have implications for the ongoing management of the Lake.

Introduction

Entrance training to permanently open NSW estuaries that intermittently close to the ocean is often raised as a solution to declines in water quality and estuary health by local communities. However, while some benefits may be realised, a number of unexpected consequences can and/or have been identified where this has occurred (Neilson and Gordon 2008; Duchatel *et al.,* 2014). As the costs for training estuary entrances are high and ongoing, the full range of impacts (short term and long term) need to be weighed up against the expected benefits to properly understand if significant investment in such infrastructure is the best management approach.

The relatively recent training and resultant permanent opening of Lake Illawarra, and data set availability from monitoring programs, allows an opportunity to more fully quantify the range and magnitude of impacts that can result from this type of management approach. While Lake Illawarra provides a useful case study to be considered in future proposals for entrance training of other NSW estuaries, an understanding of the changes and how these may be impacting on both built and natural assets is of critical importance for the ongoing management of Lake Illawarra.

Wollongong and Shellharbour City Councils, the two councils responsible for the management of Lake Illawarra, are currently preparing a coastal zone management plan

(CZMP) for the Lake. Water quality, channel and foreshore erosion and accretion, and the distribution and health of estuarine vegetation are considered priorities for management, with all these aspects impacted in some way by the entrance works.

Some initial work on quantifying these impacts was completed in 2010 based on the available data and completed analysis at the time (Baxter and Daly 2010). Key conclusions of this study included that the entrance works had increased tidal flows leading to some improvements in some water quality parameters; there had been a shift to a more marine influenced system; and, that this shift will cause some species/communities to prosper and others to decline.

This study attempts to more fully quantify a number of the key changes and their potential impacts as they relate to the ongoing management of the Lake based on an increased range and time period of monitoring data sets. For the purposes of this study, these changes are considered under the following headings:

1. Tidal regime
2. Entrance morphology
3. Water quality, and
4. Estuarine vegetation

1. Tidal Regime

The tidal regime (tidal range, velocity, prism and discharge) of an estuary exerts a major influence on estuary processes relating to sediment movement and deposition, water quality, and the distribution and health of ecological communities and the species that depend on them.

To gain a thorough understanding of how the tidal regime of Lake Illawarra has changed since entrance training, and therefore what potential impacts this has had and may continue to have on the Lake, several tidal data collection exercises have been completed (in 2008, 2012, and 2016), as well as analysis of long term water level data.

Tidal range change

Generation of yearly tidal planes and tidal ranges have been calculated based on analysis of water level data between 2007 and 2016 collected from three permanent water level gauges in the Lake: at the entrance channel; Cudgeree Bay (in the Lake immediately north of the entrance); and Koonawarra Bay (western side of the lake proper) (MHL 2016). Prior to May 2007 the Lake Illawarra entrance was intermittently closed and open to the ocean and tidal planes analysis was unable to be performed on the water level data as the hydraulics were too variable. While these tidal planes are useful for monitoring change, limitations and inaccuracies associated with the method used to calculate them for estuaries are acknowledged (MHL 2009).

The tidal analysis completed shows that the mean spring tidal range (MHWN-MLWN) has increased by 70mm in total at an average rate of 8mm/year at the entrance, and by 56mm in total at an average rate of 6mm/year at Koonawarra between 2007 and 2016 (Figure 1). While for absolute tidal range (HHWSS-ISLW), this increased by 109mm in total at an average rate of 12mm/year at the entrance, and by 105mm in total at an average rate of 12mm/year at Koonawarra between 2007 and 2016 (Figure 1).

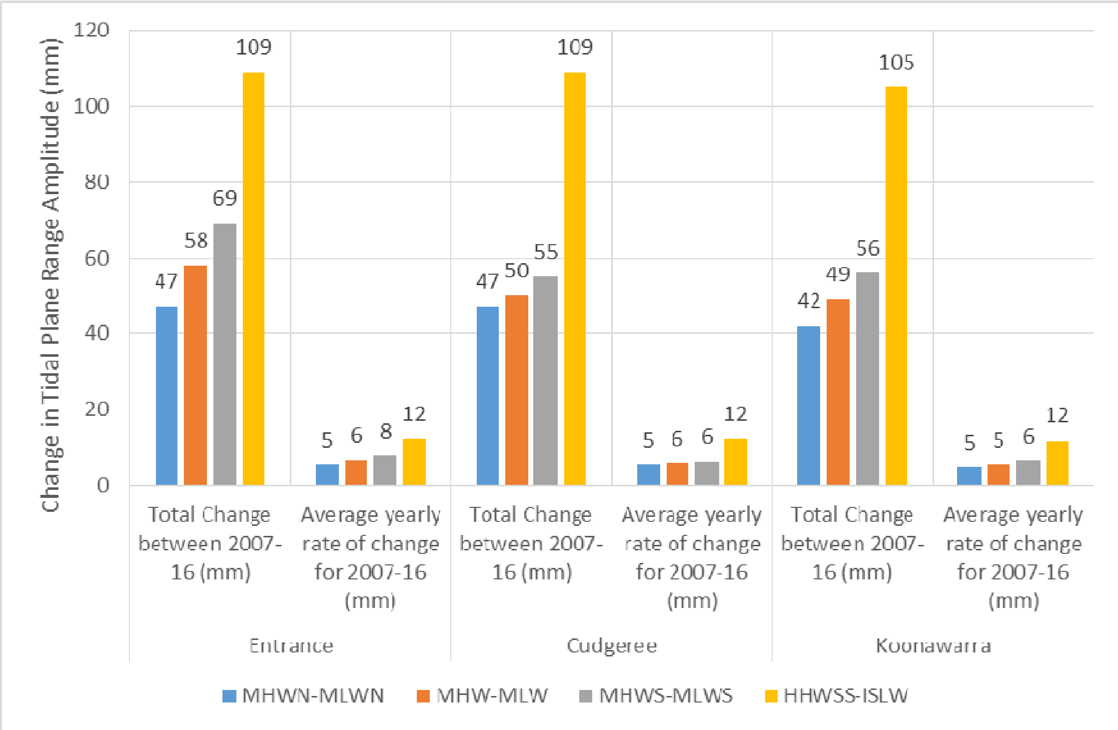

Figure 1: Total and yearly average rate of change in tidal plane amplitude for the entrance channel, Cudgeree Bay and Koonawarra Bay for four tidal plane ranges.

While the above results show that tidal range has increased overall between 2007 and 2016, a consistent year to year increase was only observed from the Koonawarra Bay water level recorder (Figure 2). Results from the two other locations were more variable having decreased spring tidal ranges between some years, but an overall total increase (Figure 2). MHL indicate that tidal analysis for the entrance water level recorder prior to 2013 should be used with caution, as prior to its relocation in 2013, it was not capturing full low water due to accretion of sand around the recorder (MHL 2016). As the Koonawarra gauge is located on the western side of the Lake well away from the entrance, it is a more reliable indicator of tidal range change in the main body of the Lake.

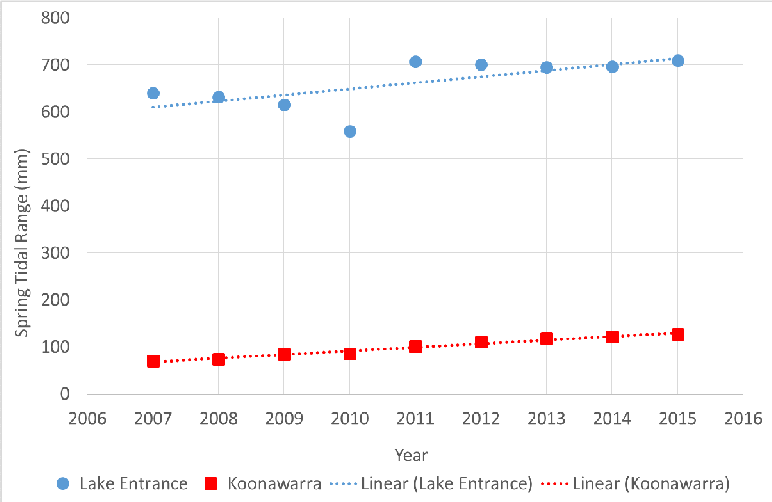

Figure 2: Mean spring tidal range for the Lake entrance and Koonawarra Bay showing the change in tidal range from year to year and the overall trend of tidal range increase between 2007 and 2016.

