Lake Illawarra entrance channel: preliminary management options assessment

WRL TR 2022/23, November 2023

By I R Coghlan, T A Tucker and D S Rayner

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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 (this report)
    - Report 2: Data compilation (Tucker et al., 2023)

- 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 Development of management options

2.1 Objectives

While many of the values for Lake Illawarra (BMT, 2020b) are inter-related, long-term management options were developed primarily to reduce foreshore and bed erosion in the entrance channel and reduce an increasing tidal regime in the lake. These issues are discussed in greater detail in the Stage 1 data compilation report (Tucker et al., 2023) but a brief summary is provided below.

Prior to the permanent opening of the entrance in 2007, WBM (2003) estimated that the tidal range within the lake varied between 0 m (when the entrance was closed) to a maximum range of 0.1 m after the lake entrance was scoured from a significant catchment runoff event. The median tidal range was approximately 0.02 m (WBM, 2003). In the year between July 2018 and June 2019, MHL (2023) calculated the mean tidal range (mean high water minus mean low water) at Cudgeree Bay and Koonawarra Bay to be 0.161 m and 0.141 m respectively. As such, the average tidal range in the lake is at least seven times higher than prior to the construction of the training walls in 2007. MHL (2017) showed that the mean spring tidal range has been increasing at an average rate of 6 to 8 mm/year since the entrance was opened in 2007. Wiecek et al. (2016) also showed that following the permanent opening, daily mean and minimum water levels in the lake dropped by approximately 0.20 and 0.24 m, respectively (Figure 2.1).

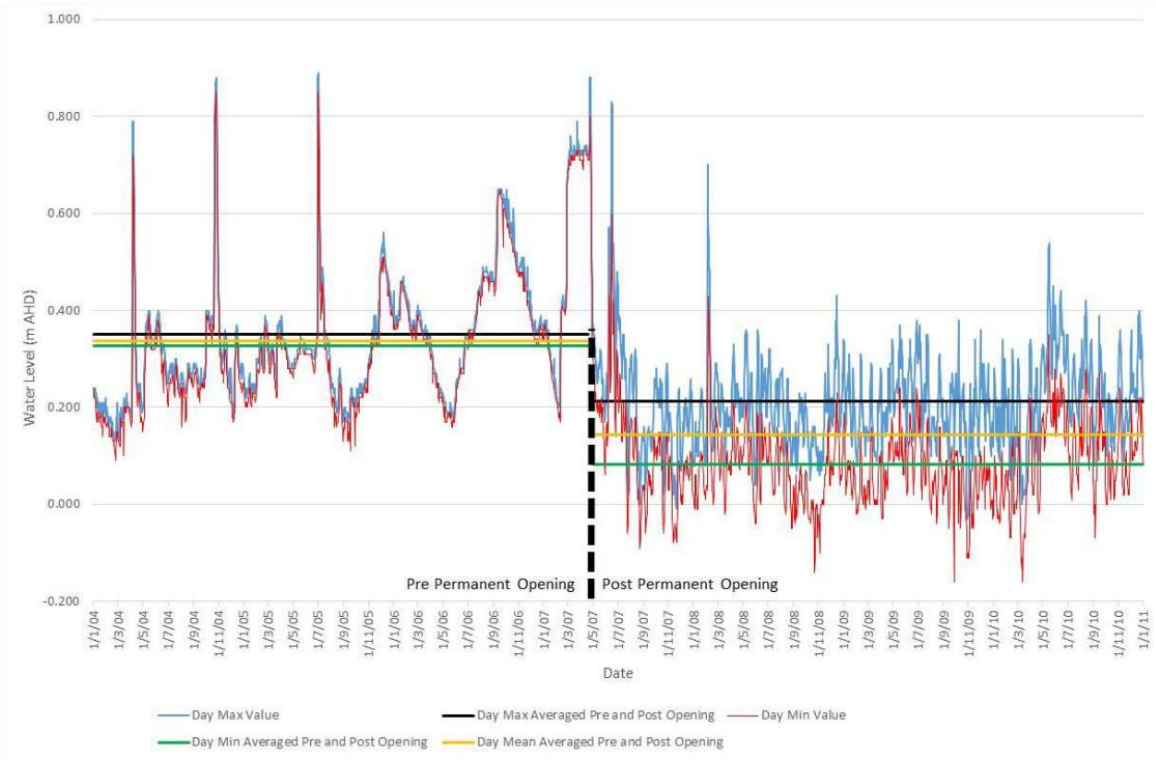


Figure 2.1 Analysis of average daily maximum, mean and minimum water level in Lake Illawarra (Source: Wiecek et al., 2016)

Accordingly, since 2007, the tidal prism (the volume of water in the Lake Illawarra estuary between high tide and low tide), maximum tidal velocities and maximum tidal discharge have increased. Analysis of seven tidal gauging measurements indicated that the tidal prism almost quadrupled in volume between

2008 and 2021 (Tucker et al., 2023). This is unequivocal evidence that the efficiency of the channel has increased since the entrance was permanently opened in 2007.

The increasing tidal velocities have also caused significant morphological changes within the entrance channel resulting in shoaling in some areas and significant scouring in others. Regena (2016) and Wiecek et al. (2016) demonstrated that substantial changes had occurred in the entrance channel between 2008 and 2016, with channel scouring (approximately 2 to 4 m deepening) along the Windang foreshore, while there had been complimentary accretion around Berageree Island, and on the flood and ebb tide deltas. Tucker et al. (2023) showed that there was a net loss of sediment from inside the entrance channel of almost 900,000 m^3 between 2008 and 2022 and inferred that most of this sediment has been transported into either the lake or offshore beyond the ebb tide delta to the littoral zone. The trend of ongoing erosion to the channel bed and foreshore also threatened the stability of Windang Bridge, requiring rock to be placed beneath a section of the northern end of the bridge which occurred in 2019-2020 (MHL, 2019). TfNSW is committed to placing additional rock under the rest of Windang Bridge for the purpose of stability in the near future.

In addition to causing the foreshore and bed erosion in the entrance channel, the increasing tidal regime has resulted in higher high tides and lower low tides which have affected estuarine vegetation (increase in mangroves and decrease in saltmarsh and seagrass) and amenity (exposure of greater areas of sand/mud flats at low tide).

On this basis, the primary objectives of the long-term management options are to reduce foreshore and bed erosion in the entrance channel and halt the increasing tidal regime in the lake, and preferably decrease it to a similar regime to that which existed either:

- Before the entrance was permanently opened (when the entrance was in a scoured state following a major catchment runoff event) or
- Shortly after the entrance was permanently opened.

2.2 Workshops

A list of potential management options for the Lake Illawarra entrance channel for consideration by the PCG was developed by combining the outcomes from the following two ideas workshops:

- Ideas developed by WCC, SCC and DPE staff provided to WRL by e-mail on 14 September 2021 (WCC, 2021a), and an
- Ideas workshop with WRL and MHL staff from 11 AM – 1 PM on 14 September 2021 (list of participants shown overleaf).

The WRL and MHL staff who participated in the ideas workshop are highly experienced in solving coastal engineering and hydraulics problems. The two neighbouring laboratories, located below Manly Dam in Manly Vale, have been providing expert advice on issues related to water for more than 60 years, commencing operations in 1944 (MHL) and 1959 (WRL), respectively. WRL and MHL (as Australian Water and Coastal Studies Pty Ltd) first undertook a study together to improve the Lake Illawarra entrance channel in 1991 (Wilson et al., 1991) and two of the 1991 report authors (Ed Couriel and A/Prof. Ron Cox) participated in the 2021 ideas workshop. As discussed in Tucker et al. (2023), WRL and MHL were not involved in later projects focused on designing training walls extending beyond the natural Windang Beach shoreline. Since the construction of the training walls in 2007, WRL and MHL have undertaken a range of investigations in the entrance channel with

accompanying reports. Note that 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).

WRL-MHL Participants:

- Matt Blacka (WRL)
- James Carley (WRL)
- Ed Couriel (MHL)
- Ian Coghlan (WRL & Secretary)
- A/Prof. Ron Cox (WRL)
- Mathieu Deiber (WRL)
- Dr Stefan Felder (WRL)
- Dr Francois Flocard (WRL)
- Matthieu Glatz (MHL)
- Dr Mitchell Harley (WRL)
- Alice Harrison (WRL)
- Indra Jayewardene (MHL)
- Brett Miller (WRL)
- Ben Modra (WRL)
- Duncan Rayner (WRL)
- Jamie Ruprecht (WRL)
- Grantley Smith (WRL & Chair)
- Dr Kristen Splinter (WRL)

The list of potential management options incorporated suggestions previously provided through community feedback. Note that all potential management options generated by these ideas workshops were considered to be “on the table” without judgement, with any implementation constraints to be assessed during the Stage 1 MCA. That is, some of the initial list of 50 long-term entrance management options may seem far-fetched.

2.3 Long-term management options

The list of 50 long-term management options has been separated into six categories (Tables 2.1 to 2.6), within each of which, ideas are sorted alphabetically. That is, the options in this list are not ranked. Illustrations (or example photos from other sites) for a selection of 16 of the management options (including those in the top 11 discussed later in Section 5) are shown in Figures 2-2 to 2-17 to provide an indication of the scale of some of the options as modelled and costed.

Table 2-1 Structural management options 1 of 2: protection of bed and foreshore

Ref.	Description
1	Business as usual (follow existing investment spending rate on maintenance of bridge, foreshore and training walls)
2	Construct a more efficient central channel (via internal training walls) to keep the main tidal flow away from existing banks (Figure 2.2)
3	Construction of groyne fields upstream (northern side) and downstream (southern side) of bridge to keep the main tidal flow away from existing banks (Figure 2.3)
4	Place rock on the bed along the entire entrance channel (training walls to lake) to stabilise the channel bed
5	Stabilise the existing shoreline by installing large deep structures (e.g. concrete caissons) along both sides of the entrance channel to account for the assumed future channel deepening

Table 2-2 Structural management options 2 of 2: conveyance control to reduce tidal prism, tidal velocities and tidal discharge

Ref.	Description
6	Add a large volume of sand to Lake Illawarra to raise the bed elevation above low tide level to reduce the tidal prism within the lake (and therefore entrance channel velocities/erosion)
7	Construct a lock system across the western end of the entrance to isolate Lake Illawarra (additional opportunities: walkway on top and turbines for hydropower) (Figure 2.4)
8	Construct a second entrance to Lake Illawarra at Kemblawarra to reduce conveyance through existing channel (potentially with control structures so that water can come in at one and out the other)
9	Construct a north-south wall to split Lake Illawarra in two: the eastern part tidal, the western part non-tidal (to reduce the tidal prism within the lake and therefore entrance channel velocities/erosion)
10	Construction of a staggered groyne field in the entrance channel to reduce cross-sectional flow area (head loss by choke points) (Figure 2.5)
11	Construction of an artificial reef or other structure seaward of the training walls to disturb the ebb tide jet and restrict the entrance (head loss by choke point) (Figure 2.6)

Table 2-2 Structural management options 2 of 2 (cont.): conveyance control to reduce tidal prism, tidal velocities and tidal discharge