Analyses completed in 2013 found similar tidal range increases and used empirical (Escoffier) analysis and tidal harmonic analysis to describe how the entrance would continue to scour for 100+ years before an unconstrained equilibrium cross sectional entrance area is met, which would result in a tidal range close to that of the open ocean (MHL 2013).

While the tidal regime has changed and is continuing to change since the entrance works were completed in 2007, comparing the current tidal range to the historical tidal range of the Lake shows how different the Lake's tidal range has now become. Historically the Lake only had a small tidal range, with previous tidal analysis over the period 1993 to 2000 showing the Lake's tidal range varied between 0.0m (when closed) to a maximum of 0.1m (after a big flood scour event), but was only over 0.05m for less than 10% of the time (WBM 2003). Maximum tidal range over spring tides in 2016 at Koonawarra is now around 0.3m, while the tidal range for the Lake now is over 0.1m most of the time.

For coastal lakes such as Lake Illawarra, the fortnightly tidal cycle related to ocean spring and neap tides can also have a major influence on water levels. Water levels may be pumped up during spring tides and then drain during neap tides (MHL 2009), and this fortnightly water level variation can be similar or larger than the actual tidal range in some estuaries. Historically in the Lake (as measured from the Koonawarra water level gauge) this accounted for greater variation in water levels then the daily tidal variation. However, as tidal penetration has improved through increased hydraulic efficiency associated with the entrance breakwaters, the daily tidal range is of greater significance.

Average water levels

As entrance training is designed to maintain a permanently open entrance, one of the changes that result is a reduction in the major fluctuations in water levels associated with periodically closed entrance conditions. This can also result in a drop in average lake water levels. To understand whether this has occurred in the Lake after the 2007 entrance works, analysis of the water level data from Koonawarra Bay for approximately three years both pre and post the permanent opening was undertaken. This time period was chosen to allow comparison of the water levels that estuarine vegetation such as seagrasses would have been acclimatised to in the immediate years before the permanent opening.

Daily minimum, mean and maximum water levels were averaged for the pre and post opening time period chosen, and showed that they all dropped post opening (Figure 3). Importantly, averaged minimum water levels dropped by around 24cm and averaged mean water levels dropped by around 20cm based on the time period analysed. The drop in average water levels pre and post opening would have had an influence on the distribution of ecological communities such as seagrasses, mangrove and saltmarsh.

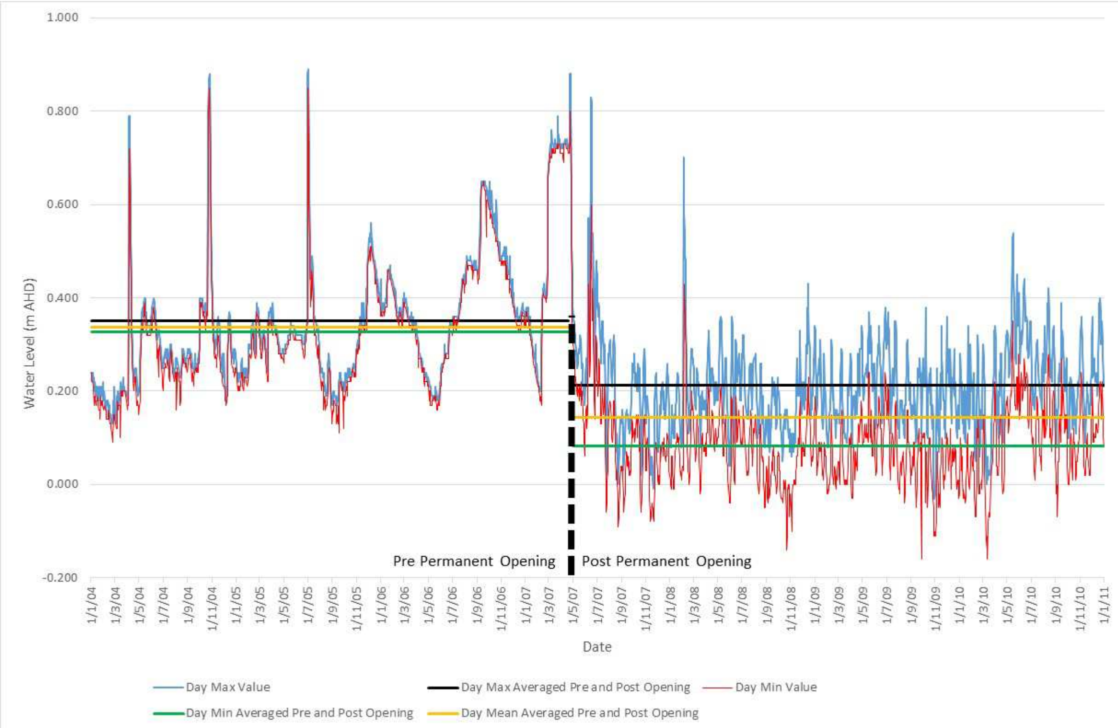

Figure 3: Average daily minimum, mean and maximum water levels calculated for pre and post opening conditions based on daily mean water level records extracted from Koonawarra Bay between 2004 and 2011.

Tidal prism and maximum tidal discharge and velocity

Tidal prism consecutively increased between the tidal gauging events of 2008, 2012 and 2016 (Table 1). The total increase from 2008 to 2016 represents more than a doubling in tidal prism. However, the magnitude of increase between 2008 and 2012 was larger than between 2012 to 2016. Maximum discharges and velocities for both flood and ebb tides also consecutively increased between the tidal gauging events of 2008, 2012 and 2016 (Table 1).

While there is no doubt that tidal prism, discharges and velocities have increased between each tidal gauging as a direct result of the entrance works, some qualifications need to be made when comparing them. As the 2016 tidal gauging occurred slightly more downstream compared to the 2008 and 2012 gaugings, a closer proximity to the ocean may have contributed to some of the increased tidal prism since 2012. In addition, as the gauging was done in a different location, the bed profile over the channel cross section would be different between 2016 and the prior years, which would have an influence on tidal velocities. The ocean tidal range on the day of gauging was also different between the three tidal gauging events, with the ocean tidal range for the 2008 gauging slightly smaller than for 2012 and 2016, which were similar. This can account for some of the tidal prism increase between 2008 and 2012 in particular, but is not considered to be a significant contribution.

Table 1: Summary of Lake Illawarra tidal prism, maximum discharge and maximum tidal velocity from three separate tidal gauging runs from 2008, 2012 and 2016 (data from MHL 2009, MHL 2013 and MHL 2016).

Year	**Tidal prism**		**Maximum discharge**		**Maximum tidal velocity**	
	Flood ($m^3 \times 10^6$)	Ebb ($m^3 \times 10^6$)	Flood (m^3/s)	Ebb (m^3/s)	Flood (m/s)	Ebb (m/s)
2008	2.7	2.14	222	131	0.72	0.84
2012	4.85	4.09	320	205	1.08	1.05
2016	5.46	4.8	388	245	1.22	1.4
Note: 2016 tidal gauging was completed at a different location to the previous gaugings making direct comparison indicative only.						