Ref.	Description
12	Disguised gate structures across the channel beneath the bridge to fine tune flow (with scour protection of surrounds) (flow control by choke point) (Figure 2.7)
13	Fields of piers along a reach (~200 to 500 m long) to add form loss into the channel (head loss along a channel stretch)
14	Half tide rock weir all the way across the channel beneath the bridge + new boat ramp upstream (flow control by choke point) (Figure 2.8)
15	Head loss structure (rock weir/concrete weir/wavescreen) at the western end of the entrance (near Bevans Island) + new boat ramp upstream (Figure 2.9)
16	Increase the effective length of the channel by introducing meanders within it (gradual head loss via friction over a longer distance)
17	Installation of a tidal energy device(s) at some point within the entrance channel (slow down flow and reduce erosion by taking energy out of the flow)
18	Large concrete culvert weir all the way across the channel beneath the bridge + new boat ramp upstream (flow control by choke point) (Figure 2.8)
19	Move one of the training walls to narrow the distance between them (flow control by choke point) (Figure 2.10)
20	Move one of the training walls to widen the distance between them (reduce tidal velocities by increasing flow area) (Figure 2.11)
21	Narrow the entrance throat by creating a wave trap beach and other engineered beaches within the channel on the northern side (flow control by choke point)
22	Place rock at several locations within the entrance channel to reduce the cross-sectional area at multiple locations (flow control by choke points)
23	Place rock on the bed over the first 250 to 500 m of the channel (seaward end) to reduce the cross-sectional area (head loss by choke point) (Figure 2.12)
24	Porous wavescreen breakwater all the way across the channel beneath the bridge + new boat ramp upstream (head loss by choke point) (Figure 2.13)
25	Reclaim land on the edge of Lake Illawarra to reduce the tidal prism within the lake (and therefore entrance channel velocities/erosion)
26	Retractable overshot weir that could be lowered during a flood (SmartGate / Thames Barrier) (flow control by choke point) (Figure 2.14)
27	Sink a ship at the ocean entrance to block it (flow control by choke point / total closure)

Table 2-3 Non-Structural management options

Ref.	Description
28	"Sand shifter" network to capture littoral drift on Windang Beach (similar to Noosa) and/or sand deposited on the flood-tide delta to be pumped back into the entrance (increase sediment supply into entrance channel to increase head loss via friction)
29	Actively dredge sand from the flood-tide delta and place it back into the entrance in an ongoing fashion to restrict tidal flows (increase sediment supply into entrance channel to increase head loss via friction)
30	Construction of an artificial reef or sandbar seaward of the training walls to encourage the supply of marine sediment into the entrance (increase sediment supply into entrance channel to increase head loss via friction)
31	Construction of mangrove forest at the western end of the entrance to increase roughness (head loss via friction along a channel stretch) (Figure 2.15)
32	Construction of oyster reefs at the western end of the entrance to increase roughness (head loss via friction along a channel stretch)
33	Create intertidal/wetland area in the flood-tide delta with different zones for different ecosystem services (head loss via friction along a channel stretch)
34	Install aquaculture on the northern bank, downstream of the bridge (reduce vulnerability to erosion)
35	Large scale sand nourishment on the flood-tide delta to create a berm and islands with maintenance of a notch for flooding (similar to the "Sand Motor" in Netherlands) (head loss by choke point)
36	Periodically place sand between the training walls to shallow the entrance, repeat when eroded by tidal or flood velocities (increase sediment supply into entrance channel to increase head loss via friction)
37	Place a large volume of sand between the training walls to block the entrance, repeat when eroded by flood velocities (total closure)
38	Planting large riparians trees and other vegetation on foreshores with no structural protection (reduce vulnerability to erosion)
39	Rehabilitation of historical seagrass beds for stabilisation (head loss via friction along a channel stretch)
40	Sand transfer in ongoing campaigns via dredging ship or truck movements (increase sediment supply into entrance channel to increase head loss via friction)
41	Sand transfer system from adjacent beaches to maintain or improve current condition ~100,000 m^3/year (prevent entrance channel become more efficient by increasing sediment supply to maintain/increase head loss via friction)

Table 2-4 Non-additive management options

Ref.	Description
42	Do nothing (no maintenance of bridge, foreshore or training walls)
43	Planned retreat (remove training walls, groynes, revetments, new bridge without piers)
44	Remove both training walls (return to pre-2007 conditions) (Figure 2.16)
45	Remove northern training wall only (Figure 2.17)

Table 2-5 Management options creating opportunities from ongoing erosion

Ref.	Description
46	Construction of a canal estate on the flood-tide delta
47	Make the entrance channel seaworthy and aid its development into a commercial port/harbour within Lake Illawarra

Table 2-6 Combined management options

Ref.	Description
48	Building a series of engineered, stabilised islands (perhaps protected by oyster bags/reefs) in the flood-tide delta (head loss by choke point)
49	Shorten training walls so that littoral sand starts infilling (maybe with a nourished shoal in the entrance to get started) (increase sediment supply into entrance channel)
50	Temporarily close the entrance (rock bags could be used), re-engineer the entrance channel with protection/nourishment and then re-open the entrance



Figure 2.2 Option 2: Construct a more efficient central channel (via internal training walls) to keep the main tidal flow away from existing banks



Figure 2.3 Option 3: Construction of groyne fields upstream (northern side) and downstream (southern side) of bridge to keep the main tidal flow away from existing banks



Figure 2.4 Option 7: Construct a lock system across the western end of the entrance to isolate Lake Illawarra (additional opportunities: walkway on top and turbines for hydropower)

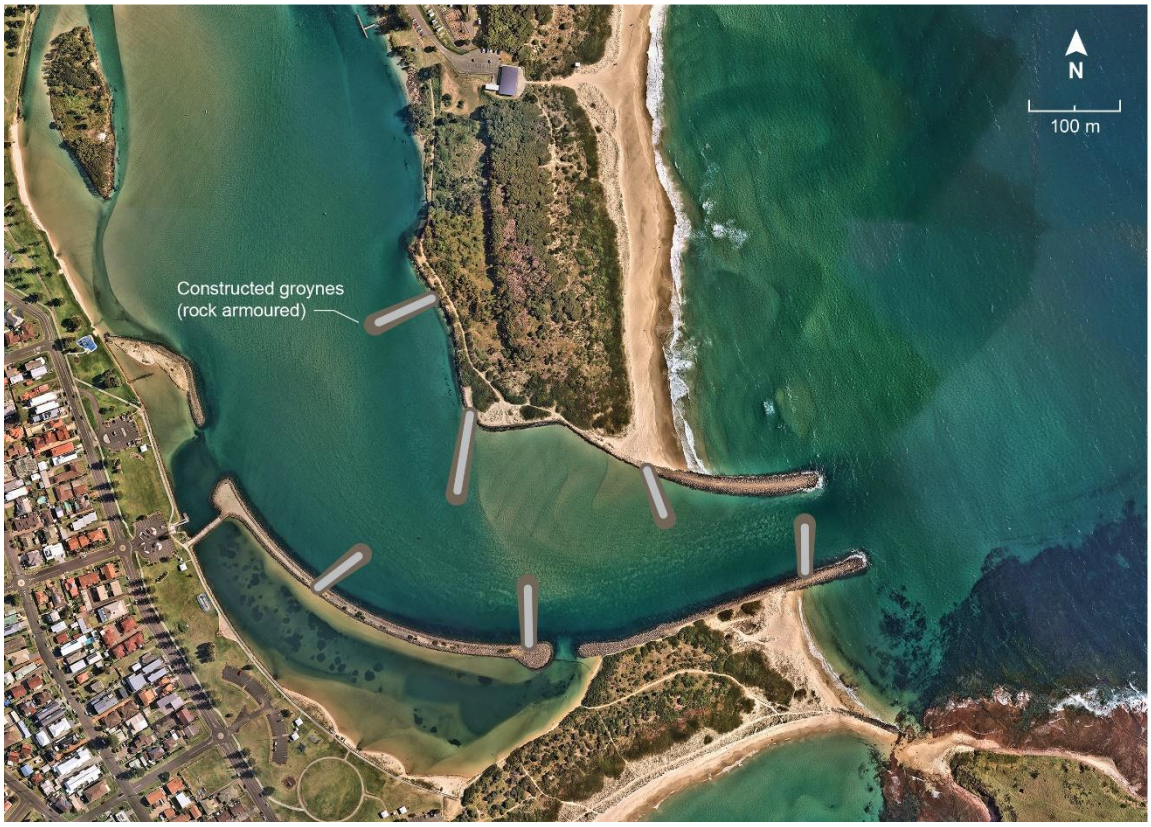


Figure 2.5 Option 10: Construction of a staggered groyne field in the entrance channel to reduce cross-sectional flow area (head loss by choke points)

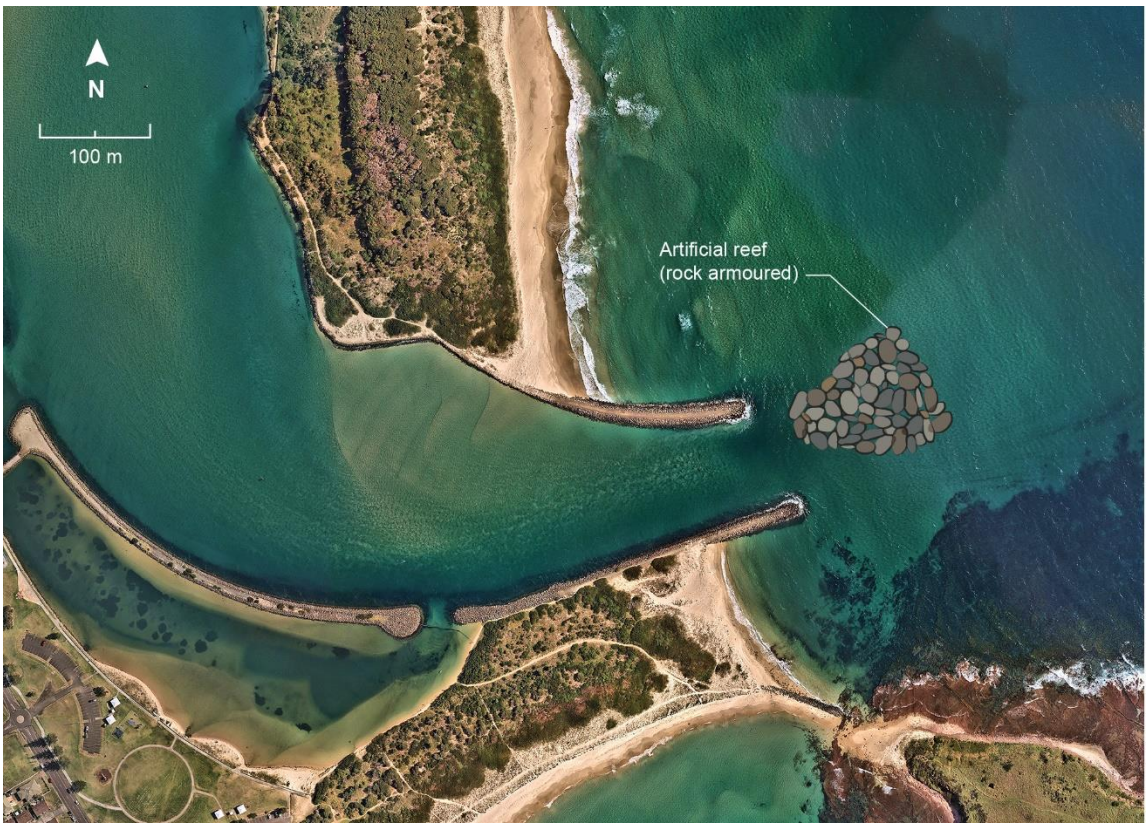


Figure 2.6 Option 11: Construction of an artificial reef or other structure seaward of the training walls to disturb the ebb tide jet and restrict the entrance (head loss by choke point)

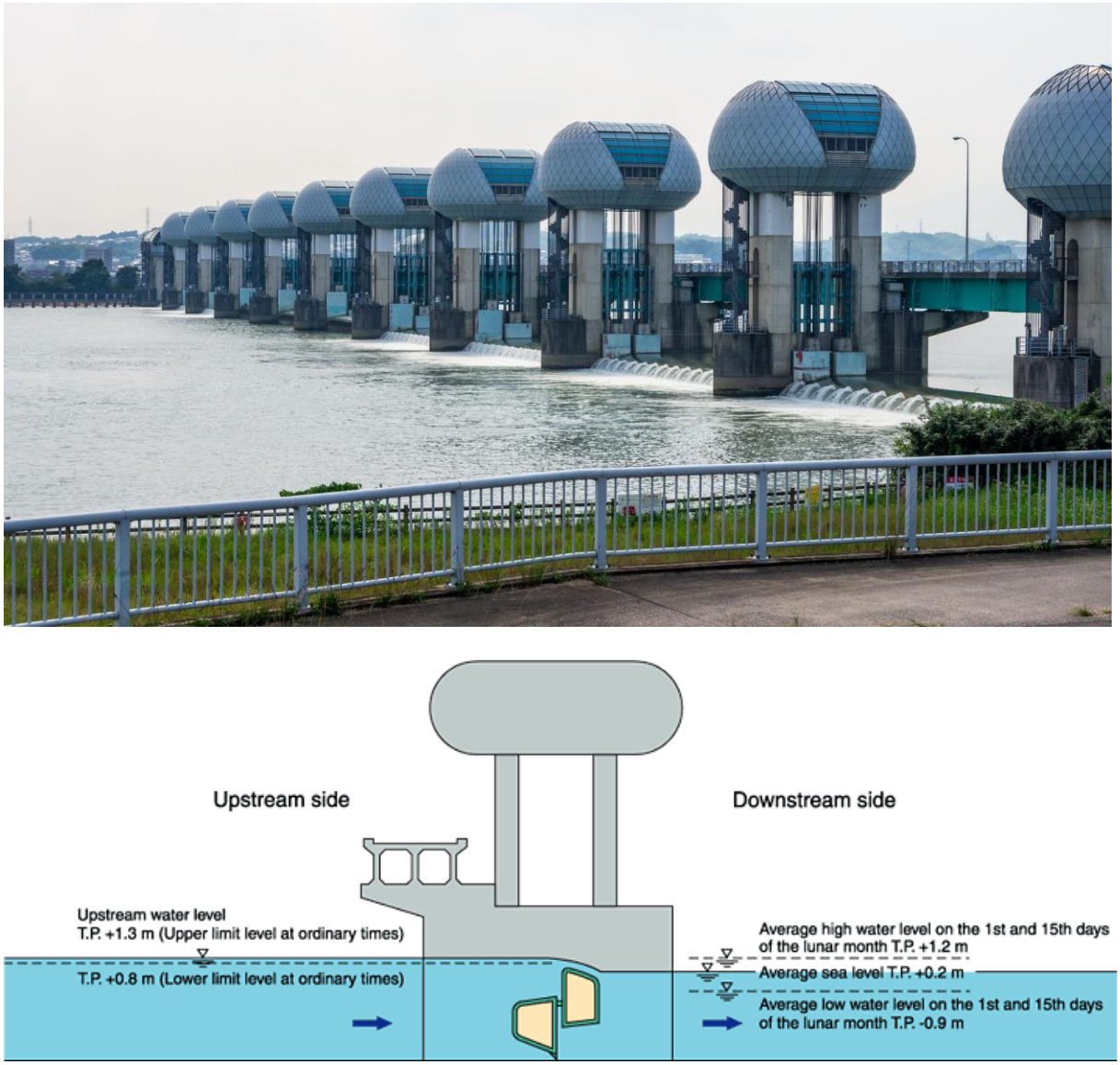


Figure 2.7 Option 12: Disguised gate structures across the channel beneath the bridge to fine tune flow (with scour protection of surrounds) (flow control by choke point)
[Example photo and diagram of Nagara River Estuary Barrage, Japan]



Figure 2.8 Half tide rock weir (Option 14) or large concrete culvert weir (Option 18) all the way across the channel beneath the bridge + new boat ramp upstream (flow control by choke point)

[Example photos showing a half tide weir at various stages of the tide at Coquet River, Amble, UK – ocean is to the right]



Figure 2.9 Option 15: Head loss structure (rock weir/concrete weir/wavescreen) at the western end of the entrance (near Bevans Island) + new boat ramp upstream



Figure 2.10 Option 19: Move one of the training walls to narrow the distance between them (flow control by choke point)



Figure 2.11 Option 20: Move one of the training walls to widen the distance between them (reduce tidal velocities by increasing flow area)



Figure 2.12 Option 23: Place rock on the bed over the first 250 to 500 m of the channel (seaward end) to reduce the cross-sectional area (head loss by choke point)

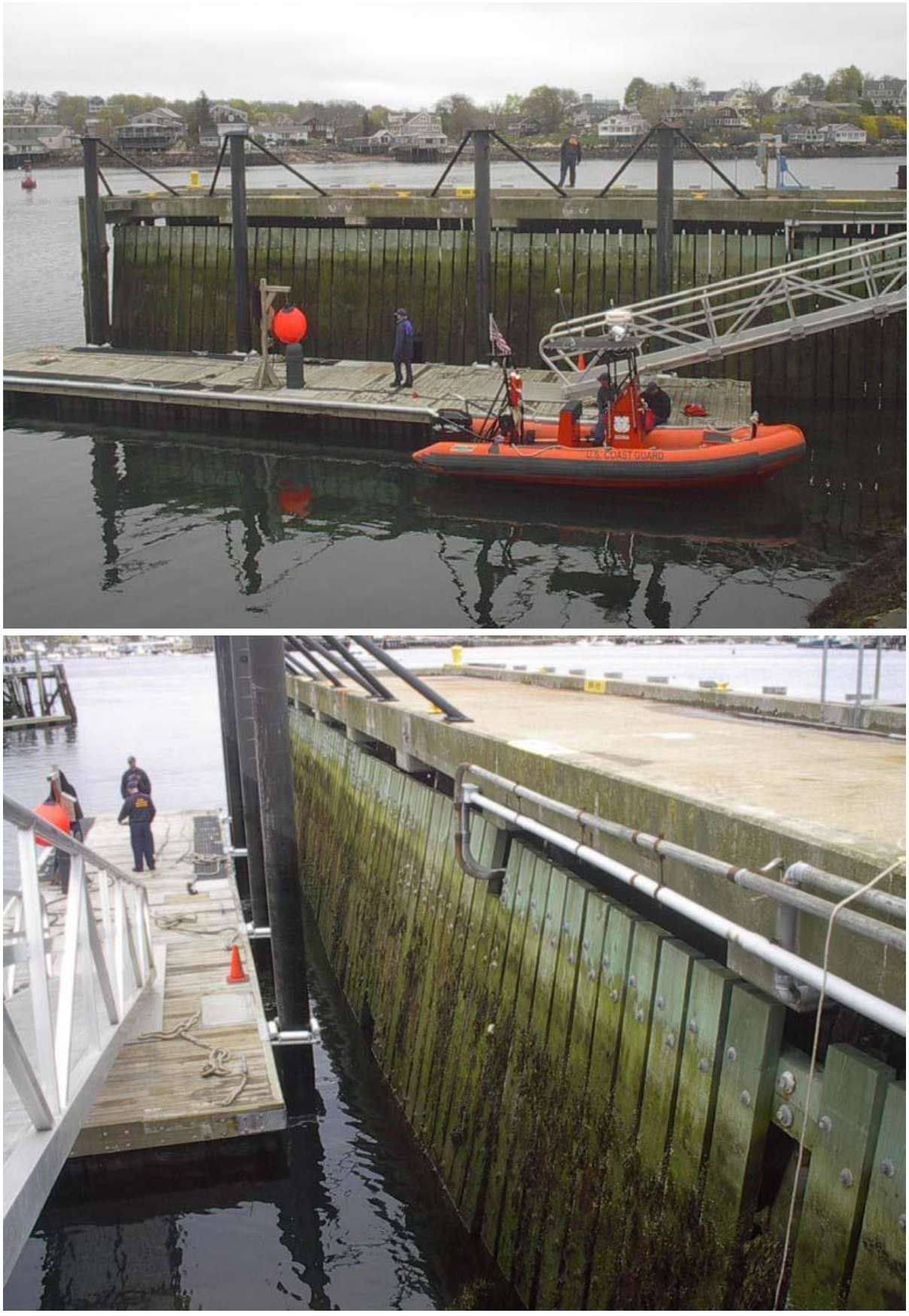


Figure 2.13 Option 24: Porous wavescreen breakwater all the way across the channel beneath the bridge + new boat ramp upstream (head loss by choke point)
[Example photos from Gloucester, Massachusetts, USA]