Tidal prism has a direct influence on the amount of exchange an estuary has with oceanic water and the rate at which an estuary is flushed of pollutants. An increasing tidal prism means that there is a greater exchange of water within the estuary over a given time period. In theory a greater turnover of water in an estuary like Lake Illawarra should translate to better water quality. However, it is not as simple as this as the water quality for coastal lakes is generally more related to the amount and quality of runoff coming from the catchment, and how pollutants within this runoff are assimilated and internally cycled.

If pollutants are constantly entering the Lake from runoff and/or being released through other internal cycling processes at a more rapid rate then can be exchanged with ocean water, then water quality will remain similar or worsen. However, if tidal prism increases continue as predicted (MHL 2013), tidal exchange is likely to have a greater impact on water quality within Lake Illawarra into the future, provided catchment inputs also do not increase.

An increasing tidal prism also means that the dimensions of the entrance channel need to expand to cope with the additional volume of water moving in and out each tidal cycle. By the time stable equilibrium entrance channel dimensions are reached, the cross sectional area of the entrance channel is expected to have increased over sevenfold (MHL 2013). This has major implications on foreshore assets and infrastructure that are currently and will continue to be undermined and eroded into the future as the channel widens and deepens.

Increased tidal velocities also have implications for the entrance channel. Tidal velocities influence bed scour, foreshore erosion, as well as sediment transport, which in turn impact on foreshore infrastructure, estuarine vegetation, particularly seagrasses, and boating navigation and recreational activities.

Key Points

- The tidal range in Lake Illawarra is increasing, high tides are getting higher and low tides are getting lower, and this increase in tidal range is likely to continue for a long time.
- Average and minimum water levels in the Lake have dropped since the 2007 permanent opening.
- Tidal prism and tidal velocities have significantly increased since 2007, and are expected to continue increasing for a long time.

2. Entrance morphology

Shoaling and scouring

The impacts of increased tidal prism and tidal velocities have included changes to the pattern and scale of shoaling and scouring in the entrance channel. Comparison of hydrosurveys completed by the Office of Environment and Heritage (OEH) between 2008 and 2016 show specific areas where significant scouring and accretion have occurred (Figure 4). An average deepening of around 2-4m has occurred along the thalweg of the main channel downstream of Windang Bridge, while accretion of the same magnitude has occurred on shoals east of Berageree Island and on the ebb tide delta seaward of the breakwalls. Upstream of Windang Bridge in the entrance channel, similar scouring in the thalweg of the main channel of around 1-2m has occurred, with both accretion (up to 2-3m) and scouring (1-2m) associated with progradation of the marine flood tide delta and movement of the main flood channel (as well as formation of secondary channels) where it enters the Lake basin (Regina 2016).

Other key changes include two isolated areas of major scouring associated with eddying off the front of groynes built to limit foreshore erosion downstream of Windang Bridge, which have seen deepening of up to 8m between 2008 and 2016 (Figure 4). Extensive reworking of the shoals to the east of Windang Bridge has also occurred. These changes in scouring and accretion are consistent with other estuaries that have had their hydrodynamic regimes changed through entrance training (Neilson and Gordon 2008). These changes have had impacts on seagrasses as well as boat navigation and recreational safety in Lake Illawarra and will need to be managed into the future.

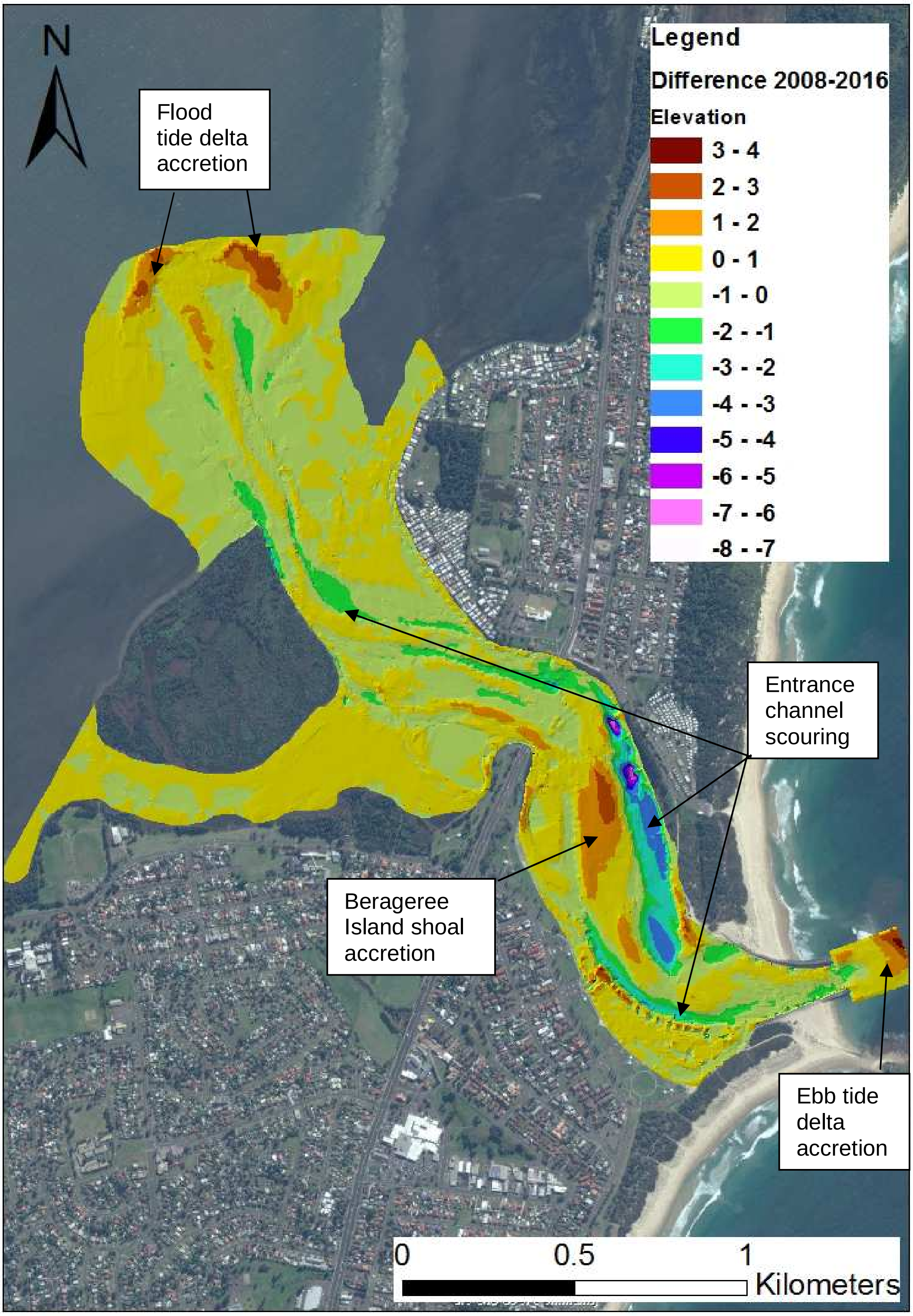

Figure 4: Difference in elevation between bathymetric surveys completed by OEH in 2008 and 2016, highlighting key areas of change (adapted from Regina 2016).

Foreshore Erosion

Changes to the pattern and scale of scouring and accretion in the entrance channel as a result of tidal prism and velocity increases have also led to increased foreshore erosion. For example, channel expansion and migration due to enhanced tidal prism and tidal flow velocities have resulted in the complete loss of a large shoal attached to the NE side of the entrance channel downstream of Windang Bridge (Figure 5). This shoal lined the foreshore for a distance of ~800m and was over 100m at it widest. This scouring has resulted in the loss of sections of boardwalk through undermining of their pilings (Figure 6), and is continuing to erode the foreshore and impact on other assets.