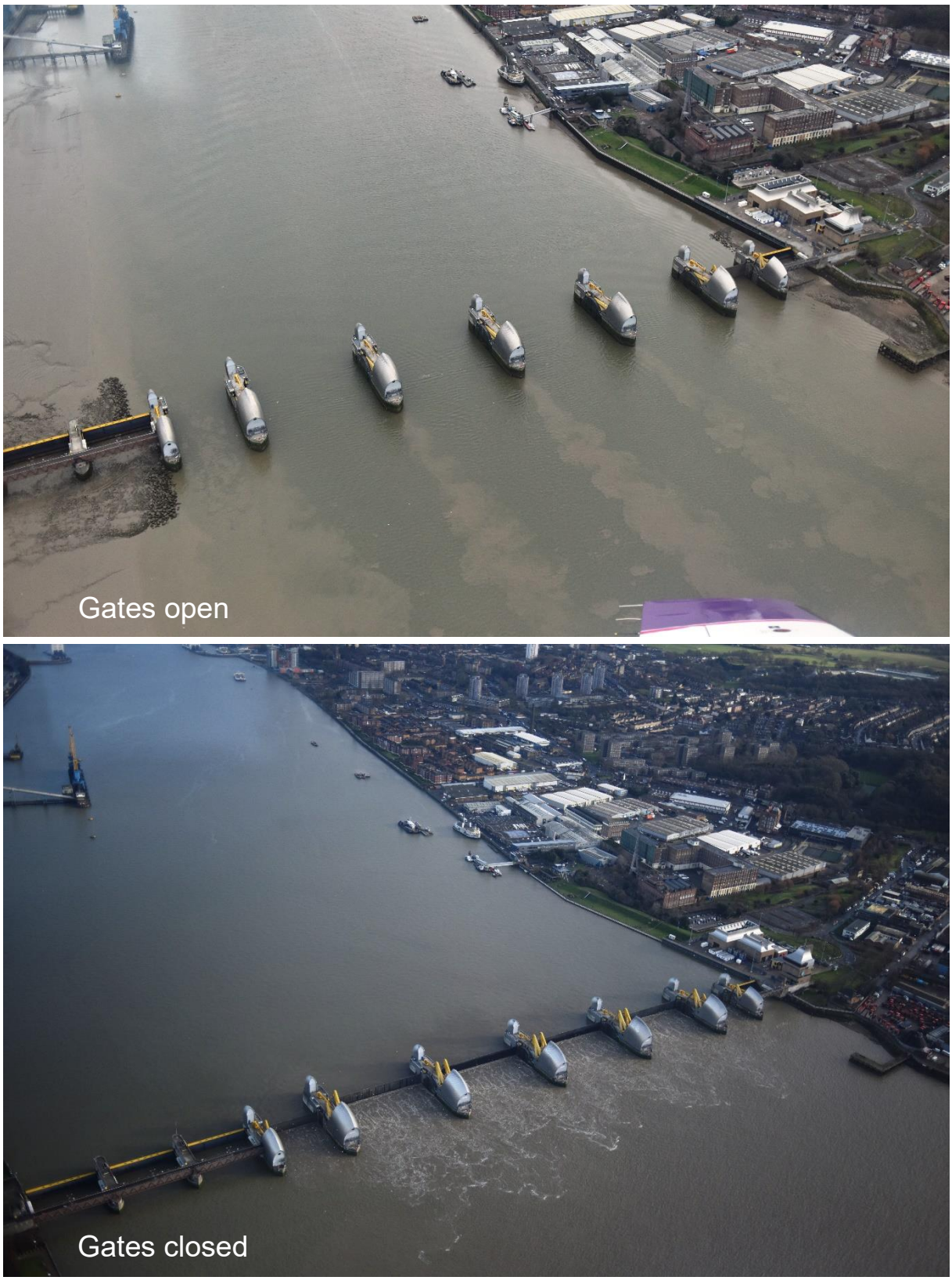


Figure 2.14 Option 26: Retractable overshot weir that could be lowered during a flood (SmartGate / Thames Barrier) (flow control by choke point)
[Example photos of open (top) and closed (bottom) gates at Thames Barrier, London, UK]



Figure 2.15 Option 31: Construction of mangrove forest at the western end of the entrance to increase roughness (head loss via friction along a channel stretch) [with sand nourishment]



Figure 2.16 Option 44: Remove both training walls (return to pre-2007 conditions)



Figure 2.17 Option 45: Remove northern training wall only

3 Gateways for management options

The PCG established the following two gateways that each long-term management option needed to pass to be considered in the MCA:

- Is there a well-worn legislative pathway to progress the option? (Eliminate if No)
- Will the option impact on stability of Windang or Warilla Beaches? (Eliminate if Yes)

The gateways were established by the PCG and provided to WRL by e-mail on 25 November 2021 (WCC, 2021b). WRL assessed each option against the gateways using coastal engineering judgement. Out of the 50 management options identified in Section 2.3, 15 options were eliminated by at least one of the gateways (Table 3-1).

Table 3-1 Long-term management options eliminated by gateway questions

Management option		Gateway	
Ref.	Description	Legislative Pathway?	Beach stability impacts?
6	Add a large volume of sand to Lake Illawarra to raise the bed elevation above low tide level to reduce the tidal prism within the lake (and therefore entrance channel velocities/erosion)	×	
8	Construct a second entrance to Lake Illawarra at Kemblawarra to reduce conveyance through existing channel (potentially with control structures so that water can come in at one and out the other)	×	✓
9	Construct a north-south wall to split Lake Illawarra in two: the eastern part tidal, the western part non-tidal (to reduce the tidal prism within the lake and therefore entrance channel velocities/erosion)	×	
13	Fields of piers along a reach (~200 to 500 m long) to add form loss into the channel (head loss along a channel stretch)	×	
16	Increase the effective length of the channel by introducing meanders within it (gradual head loss via friction over a longer distance)	×	
17	Installation of a tidal energy device(s) at some point within the entrance channel (slow down flow and reduce erosion by taking energy out of the flow)	×	
25	Reclaim land on the edge of Lake Illawarra to reduce the tidal prism within the lake (and therefore entrance channel velocities/erosion)	×	
27	Sink a ship at the ocean entrance to block it (flow control by choke point / total closure)	×	

Table 3-1 Long-term management options eliminated by gateway questions (cont.)

Management option		Gateway	
Ref.	**Description**	**Legislative Pathway?**	**Beach stability impacts?**
30	Construction of an artificial reef or sandbar seaward of the training walls to encourage the supply of marine sediment into the entrance (increase sediment supply into entrance channel to increase head loss via friction)		✓
35	Large scale sand nourishment on the flood-tide delta to create a berm and islands with maintenance of a notch for flooding (similar to the "Sand Motor" in Netherlands) (head loss by choke point)	×	
41	Sand transfer system from adjacent beaches to maintain or improve current condition ~100,000 m^3/year (prevent entrance channel become more efficient by increasing sediment supply to maintain/increase head loss via friction)		✓
42	Do nothing (no maintenance of bridge, foreshore or training walls)	×	
43	Planned retreat (remove training walls, groynes, revetments, new bridge without piers)	×	
46	Construction of a canal estate on the flood-tide delta	×	
47	Make the entrance channel seaworthy and aid its development into a commercial port/harbour within Lake Illawarra	×	

4 Multi criteria analysis of management options

4.1 Overview of the process

The MCA process used a range of logical scoring criteria to rank individual long-term management options for the Lake Illawarra entrance channel as recommended by Infrastructure Australia (2021). Recognising that the scoring criteria each have a different level of importance, each criteria was weighted with regards to its relative importance using a decision matrix. This process is illustrated in Figure 4.1 and discussed in detail in the remainder of this chapter.

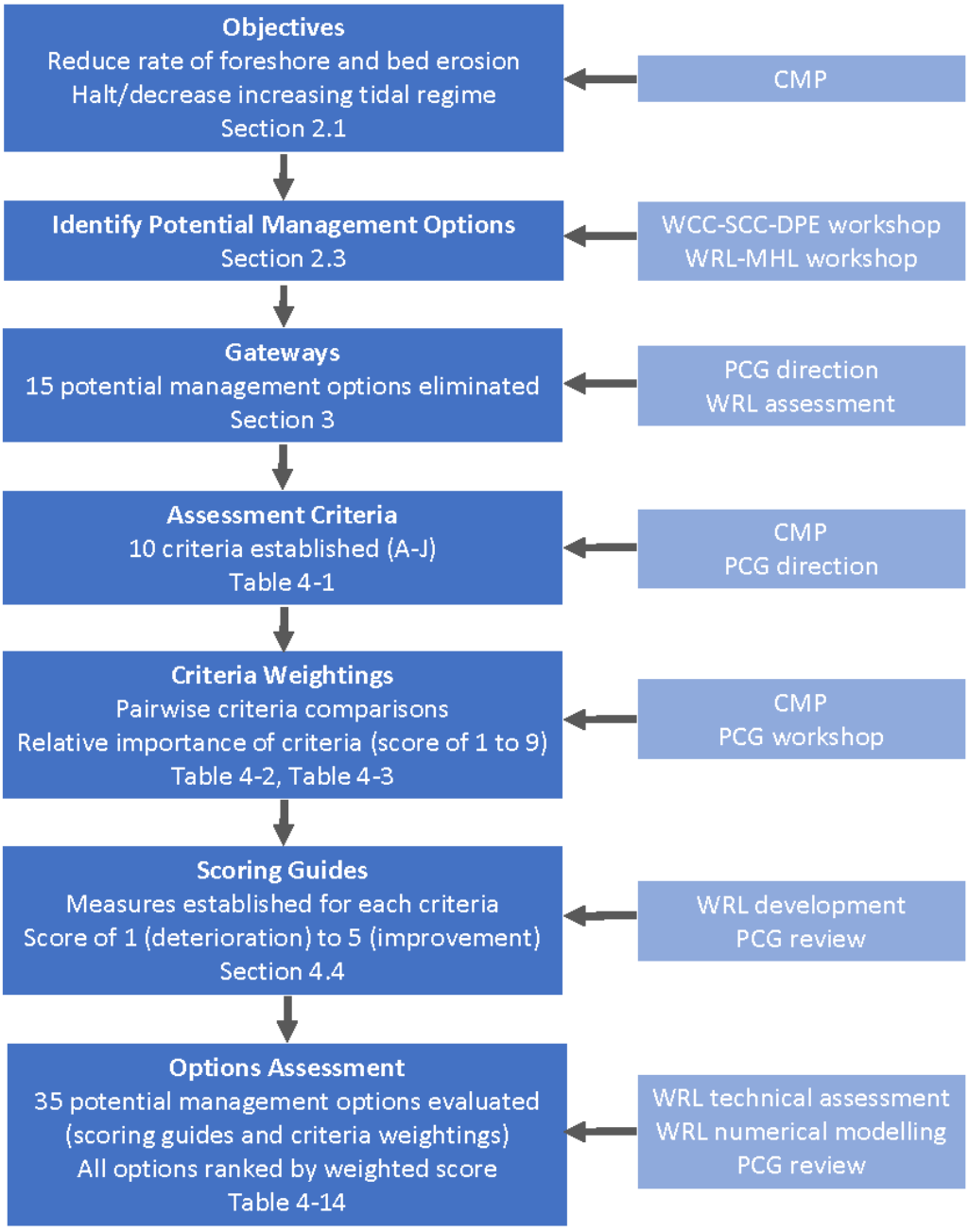


Figure 4.1 Multi criteria analysis process for assessing long-term management options

4.2 Assessment criteria

Following consideration of the primary objectives of the long-term management of the Lake Illawarra entrance channel and the stakeholder values for the area as identified as part of the Coastal Management Program (BMT, 2020b), 10 criteria for assessing the management options were established by the PCG and provided to WRL by e-mail on 25 November 2021 (WCC, 2021b). Each of the criteria are described in detail in Table 4-1.