Figure 5: Aerial image of the shoals and shoreline downstream of Windang Bridge in 31/3/2008 (left) and 5/6/2016 (right), showing the complete loss of the shoals attached to the eastern shoreline, and a boardwalk (circled in above images) that extended over intertidal flats in 2008 which by 2016 has been undermined and partially lost.

As a result of this scouring and foreshore erosion impacting on assets including the boardwalk, sections of footpath, lighting and other park infrastructure, the LIA constructed three groynes and sections of seawall to halt further erosion in 2012. While these engineering solutions have maintained the shoreline over their footprint, protection of the shoreline both upstream and downstream has not occurred, and extensive erosion is continuing to threaten assets. This highlights how unexpected consequences of training an estuary can lead to ongoing costs associated with managing entrance channel erosion and scour as a result of channel adjustments to accommodate an increased tidal prism and velocities. The Lake Illawarra CZMP will need to look at long term engineering management options for the whole length of this foreshore to manage further erosion and future impacts to assets.

Figure 6: Shots of the northern entrance channel foreshore downstream of Windang Bridge taken on the 14-6-2012 (left) and 12-3-2015 (right), showing the loss of intertidal shoals and sections of boardwalk lost through scouring of the pilings.

Key Point

- Patterns of shoaling and scouring in the entrance channel have changed due to an increased tidal prism and tidal velocities, resulting in significant channel deepening, accretion on the flood and ebb tide deltas, and foreshore erosion and damage to assets along parts of the entrance channel.

3. Water Quality

One of the primary drivers for a permanent opening of Lake Illawarra was to improve the water quality (and thereby the health) of the estuary through constant exchange of waters with the ocean. In the 1970's and 80's water quality in the Lake was poor and symptoms of eutrophication including algae blooms common. In response the Lake Illawarra Authority (LIA) was set up in 1988 and while in operation instigated a number of strategies to improve water quality in the Lake (LIA 2010). Since this time some water quality improvements have been reported, but water quality has remained a key issue in terms of managing the Lake.

Previous water quality assessments

Some initial analysis in 2010 noted aesthetically the Lake waters looked better, particularly the entrance area, and that there had been reductions in malodorous conditions, algal blooms and fish kills, which were signs of improving water quality (Baxter and Daly 2010). However, it was reported that water quality improvements based on the water quality monitoring data collected were difficult to determine (LIA 2010). Some parameters like total phosphorous, total nitrogen and filterable reactive phosphorous were found to decrease in variability and levels, while turbidity and chlorophyll a were more variable. However, high rainfall events were found to still result in temporary declines in water quality.

One change that could be readily quantified was an increase in average salinity levels (recorded at continuous monitoring stations at Koonawarra and Cudgeree Bay), and less fluctuation due to quicker recovery after rainfall events as a result of the increased tidal exchange associated with the permanent opening (Baxter and Daly 2010; Wollongong City Council 2015).

Current water quality assessment

Two key monitoring data sets are available that allow for greater scrutiny of whether the increased tidal prism and tidal range that has been documented since entrance training has led to an improvement in water quality: from OEH and another from the LIA/Wollongong City Council.

OEH have consistently monitored chlorophyll a and turbidity across three broad zones within the Lake on a yearly basis from 2007 until present, following sampling protocols outlined in OEH (2016). Results averaged across the three lake zones indicate that both chlorophyll a and turbidity exceeded OEH trigger values the least in 2007-08 and the most in 2014-15 (Figure 7). While a weak trend of increasing non-compliance with trigger values for both parameters from 2007 to present may be evident, particularly turbidity, what is clear from this data is that neither parameter has improved since entrance training.

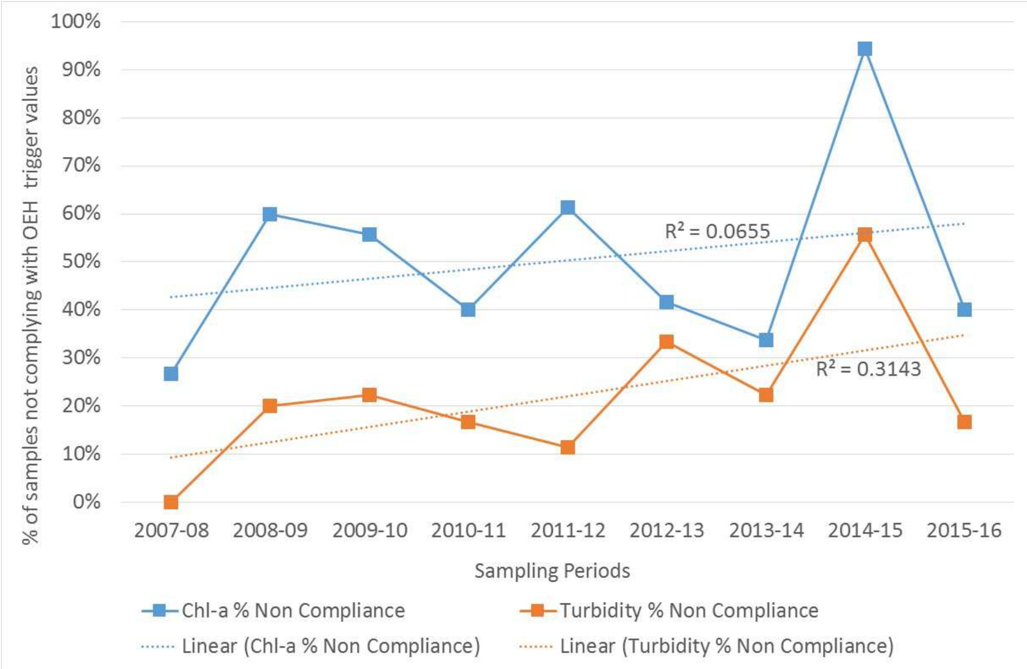

Figure 7: Percentage of yearly samples that exceed OEH trigger values for chlorophyll a and turbidity between 2007 and 2016 averaged across the three broad zones sampled within the lake basin. Trendlines have been fitted through the data to give an indication of any trend with time.

Water quality monitoring instigated by the LIA in 2005, and continued by Wollongong City Council after 2013, involved monthly sampling for a range of parameters at three sites (shore based off the end of jetties or bridge) within the Lake (Griffins Bay – north east foreshore, Kanahooka – western foreshore, Entrance – back channel). Analysis of this data shows a similar trend to the OEH data for chlorophyll a and turbidity (Figure 8). A weak trend of increasing non-compliance with trigger values for chlorophyll a existed from 2005 to present based on averaging across the three sites, but this trend is primarily driven by a number of years of high non-compliance with trigger values at Griffins Bay post the 2007 opening. However, a trend of increasing non-compliance with trigger values was more obvious for turbidity, particularly for the Griffins Bay and Entrance sites with most years post the 2007 entrance training having higher non-compliance compared with the pre entrance training years.

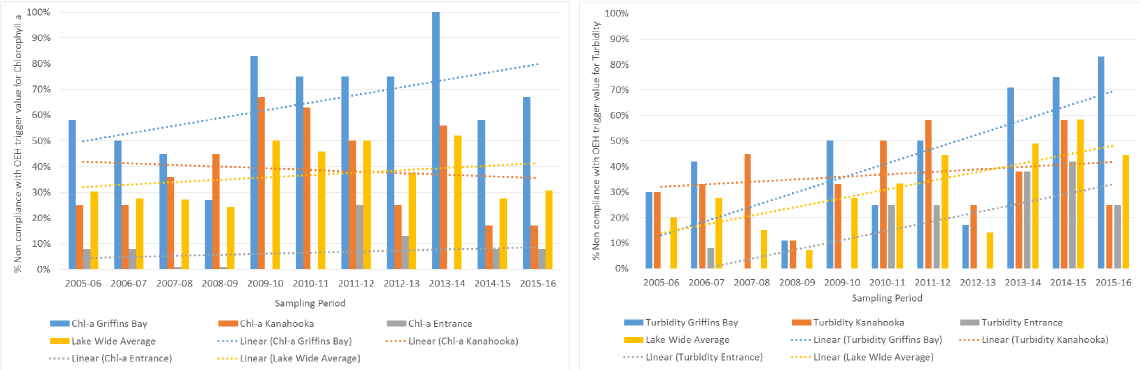

Figure 8: Chlorophyll a (left) and turbidity (right) % non-compliance with OEH trigger values for the three Lake sites, and a Lake average based on these sites.

In regards to nutrient parameters including TP, TN, and FRP (NH_3 and NOx not available until 2009-10 and not included) the results indicate that there has been an improvement in the lake based on the yearly non-compliance with trigger values averaged across the three sites around the Lake (Figure 9). This improvement was consistent across the three sites for TP, but site variation occurred with TN and FRP. The Entrance site typically showed the most improvement across the nutrient parameters when comparing the results pre and post entrance training. While Griffins Bay continued to show high non-compliance for TN in particular over the last five sampling years, similar to conditions pre 2007 entrance training.

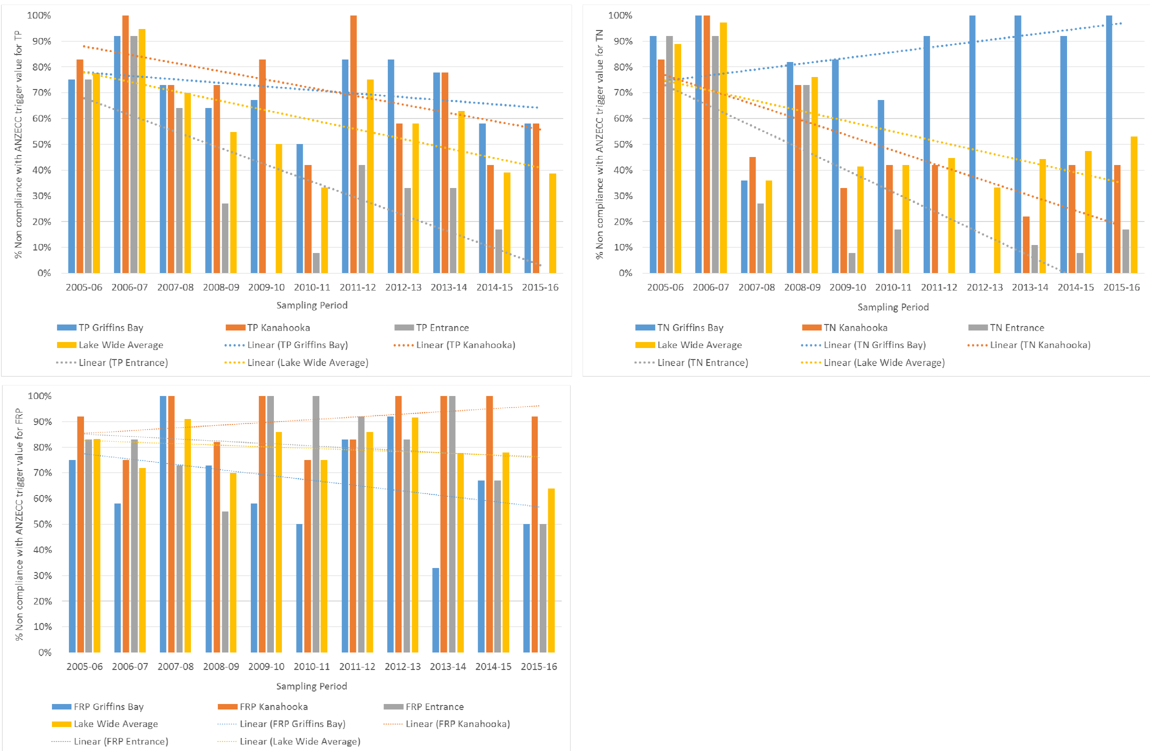

Figure 9: TP (left) and TN (right) and FRP (bottom) % non-compliance with ANZECC trigger values for the three Lake sites, as well as an average for the lake based on these sites.

Overall the results from this monitoring show that while there may be some improvement in terms of nutrients after the 2007 entrance works, it isn't consistent for all parameters and across all sites. In addition no improvement is evident for chlorophyll a and turbidity, which are considered better indicators of estuary health (OEH 2016). This highlights that water quality is currently more influenced by catchment runoff, internal cycling processes, and other weather phenomenon including wind compared to the increased flushing of the Lake driven by an increased tidal prism.

Of particular interest is the turbidity results from both OEH and the LIA/Council sampling that show that the Lake may in fact be getting more turbid, while anecdotally the waters of the entrance channel in particular are described as looking clearer. Apart from influences of weather and catchment runoff, this is possibly due to an enhanced influence of wind induced bed stirring from a shallower Lake since 2007, resulting in a greater ability to resuspend bed sediments. In the entrance channel other factors may be increased velocities leading to enhanced scour and transport of sediments in suspension, as well as whether the tide is incoming (ocean water) or outgoing (lake basin water). Higher lake turbidity has implications for seagrasses, as the depth they can grow to may be decreasing as less light is available over time.

Tidal flushing is likely to be only having limited influence on the more enclosed NE and SW sections of the Lake. A comprehensive assessment of recent Lake Illawarra water quality monitoring data (from 2013-2016) found high nutrient and chlorophyll a concentrations in these more enclosed sections, compared to the rest of the Lake (Wollongong City Council 2016). This highlights the importance of both continuing to retrofit stormwater improvement through water sensitive urban design strategies in built up areas, and ensuring new development in the west of the catchment follows a risk based framework in managing stormwater as has been proposed for Lake Illawarra (Dela-Cruz *et al.,* 2016).

Key Points

- Water quality in the Lake does not show a convincing trend of improvement since completion of the 2007 entrance works.
- Turbidity in particular appears to have worsened since the 2007 entrance works.
- Management of stormwater and other pollutants entering the Lake will continue to be critical to maintaining water quality acceptable to the community and key stakeholders.

4. Estuarine vegetation

Converting an ICOLL, as Lake Illawarra previously was, to a permanently opened tidal lake has a number of potential ecological consequences for estuarine vegetation, including mangroves, saltmarsh and seagrasses.

Mangroves

Historical distribution

ICOLLs typically do not support mangroves, or, if present, are isolated and usually stunted. This is because mangroves need constant tidal exchange to flourish. While mangroves can tolerate periods of closure, particularly once well established, prolonged inundation associated with lengthy entrance closures usually results in mortality and is why historically mangroves have never flourished in Lake Illawarra.

Statewide mapping of mangroves in NSW estuaries (West *et al*. 1985; Creese *et al*. 2009) reported the presence of limited cover of mangrove (*Avicennia marina*, or grey mangrove) in Lake Illawarra. These surveys were based on aerial photographs and field inspection, with the latter study identifying only one patch of trees, of about 57m^2, on the south side of the entrance back channel (NSW DPI/Fisheries, unpublished data). The sparse cover of mangroves mapped prior to 2007 is further confirmed by a survey of mangrove limits (MHL 2006) that located individual trees in a few of the tributary creeks and one sheltered bay (Table 2). Hence, there were only a few scattered mangroves in the Lake prior to 2007.

Table 2: Location of mangroves in Lake Illawarra identified in mangrove limit mapping of NSW estuaries (MHL 2006).