Table 4-1 Criteria for long-term management options assessment

Ref.	Name	Description
A	Risk reduction effectiveness: foreshore and bed erosion	This criteria scores how well a management option will change the present rate of erosion on the channel and island banks (incl. undermining training walls, revetments, groynes, boat ramps and jetties) and the channel bed.
B	Mitigation of increasing tidal regime	This criteria scores how well a management option will change the present trend to increasing tidal regime (incl. increasing tidal prism, tidal range, maximum tidal discharge, and salinity).
C	Upstream flooding	This criteria scores how a management option will change the present duration of catchment flooding events.
D	Water quality	This criteria scores how a management option will change the present water quality in the eastern side of Lake Illawarra near the entrance channel because of changes to tidal flushing (both in terms of pollutant concentrations and visual amenity).
E	Estuarine flora and fauna	This criteria scores how a management option will impact estuarine vegetation (e.g. reduction in saltmarsh, loss of seagrasses, etc.) and estuarine fauna (shorebirds, fish populations, etc.) within Lake Illawarra.
F	Indigenous heritage	This criteria scores how a management option will impact on the values of the Indigenous community and considers how it will change the present impact on Indigenous archaeological sites from erosion or the addition of structural/non-structural features.
G	In-water recreation	This criteria scores how a management option will impact on community recreational activities within Lake Illawarra (e.g. boating, swimming, fishing, etc.).
H	Foreshore recreation	This criteria scores how a management option will impact on foreshore open spaces and infrastructure that delivers recreation and amenity for the community (e.g. walking, other recreation activities on the foreshore, fishing access, access to the water for swimming, etc.).
I	Capital cost	This criteria scores a management option on the basis of its capital cost.
J	Ongoing costs	This criteria scores a management option on the basis of its ongoing costs (operations and maintenance costs of implemented option only; other ongoing costs within the lake and entrance channel are not considered).

4.3 Criteria weightings

On 25 November 2021, WRL and MHL facilitated a workshop with staff from WCC, SCC and DPE to establish a weighting (prioritisation) for each criteria, based on their importance to the Coastal Management Program objectives. The Analytic Hierarchy Process (AHP) (Saaty, 1980) was adopted for weighting the criteria as it is a widely used method in multi criteria analysis. This process is a theory of measurement through pairwise criteria comparisons and relies on the judgment of experts to derive priority scales, these scales that measure intangibles in relative terms. Each criteria were compared, and a consensus decision was made by WCC, SCC and DPE staff as to the relative importance of one criteria over another by assigning a score of 1 to 9 (see Saaty's 9-point intensity of importance scale in Table 4-2). It is noteworthy that a similar (but not identical) pairwise criteria comparison process was used to develop the *Wollongong Dune Management Strategy for the Patrolled Swimming Areas of 17 Beaches* (GHD, 2014).

Table 4-2 Saaty's 9-point scale for pairwise comparison in AHP (adapted from Saaty, 1980)

Intensity of importance	Definition	Explanation
1	Equal importance	The two criteria contribute equally to the objective
2	Weak or slight	*(intermediate value)*
3	Moderate importance	Experience and judgement slightly favour one criteria over the other
4	Moderate plus	*(intermediate value)*
5	Strong importance	Experience and judgement strongly favour one criteria over the other
6	Strong plus	*(intermediate value)*
7	Very strong	One criteria is favoured very strongly over the other and its dominance demonstrated in practice
8	Very, very strong	*(intermediate value)*
9	Extreme importance	The evidence favouring one criteria over the other is of the highest possible order of affirmation

During the workshop, each of the 10 criteria in Table 4-1 were compared relative to all other criteria and a consensus intensity of importance (score of 1 to 9; Table 4-2) assigned. Each of the 45 pairwise criteria comparisons are summarised in Appendix A, with a selection of three examples provided below:

- Mitigation of increasing tidal regime (Criteria B) was considered of equal importance (score of 1) compared with estuarine flora and fauna (Criteria E)
- Ongoing costs (Criteria J) were considered of strong importance (score of 5) compared with capital cost (Criteria I)
- Risk reduction effectiveness: foreshore and bed erosion (Criteria A) was considered of extreme importance (score of 9) compared with in-water recreation (Criteria G).

The online software tool developed by Goepel (2018) for the Analytic Hierarchy Process (Saaty, 1980) was used to determine the weightings for each criteria (see Appendix A for further discussion of these calculations). The resulting criteria weightings are shown in Table 4-3 (sorted by increasing rank). Quantitative checks also indicated an acceptable level of consistency in the pairwise comparisons.

Table 4-3 Summary of criteria weightings (sorted by increasing rank)

Ref.	Name	Weighting	Rank
J	Ongoing costs	1.67	1
A	Risk reduction effectiveness: foreshore and bed erosion	1.54	2
B	Mitigation of increasing tidal regime	1.49	3
D	Water quality	1.37	4
E	Estuarine flora and fauna	1.22	5
F	Indigenous heritage	1.03	6
C	Upstream flooding	0.80	7
I	Capital cost	0.39	8
H	Foreshore recreation	0.34	9
G	In-water recreation	0.15	10

4.4 Scoring guide

4.4.1 Preamble

This section describes the scoring guides that were developed for each of the 10 criteria. For each long-term management option being assessed, a score of 1 to 5 was assigned for each criteria. A score of 1 was considered least favourable for the objectives/values of the criteria and a score of 5 was considered most favourable. Note that for the “base case” (Option 1 – business as usual), a score of 3 was given for all criteria, except for capital cost and ongoing costs which were both given a score of 5.

4.4.2 Numerical modelling

Background

Assessment of the first three criteria (foreshore and bed erosion, increasing tidal regime and upstream flooding; Ref. A, B and C in Table 4-1) was primarily informed by hydrodynamic numerical modelling to test a number of the long-term management options for Lake Illawarra. Numerical modelling was completed using the RMA modelling package. An RMA-2 (King, 2019), two-dimensional, depth-averaged, finite element hydrodynamic model was originally developed for Lake Illawarra by WRL in 2019 to assess the impact of rock protection works beneath the northern end of Windang Bridge. The Lake Illawarra model domain (Figure 4.2) covers the entire lake to the open sea boundary. The RMA-2 model computes finite element solutions for water surface elevations and horizontal velocity

components. This model was verified against tidal flow and water level data captured in September and October 2018. This existing calibrated model was utilised to assess potential management options for Lake Illawarra and inform the multi criteria analysis of each long-term management option. The reader is directed to read the original report (WRL, 2019) for further details about the model, but key details are reproduced below.

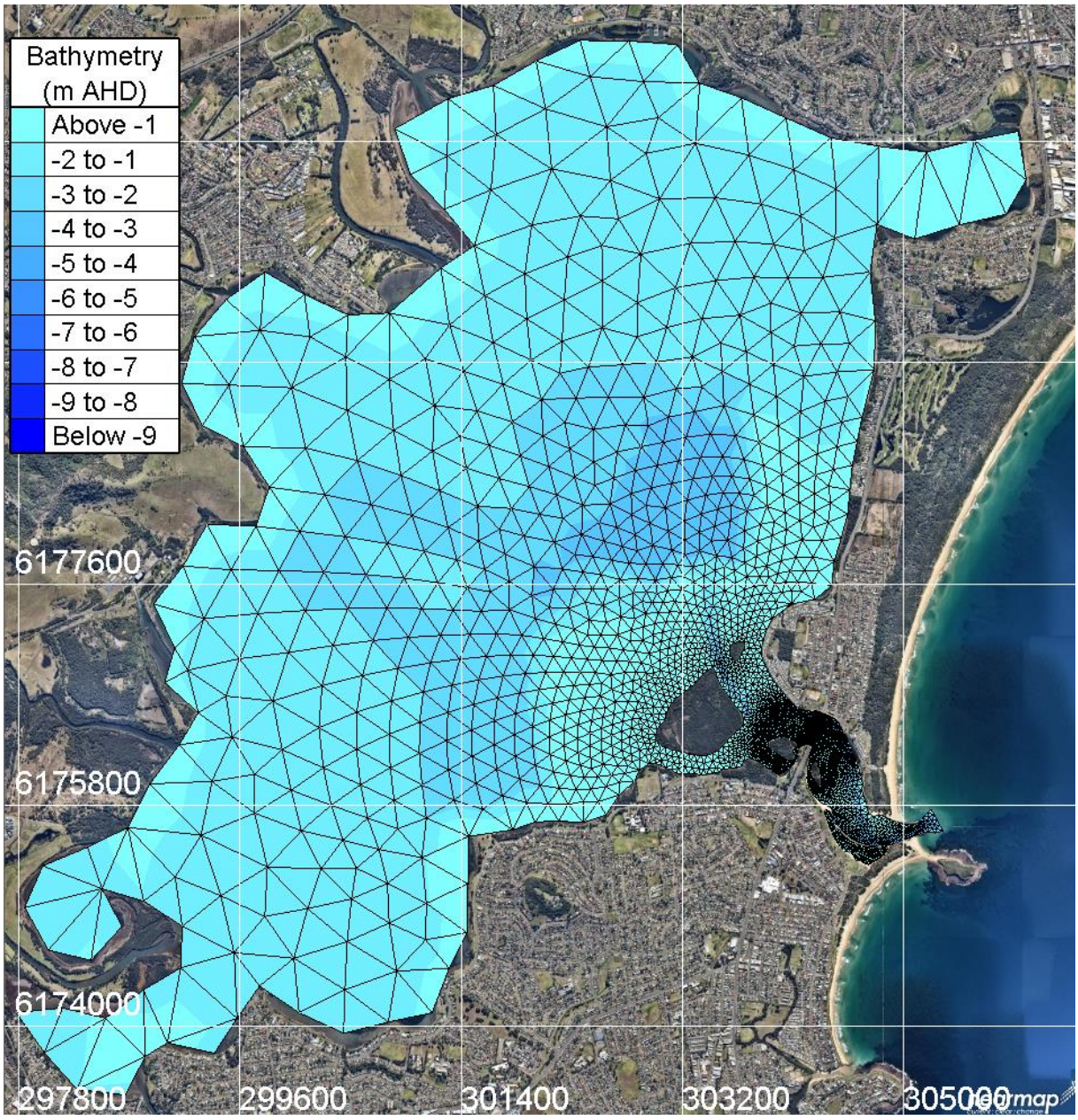


Figure 4.2 RMA-2 numerical hydrodynamic model domain (Source: WRL, 2019)

Bathymetry

The numerical model utilised bathymetric data collected in August 2019 by the Environment, Energy and Science (EES, formerly the NSW Office of Environment and Heritage (OEH) group within NSW Department of Planning and Environment (DPE)). Note that the bathymetry for WRL's existing calibrated model of Lake Illawarra does not include any rock protection beneath Windang Bridge (which was later placed in 2019-2020).

Tidal boundary conditions

A synthetic downstream tidal boundary was generated for the model from the tidal constituents. The tidal constituents were calculated from actual tide measurements collected at Port Kembla (Bureau of Metrology [BoM] station number 068253) from 1 January 2019 to 21 August 2019 (BoM, 2019).

Catchment inflows

There were no catchment inflows or rainfall included in the model simulations for the options.

Model simulation period

The model simulation period was from 25 May 2022 to 30 June 2022. This period was selected to allow 1 week for the model spin up followed by a month of simulation which included larger spring tide conditions (Figure 4.3). The model was run on a 15 minute timestep.

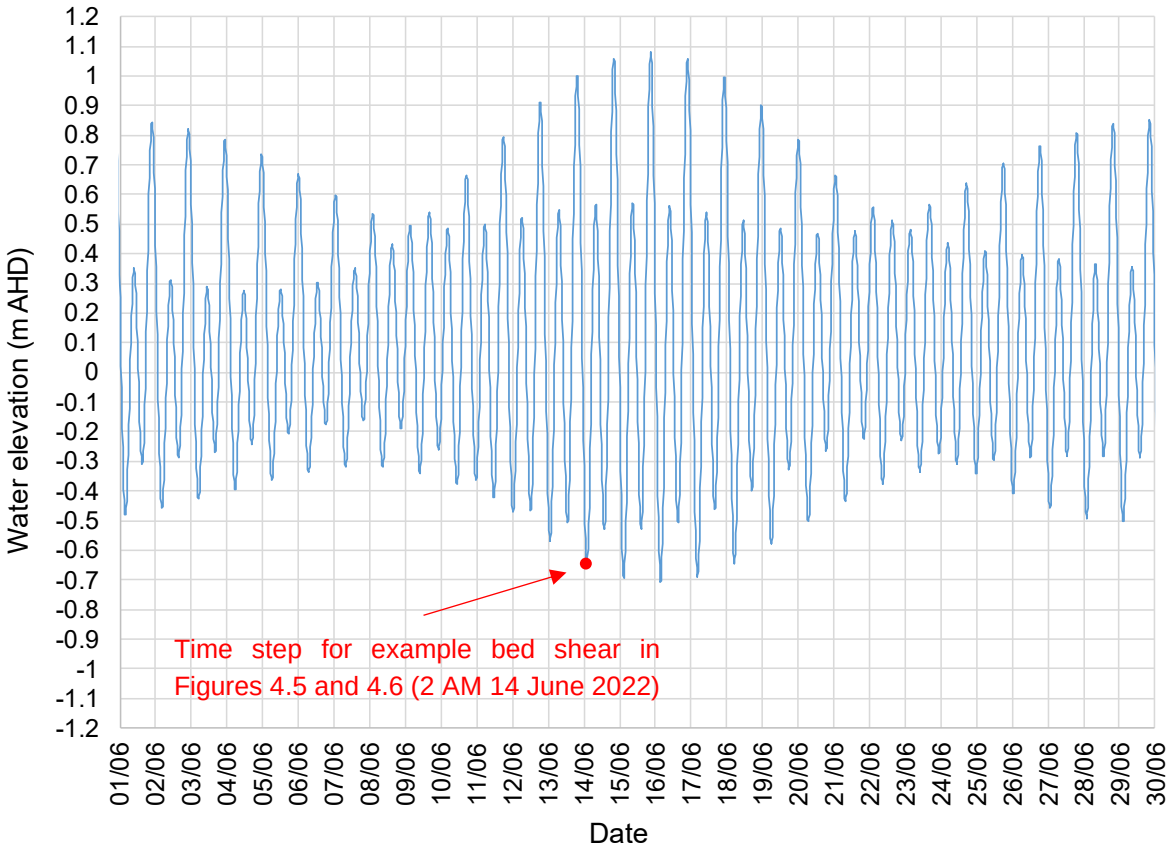


Figure 4.3 Water elevation tidal boundary for modelling management options during June 2022

Model bathymetry modifications for testing options

The numerical model was modified for each long-term management option and re-run. An example of modifications made to the August 2019 bathymetric mesh to test Option 19 (move one of the training walls to narrow the distance between them; previously illustrated in Figure 2.10) is shown in Figure 4.4.

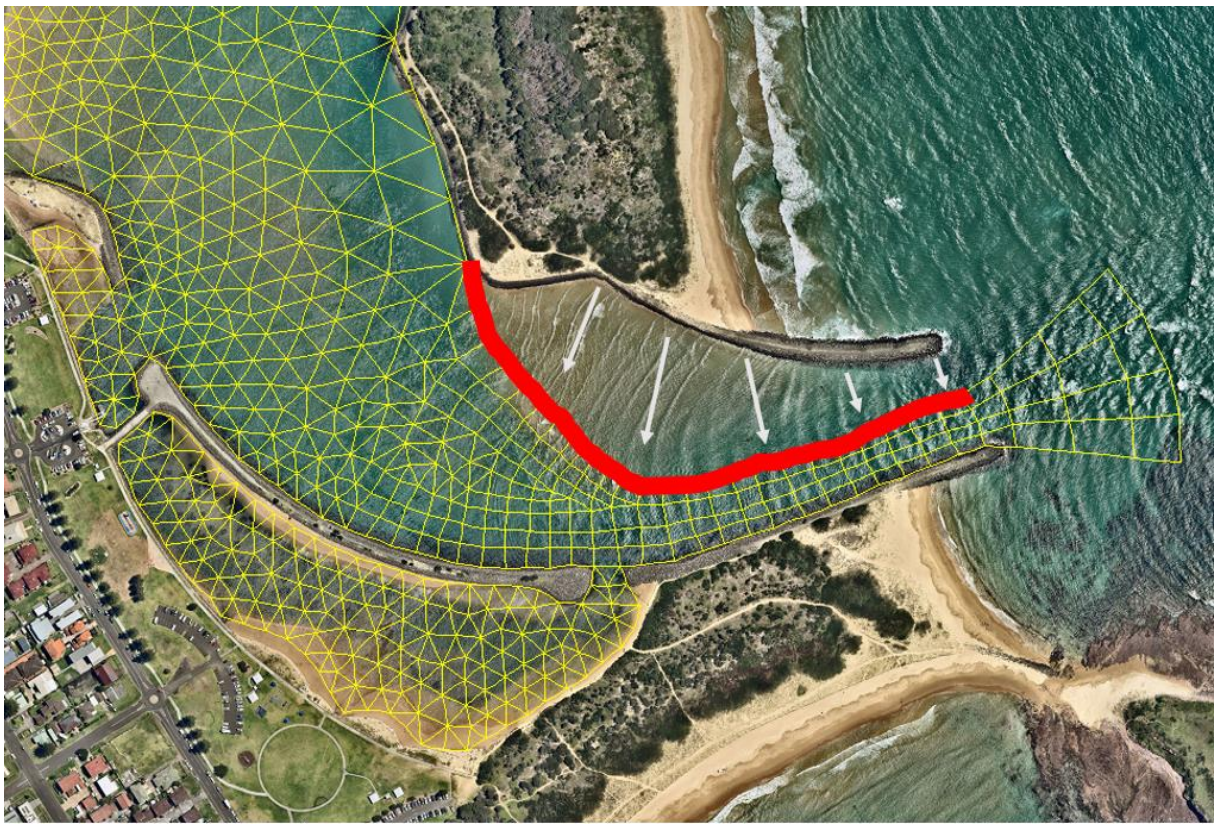


Figure 4.4 Example numerical model mesh modification for Option 19: Move one of the training walls to narrow the distance between them (flow control by choke point)

Due to close similarities between some options and the need to not model all options (e.g. those options which resulted in a closed entrance to the ocean such as Options 44 and 45), WRL undertook a total of 25 model runs which were used to represent the 35 options which passed the gateways (Section 3). Note that WRL has assumed that Option 45 (Remove northern training wall only) could result in a closed entrance based on observed behaviour of the entrance between 2001 (when the southern wall to Windang Island was completed) and the completion of the training walls in 2007 (Tucker et al., 2023).

Model output

Water level and velocity data generated by the model were used to assess the impacts of each option on bed shear, tidal range in the lake and flooding duration across Lake Illawarra, and inform the scoring of each option in the multi criteria analysis. The technical details for how the model was used to assess foreshore and bed erosion, increasing tidal regime and upstream flooding is outlined in the following three sub-sections.

4.4.3 Risk reduction effectiveness: foreshore and bed erosion (Criteria A)

The scoring guide for assessing how each option influenced the present rate of erosion at both the channel foreshore and bed is shown in Table 4-4.

Table 4-4 Scoring guide for risk reduction effectiveness: foreshore and bed erosion

Score	Description
5	Option results in considerable reduction in erosion rate at both the channel foreshore and bed.
4	Option results in minor reduction in erosion rate at both the channel foreshore and bed; or Option results in considerable reduction in erosion rate at one and no discernible change to the present rate at the other.
3 (business as usual)	No discernible change to the present rate of erosion at both the channel foreshore and bed.
2	Option results in minor increase in erosion rate at both the channel foreshore and bed; or Option results in considerable increase in erosion rate at one and no discernible change to the present rate at the other.
1	Option results in considerable increase in erosion rate at both the channel foreshore and bed.

Since the RMA-2 numerical model is a fixed bed type model, the bathymetry in the model does not evolve throughout the simulation; that is, there are no morphological changes (sediment erosion or deposition/accretion). To assess any changes to the present rate of foreshore and bed erosion that an option might cause, bed shear output from the model was used as an indicator for likely erosion.

Sediment samples collected by WRL in 2018 (Tucker et al., 2023) found that the majority of sediment in the entrance channel was medium sand (0.25 to 0.50 mm diameter) with some coarse sand/gravel (>1 mm diameter). Berenbrock and Tranmer (2008) identified the critical bed shear for medium sand as 0.27 N/m^2. Subsequently, a bed shear greater than this value is likely to result in sediment mobilisation and foreshore and/or bed erosion (e.g. higher bed shear can be inferred to equal a higher rate of erosion).

Bed shear (τ_b) throughout the model domain was calculated using the approach outlined by Chow (1959) shown in Equation 4.1.

$$\tau_b = \frac{gn^2\rho u^2}{R_h^{\frac{1}{3}}} \quad (4.1)$$

where:

g = Acceleration due to gravity (9.81 m/s^2)
n = Manning's 'n' friction (0.02 as per the model verification; see WRL, 2019)
ρ = Density of fluid (~1,024 kg/m^3 for seawater)
u = Depth averaged velocity (m/s)
R_h = Hydraulic Radius (approximated as depth (m))

Velocity and depth were taken as outputs from the numerical model to calculate bed shear over time across the model domain (Figure 4.5). Foreshore erosion was assessed based on the bed shear calculated for model elements on the channel boundary, while bed erosion was assessed based on the bed shear calculated for model elements throughout the entire entrance channel. Erosion for each option was assessed relative to the "base case" (Option 1 – business as usual). Figure 4.6 shows an example where erosion was significantly reduced for a potential long-term management option (Option 19) compared to the "base case" (i.e. Figure 4.5). While erosion was assessed across the full month of the

June 2022 simulation for each option, the example output shown in Figure 4.5 and Figure 4.6 is for a single timestep at 2 AM on 14 June near low tide (time indicated on Figure 4.3) at the ocean when velocities and bed shear were at their peak.



Figure 4.5 Example of bed shear calculated for the "base case" Option 1: Business as usual



Figure 4.6 Example of bed shear calculated for Option 19: Move one of the training walls to narrow the distance between them (flow control by choke point)

4.4.4 Mitigation of increasing tidal regime (Criteria B)

The scoring guide for assessing how each option influenced the present trend to increasing tidal regime within the lake is shown in Table 4-5.

Table 4-5 Scoring guide for mitigation of increasing tidal regime

Score	Description
5	Option results in considerable reduction in trend to increasing tidal range within the lake.
4	Option results in minor reduction in trend to increasing tidal range within the lake.
3 (business as usual)	No discernible change to the present trend to increasing tidal regime within the lake.
2	Option results in minor increase in trend to increasing tidal range within the lake.
1	Option results in considerable increase in trend to increasing tidal range within the lake.