Location	**Date Identified**	**Comments**
Hooka Creek	31/1/2002	Left bank 5m high, 175m from Lake Illawarra
Duck Creek	5/8/2000	Three mangroves 1-2m high at entrance to Wollingurry Creek
Wollingurry Creek	31/1/2002	Left bank seedling 200m upstream from Duck Creek
Koona Bay	5/8/2000	Several mangroves 2m high in Koona Bay

The origin of the documented mangrove trees in the Lake is uncertain. Some may have established from propagules carried into the Lake by tides and currents from other nearby estuaries during periods when the entrance was open, while others may have been artificially brought in or planted. The LIA planted mangroves in the back channels of the entrance in 1999 to stabilise the foreshore and some of these are likely to have survived (Baxter and Daly, 2010). Also, an anecdotal account exists from a resident who claims he collected mangrove propagules from the nearby Minnamurra River and deposited them in Hooka Creek more than 20 years ago.

Current distribution

The total area of mangrove mapped in Lake Illawarra in 2016 was 8781m^2 (Regina 2016), classified as either large trees (~744m^2), small trees (~3580m^2) or juveniles (~5555m^2) based on canopy size and height (Note: these area estimations are non-additive due to intermingling of juveniles with the larger size classes). These size classes infer that the large trees were in place prior to the 2007 opening, while the small trees and certainly the juveniles, which make up the vast majority of mapped mangroves, became established after the 2007 opening. This significant increase in mangrove distribution post 2007 can be attributed to the favourable conditions that the permanent opening has created for mangroves, specifically a constant and increasing tidal exchange.

The 2016 mangrove cover mapping (Regina 2016) shows they are concentrated within two distinct locations: entrance back channel, with 88% of the total cover, and Duck Creek and the adjoining foreshore (stretching to the Yallah Bay power station cooling water outlet canal) containing 10% of the total (Figure 10). Only single trees, or small patches of trees and seedlings, were identified at other locations around the Lake (2% of cover). Both of the major areas had one or more mangroves mapped prior to 2007, highlighting how they have only flourished in areas where they were present prior to 2007 and where environmental conditions are favourable. These favourable conditions are likely to include the shallowness and sheltered nature of both locations, enabling mangrove propagules from the existing parent stock to settle and establish, coupled with enhanced tidal exchange since the 2007 permanent opening.

Mangroves have not yet colonised other parts of the lake in significant densities. In addition, as not all of the areas that previously had mangroves prior to 2007 have seen mangroves flourish, the spread of mangroves around the lake foreshore may be limited by a range of factors. These are likely to include exposure to wind waves, lack of suitable substrate (sand and rock as opposed to muds), limited propagule distribution, steep vertical banks with a lack of intertidal area, and smothering of seedlings from wrack and other debris in periods of elevated water levels and high wind.

Figure 10: Generalised location of mangroves within Lake Illawarra identified from intensive field survey in 2016. Small circles represent individual mangroves, or small clumps of mangroves and represent 2% of total mangrove area in the lake.

Key Points

- Mangroves *(Avicennia marina)* have significantly expanded in the Lake since the 2007 permanent opening, but only in two distinct locations: the entrance back channel and Duck Creek.
- Mangrove expansion is attributable to a constant and increasing tidal exchange that has resulted from the permanent opening.
- Expansion of mangroves around Lake Illawarra is likely to continue, particularly where favourable shallow and sheltered intertidal areas exist, but will be limited along other parts of the more exposed foreshores and where other factors constrain establishment.

Saltmarsh

The Lake is ringed along the major portion of its perimeter with the Endangered Ecological Community of saltmarsh, with extensive areas also occurring on the western side of the lake. The ongoing increase to the tidal range of the Lake has the potential to impact on saltmarsh.

An increasing tidal range in an estuary has a similar effect to sea level rise, both of which increase the upper tidal limit. As saltmarsh typically inhabits the upper intertidal area and is inundated by spring tides only, over time it will be forced to transition landwards as high tides get higher and saltmarsh at lower levels is inundated more frequently. While migration of saltmarsh will be possible in undeveloped areas, at a number of locations around the Lake saltmarsh migration landward will be constrained by development, and saltmarsh may eventually be lost from these areas.

In addition, at locations where mangroves have colonised saltmarsh (or areas potentially available for colonisation in the future), an increasing tidal range is also likely to favour mangrove expansion to the detriment of saltmarsh. Mangroves have been shown to have a greater ability to adjust to increased water levels associated with sea level rise compared to saltmarsh (Saintilan *et al.,* 2013), with sea level rise shown to be a factor in the widespread mangrove encroachment into saltmarsh in NSW estuaries (Rogers and Saintilan 2009). In Lake Illawarra an increasing tidal range coupled with a rise in sea level will potentially enhance the rate of mangrove encroachment.

While no assessments of cover of saltmarsh analogous to those completed for mangroves have taken place, comparisons of aerial photos and landscape photos suggest a decline in saltmarsh due to the mangrove expansion in the entrance back channel of the Lake (Figure 11).

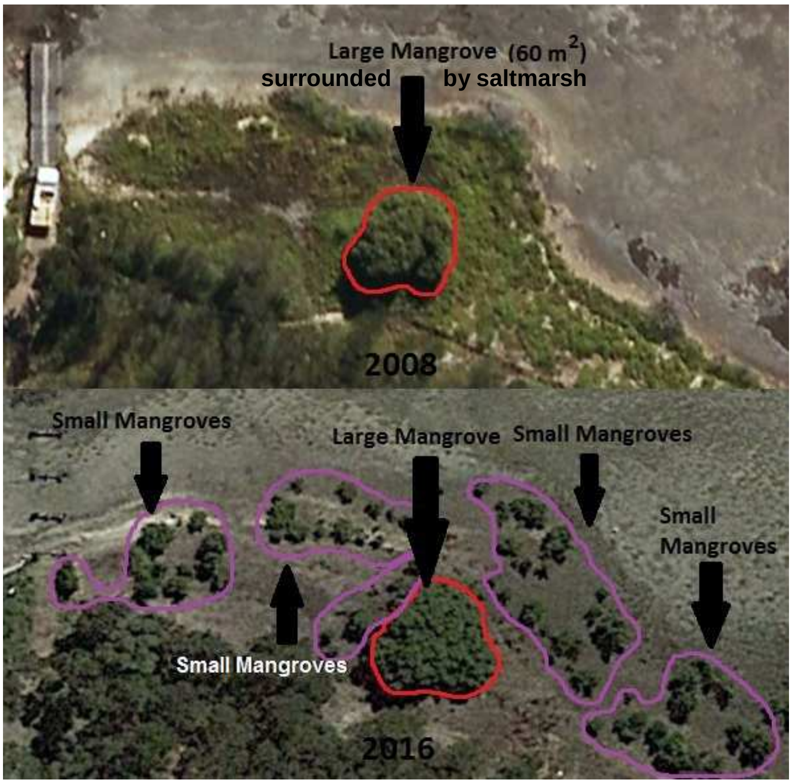

Figure 11: An example of mangrove encroachment of saltmarsh in the entrance back channel of Lake Illawarra (adapted from Regina 2016).

While expansion of mangroves may be a threat for the saltmarsh in the back channel of the entrance, at present they do not appear to be a major issue elsewhere. The biggest areas of saltmarsh around the western foreshores of the Lake have not been colonised by mangroves, despite some established mangrove trees nearby.

The Lake Illawarra CZMP will need to include a management strategy to monitor mangrove expansion and encroachment into saltmarsh, and determine whether key areas of large saltmarsh should be protected from mangrove expansion into the future.