To assess any changes to the present tidal range within the lake that an option might cause, model outputs for water level within Lake Illawarra approximately 1.5 km north of the western end of the entrance channel, upstream of the flood tide delta (blue point on Figure 4.7) were extracted from the numerical model. Water levels at this location were found to be representative of water levels across the entire lake. The long-term management options were assessed based upon whether the tidal range within Lake Illawarra was reduced or increased relative to the “base case” (Option 1 – business as usual). Figure 4.8 shows examples of two different long-term management options which result in an increase (Option 20) or reduction (Option 19) in the tidal range within Lake Illawarra compared to the “base case”.

Some of the options which are effective at reducing the tidal range in the lake, will also increase the mean water level of the lake. Downstream of these options in the entrance channel, high tide elevations will also be raised and low tide elevations will be lowered, although the velocities (and associated erosion) are significantly reduced in these downstream areas compared to the “base case”. These changes to the tide in the entrance channel and lake have been noted but are not considered in the scoring guide (Table 4-5) which focuses on the magnitude of the tidal range in the lake. Examples of options with which these byproducts (increase in lake mean water level and increase in downstream tidal range) occur include:

- Option 7: Construct a lock system across the western end of the entrance
- Option 14: Half tide rock weir all the way across the channel beneath the bridge
- Option 15: Head loss structure near Bevans Island
- Option 31: Construction of mangrove forest at the western end of the entrance
- Option 48: Building a series of engineered, stabilised islands in the flood-tide delta.



Figure 4.7 Location (blue point) where water level data was extracted from the numerical model for Figures 4-6 and 4-7 and chainage between the entrance and Lake Illawarra for Figure 4-8

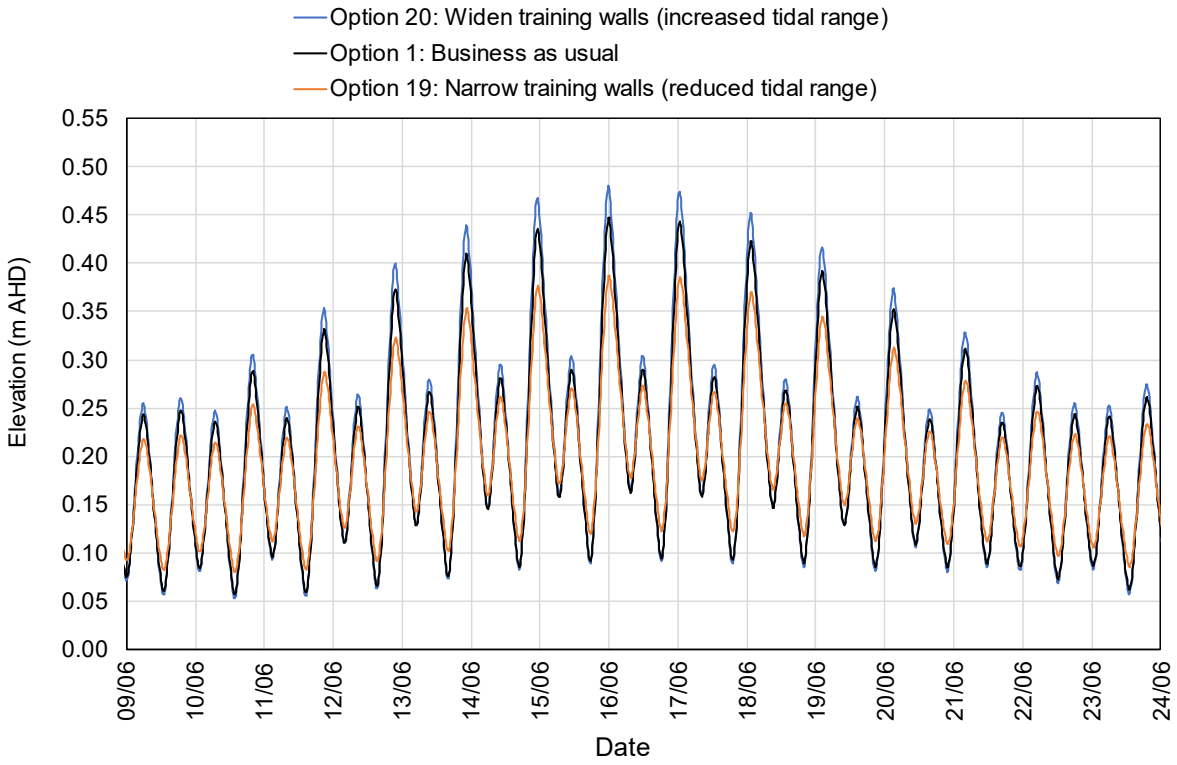


Figure 4.8 Example of changes to the tidal range for different management options

To illustrate these changes, Figure 4.9 compares levels at the same representative location for the lake for the “base case” with Option 14: Half tide rock weir all the way across the channel beneath the bridge. While the tidal range for these large spring tides has been reduced from approximately 0.35 to 0.15 m with the introduction of the weir at the bridge (crest 0 m AHD), the mean water level has increased by approximately 0.10 to 0.15 m.

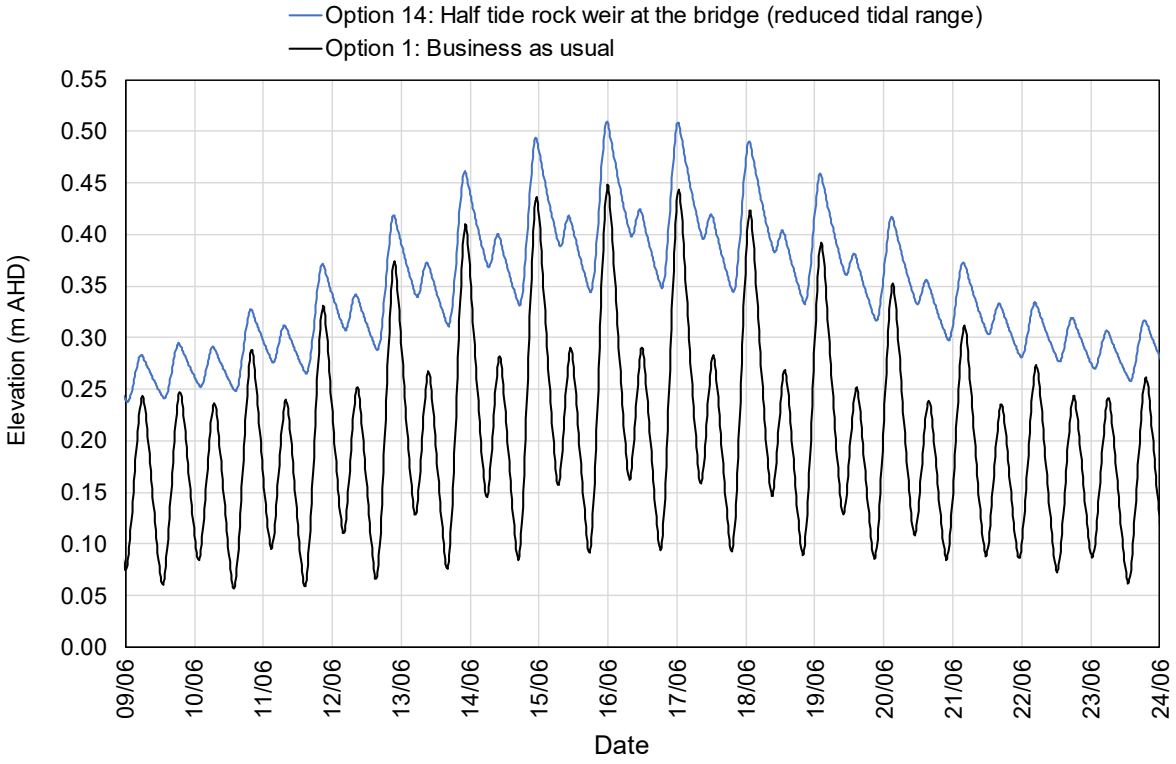


Figure 4.9 Example of changes to the tidal range for Option 14: Half tide rock weir all the way across bridge

For Options 1 and 14, the water surface elevation was extracted from the numerical model along a 2.8 km long chainage between the entrance and Lake Illawarra (black line show in Figure 4.7). From this 1 month simulation, average high tide and low tide surface elevations were calculated along the chainage and plotted in Figure 4.10. The increase in mean water level in the lake on the left side of the figure is evident, as are the higher high tides and lower low tides downstream of the weir at the bridge.

The crest level of this type of structure could be further optimised to achieve the optimal tidal regime outcome (e.g. tidal range reduction, mean water level increase in the lake, downstream tidal range increase) during Stage 2 of this project and later detailed design (if this type of option is shortlisted for further work).

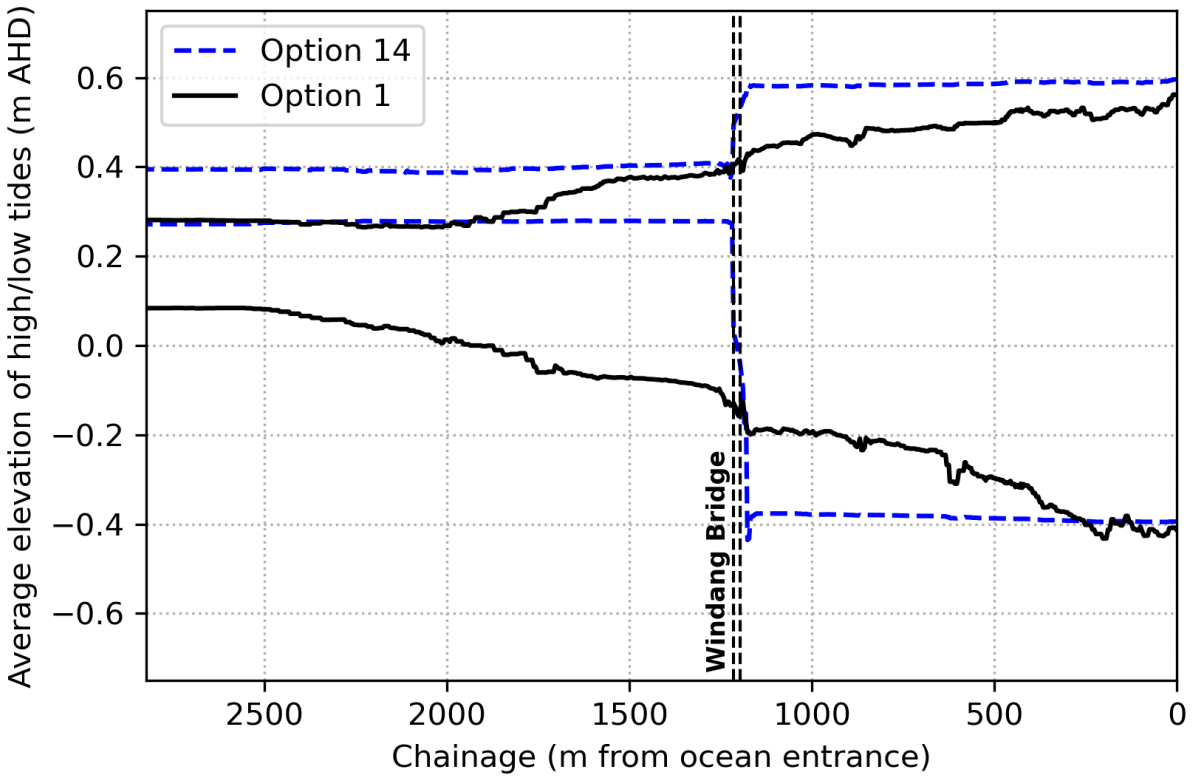


Figure 4.10 Average high tide and low tide surface elevations along the chainage for Option 1: Business as usual and Option 14: Half tide rock weir all the way across bridge

4.4.5 Upstream flooding (Criteria C)

The scoring guide for assessing how each option influenced the time it takes the lake to drain after a flood is shown in Table 4-6.