Key points

- Saltmarsh will be forced to migrate landwards as high tides get higher, but may be constrained by development in some areas.
- Some loss of saltmarsh attributable to encroachment of mangroves is currently evident, but only in one specific location, the entrance back channel.
- Ongoing monitoring is critical to identify whether management intervention is needed in the future to control mangrove encroachment into key saltmarsh areas.

Seagrasses

The changes that have occurred to the tidal regime and water quality of Lake Illawarra since the 2007 permanent opening have had a number of flow on effects to seagrasses.

Seagrass distribution change

Seagrasses in Lake Illawarra have been mapped consistently on a yearly basis from 2007 to 2016 (Aurecon 2016). In addition, periods of other historical mapping using similar methodologies allow comparisons to periods of time prior to entrance training. What the mapping shows is a clear drop in all seagrass species by the 2008-09 summer compared to levels mapped just prior to entrance training in March 2007 (Figure 12).

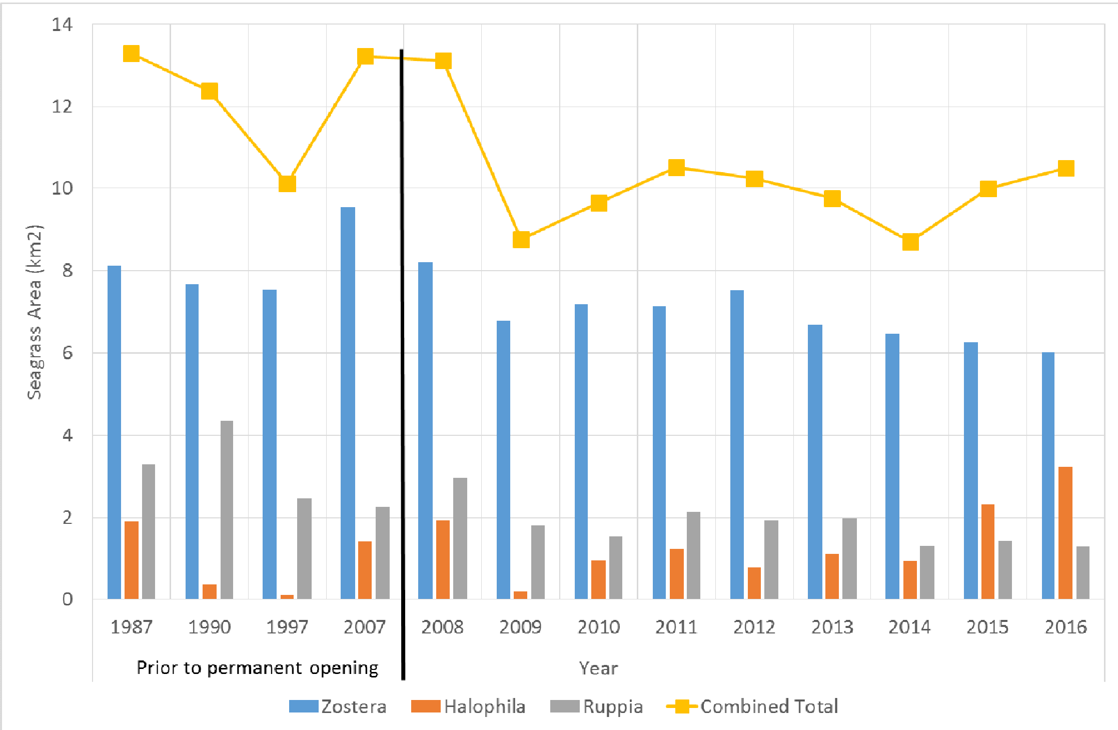

Figure 12. Seagrass distribution in Lake Illawarra pre and post the 2007 permanent opening (data from Aurecon 2016).

An initial drop in *Zostera* spp. was recorded for the first two sampling periods after the entrance training completion, while *Halophila* spp. and *Ruppia* spp. slightly increased after the opening, then dropped significantly the following summer. The most recent mapping from 2016 shows that *Zostera* has continued to decline since some increase from 2009 to 2012, while Halophila has significantly expanded since 2014 to levels not previously recorded in the Lake.

Areas of seagrass loss and causes

Key areas of seagrass loss, identified by comparing the extent of seagrasses from 2007 to 2016 (Figure 13), include the shallow margins around the entire lake foreshore and other shallow areas including Koona Bay, in front of major tributaries including Mullet Creek, Hooka Creek, and Macquarie Rivulet, as well as the flood tide delta.

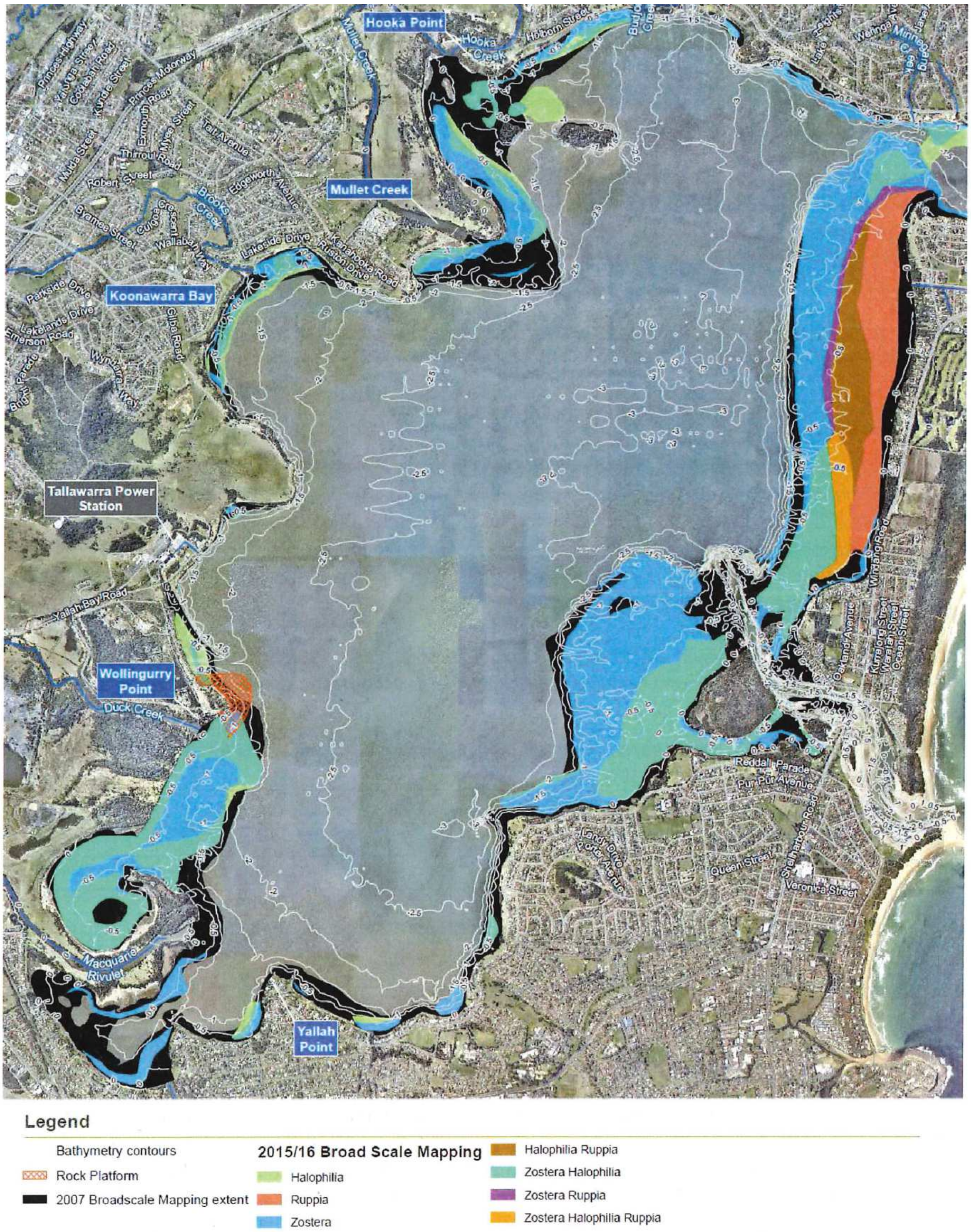

Figure 13: Locations of existing (coloured) and prior (black) coverage of seagrass in Lake Illawarra from 2007 to 2016 (from Aurecon 2016). Areas of loss are seen at the upper and lower margins of existing seagrass beds.

Seagrass loss of the shallow margins

The loss of seagrasses in the shallow regions around the lake is likely due to increased exposure associated with a reduction in mean water level, as well as increased turbidities associated with enhanced resuspension of bed sediments. The effect of sustained reduction in light availability due to resuspension of sediments is likely to be a reduction in seagrass depth limits and long-term impacts on seagrass biomass and growth.

A shallower lake caused by the drop in average water levels (see tidal regime section) would have meant that seagrasses growing in the shallowest parts of the Lake at their limit of minimum water level needed to survive would have died off due to an increased exposure to air and solar radiation, particularly over the hotter summer months. This shallowing would have also enabled enhanced bed stirring of bottom sediments through wind and waves, resulting in increased turbidities and less light reaching seagrass beds. Reduced light availability has also likely inhibited reestablishment of seagrass. Together these stressors would be responsible for a depth related pattern of seagrass loss that is evident in Figure 13.

In addition, lake shallowing would have also increased seagrass exposure to wave energy during strong winds, particularly where seagrasses front exposed areas that have a large fetch. This has also likely contributed to some of the seagrass loss observed at exposed areas such as Windang Peninsula.

An increase in frequency of desiccation events associated with a drop in mean lake levels and a trend of lower low tides is expected to favour seagrass species such as *Halophila* spp. due to their faster recovery times and smaller stature limiting their exposure during low tide. This appears to be the case in Lake Illawarra with the increase in Halophila over recent years (Figure 12).

Widespread losses of seagrasses in Lake Illawarra have previously been reported as a result of lowered water levels. In 2002-03 an extensive dry period resulted in the Lake closing and water levels dropping through evaporation to their lowest ever recorded levels. This resulted in an estimated 50% loss in seagrass as a direct result of exposure during falling water levels. The lowered water levels also meant that the remaining seagrass had a new level of exposure to wind generated waves and currents, and further losses of seagrasses were reported due to high turbidity associated with enhanced sediment resuspension experienced over sustained strong winds (West, 2004).

Seagrass loss in front of the major tributaries

Some of the largest areas of seagrass loss in Lake Illawarra since 2007 are at the discharge of major tributaries, including Mullet Creek, Hooka Creek, and Macquarie Rivulet, an outcome consistent with increased sedimentation as well as higher turbidity levels as a result of catchment runoff. A drop in mean water levels and lower low tides would have further compounded the shallowing in front of these tributaries, placing additional stress on seagrasses currently at their upper distributional limits through increased exposure and desiccation.

A drop in mean water level should have meant that over time seagrasses might be able to expand into adjacent deeper water that was previously below the depth limit at which they could grow. However, colonisation of deeper parts of the Lake, including in front of tributaries, does not appear to have occurred to date and may be the result of increased turbidity since 2007 (see water quality section), which would be reducing light penetration, inhibiting seagrass establishment.

Entrance channel and flood tide delta

Increased tidal velocities in the entrance channel (see tidal regime section) have led to the loss of seagrasses both within the entrance channel and flood tide delta through enhanced scour and burial. This is evident through the loss of substantial entrance shoals that were covered in seagrasses (see Figure 5, p9). As tidal velocities have increased, the pattern of scouring and shoaling in the entrance channel has changed. One of the major changes is significant progradation of the flood tide delta, which has resulted in the direct scour and burial of a large area of seagrasses present before the 2007 permanent opening (Figure 14).

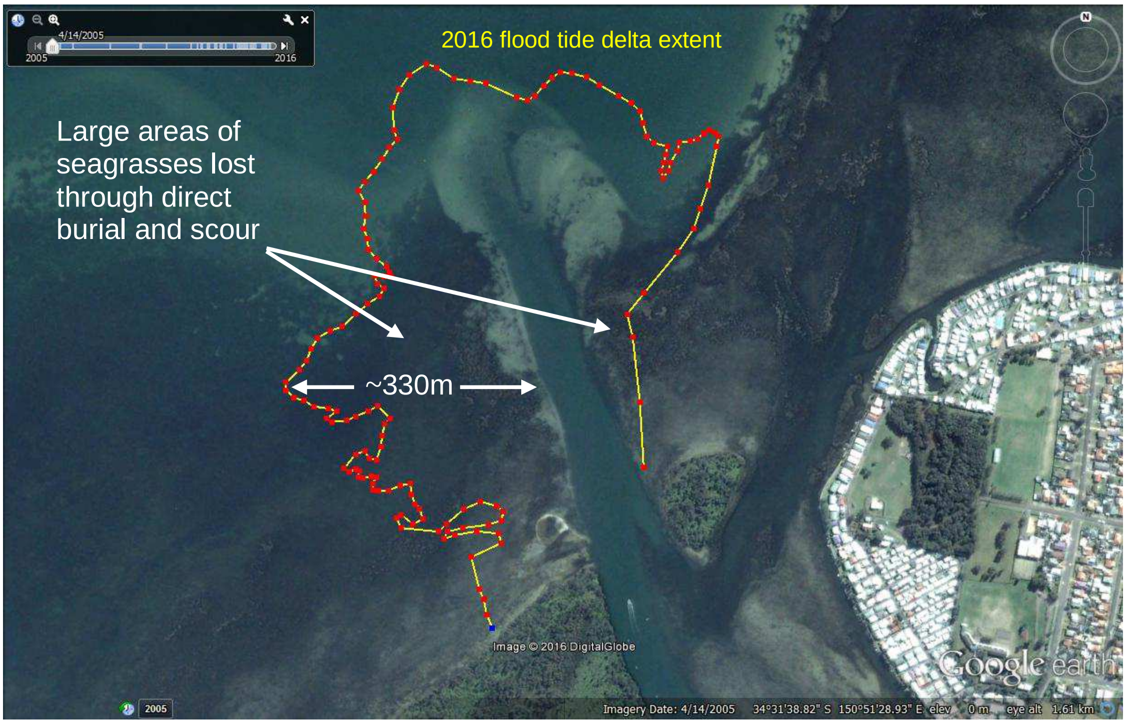

Figure 14: Plot of the flood tide delta extent from 5/6/2016 over an aerial backdrop from 4/14/2005 showing the extent of the progradation of the delta post 2007 and the seagrasses present prior to 2007 that are now lost.

Key Points

- Seagrass coverage in Lake Illawarra has decreased since the permanent opening in 2007.
- Seagrasses currently at their upper distributional limits will continue to be stressed through increased exposure and desiccation as low tides get lower.

- An increasing tidal range may provide opportunity for seagrass colonisation in other parts of the Lake but this appears not to have occurred to date.
- Turbidity associated with enhanced suspension of sediments in shallower waters as low tides get lower will continue to place stress on seagrasses.
- Management of catchment runoff to reduce additional sediment and nutrient inputs to the Lake is critical to minimising turbidity and maintaining favourable conditions for seagrasses.

Conclusions

The entrance works completed in 2007 have led to a number of changes to the Lakes physical, chemical and biological characteristics. While many in the community view the entrance works as a success, some of the changes that have occurred present new challenges that will need to be closely monitored and managed into the future.

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