Table 4-6 Scoring guide for upstream flooding

Score	Description
5	Option results in considerable reduction in the time it takes the lake to drain after a flood (R_f < 0.7).
4	Option results in minor reduction in the time it takes the lake to drain after a flood (R_f = 0.7 to 0.9).
3 (business as usual)	No discernible change to the time it takes the lake to drain after a flood (R_f = 0.9 to 1.1).
2	Option results in minor increase in the time it takes the lake to drain after a flood (R_f = 1.1 to 1.3).
1	Option results in considerable increase in the time it takes the lake to drain after a flood (R_f > 1.3).

Formal flood modelling was not undertaken to assess any changes to the present time it takes the lake to drain after a flood (i.e. there was no rainfall or catchment inflows input to the numerical model). Instead, the long-term management options were assessed against this criteria by analysing how long the water level within Lake Illawarra, at the same location used for the previous criteria (Figure 4.7), took to drain from 2.0 m AHD (which is slightly below the 100 year average recurrence interval lake flood level of 2.24 m AHD; Cardno, 2012) to 0.6 m AHD (a typical high tide level) at the beginning of the model simulation period. A flood ratio (R_f shown in Equation 4.2) was developed that compared the time it took water levels in each option (Option X) to lower versus the time it took for water levels in the "base case" (Option 1 – business as usual) to lower.

$$R_f = \frac{Time\ for\ water\ to\ lower\ from\ 2.0\ to\ 0.6\ m\ AHD\ (Option\ X)}{Time\ for\ water\ to\ lower\ from\ 2.0\ to\ 0.6\ m\ AHD\ (Option\ 1)} \quad (4.2)$$

Where R_f was equal to one, this indicated that there was no change to flood drainage times. If $R_f > 1$, this indicated an increase in flood drainage times and if $R_f < 1$ this indicated a decrease in flood drainage times.

Figure 4.11 shows examples of three different long-term management options which result in an increase (Options 31 and 23) or reduction (Option 20) in the time it takes the lake to drain after a flood compared to the "base case".

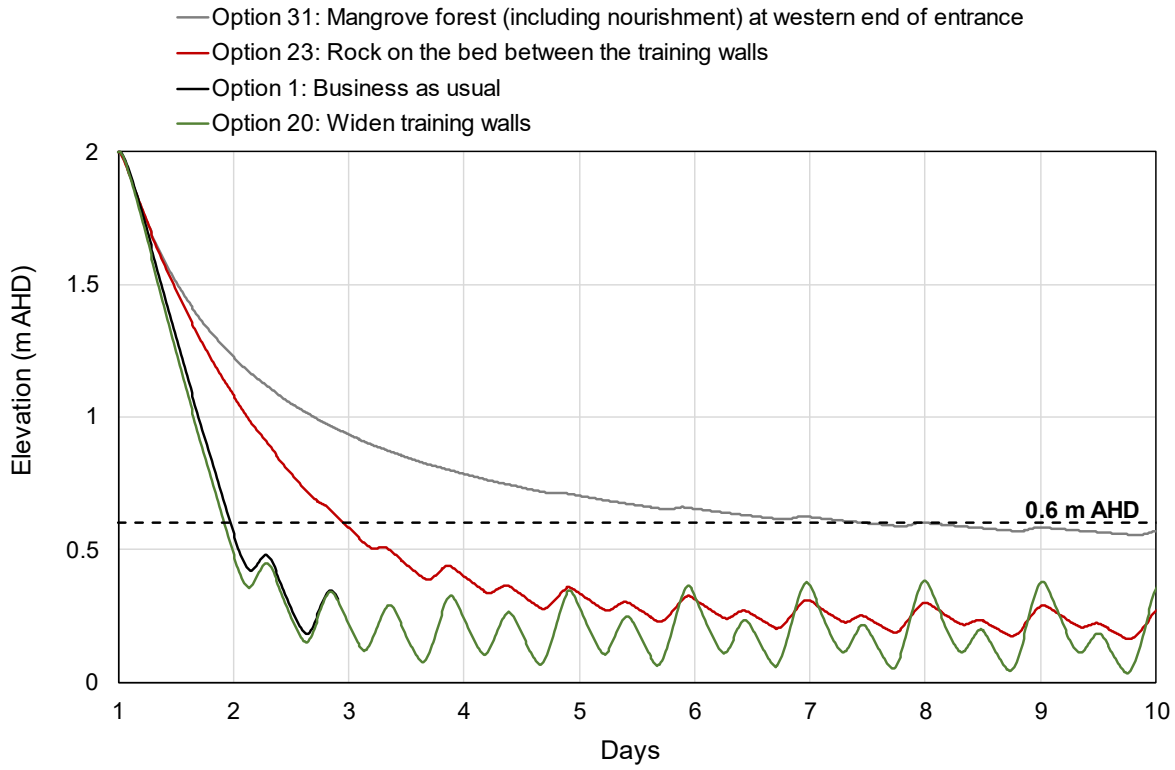


Figure 4.11 Example of drainage times for different flood ratios (Rf)

4.4.6 Water quality (Criteria D)

As discussed in Tucker et al. (2023), water quality has been monitored within Lake Illawarra prior to and following the permanent opening of the entrance in 2007. Analysis of these water quality measurements at different times has resulted in varying conclusions regarding the impact of the training works on lake water quality (e.g. Baxter and Daly, 2010, Wiecek et al., 2016, WCC, 2022).

Aside from the eastern side of Lake Illawarra near the entrance channel, with the available data, WRL does not consider that it is possible to conclusively prove that permanently opening the entrance in 2007 has influenced water quality in most of the lake. This is because the volume of tidal flushing compared to the lake volume is small and that other variables influence the water quality measurements in the lake (e.g. freshwater/flooding events, changes to catchment and industrial pollutant loads, changes to rainfall-runoff because of land use changes (urbanisation) within the catchment).

However, for the eastern side of Lake Illawarra near the entrance channel, it is evident that water quality has improved due to increased tidal flushing associated with the increased tidal range in the lake. On this basis, water quality improvements for the multi criteria assessment were primarily linked to an increasing tidal range in the lake assessed with Criteria B. Those options (Options 44 and 45) which could result in a closed entrance to the ocean again (i.e. return to an ICOLL [Intermittently Closed and Open Lakes and Lagoons] state) were scored as 2 since overall water quality in the eastern side of Lake Illawarra near the entrance may deteriorate slightly compared to the "base case" (noting that some water quality parameters may deteriorate with less tidal flushing while turbidity may improve with reduction in tidal range). Note that no numerical water quality modelling was carried out to assess the options against this criteria. The scoring guide for assessing how each option influenced the present state of water quality in the eastern side of Lake Illawarra near the entrance channel is shown in Table 4-7.

Table 4-7 Scoring guide for water quality

Score	Description
5	Option results in major improvement in water quality in the eastern side of Lake Illawarra near the entrance channel due to major increase in tidal range.
4	Option results in minor improvement in water quality in the eastern side of Lake Illawarra near the entrance channel due to minor increase in tidal range.
3 (business as usual)	No discernible change to present water quality in the eastern side of Lake Illawarra near the entrance channel.
2	Option results in minor deterioration in water quality in the eastern side of Lake Illawarra near the entrance channel due to reduced tidal range (target 2008 tidal range), or, Option results in returning it to an ICOLL where there are both closed and open periods (water quality parameters including nutrients deteriorate through less tidal flushing while parameters including turbidity improve through less bed sediment mobilisation).
1	Option results in major deterioration in water quality in the eastern side of Lake Illawarra near the entrance channel due to major reduction in tidal range (below 2008 tidal range).

4.4.7 Estuarine flora and fauna (Criteria E)

The three main communities of estuarine vegetation that occur in the lake (saltmarsh, seagrass, and mangroves) provide essential habitat, food supply and nutrient cycling (BMT, 2020b). Valued commercial and recreational fish species (e.g. bream, flathead, blue swimmer crabs and prawns) within the lake have been found to derive most of their nutrients from seagrass and saltmarsh habitats, the percentage contribution of each habitat type to the diet of these species varies across different locations in the lake (Gaston et al., 2019). The presence of these fish species further supports fish assemblages and other wildlife.

There is a relationship between the health of estuarine flora and fauna and the tidal range within the lake. Increasing or decreasing the tidal range in Lake Illawarra would have differing effects on the abundance of different species. Some flora and fauna would be expected to flourish with a higher tidal range, while others would decline, and vice versa for a lower tidal range.

Since the entrance was permanently opened in 2007, mangroves (one of the three key vegetation types) have significantly expanded in the lake which has been linked with the associated increasing tidal regime (Regina, 2016; Wiecek et al., 2016; Williams and Wiecek, 2017). As the tidal range in the lake increases and mangroves continue to expand landwards and encroach on areas currently occupied by saltmarsh, expansion of the saltmarsh landward may be constrained by development in some areas. That is, it would be beneficial to saltmarsh (without negative consequences for mangroves) if the tidal range could be reduced to what it was shortly after permanent opening. This is also an important consideration for preserving diversity of flora, as there are at least six different species of saltmarsh around Lake Illawarra and only one species of mangrove (BMT, 2020c).

Seagrass is also important for supporting fish within the Lake, as it provides a food source and shelter for different fish during different stages of their life cycles (BMT, 2020b). However, since the entrance was trained, seagrasses on the flood tide delta in the lake have been smothered by sand and seagrasses in the entrance channel have been lost due to increased flow velocities and scour (Wiecek et al., 2016). Both of these mechanisms for seagrass loss are linked to the increasing in tidal range since 2007.

On this basis, estuarine flora and fauna improvements for the multi criteria assessment were primarily linked to a decreasing tidal range in the lake assessed with Criteria B.

Those options (Options 44 and 45) which could result in a closed entrance to the ocean again (i.e. return to an ICOLL state) were scored as 4 since a closed condition is historically favourable for saltmarsh and seagrass and the fauna that benefit from them, but not mangroves (which may experience dieback).

It is acknowledged that potential impacts on fish passage and fish recruitment into Lake Illawarra from implementation of each option were not considered as part of the Stage 1 assessment.

The scoring guide for assessing how each option influenced estuarine flora and fauna within the lake is shown in Table 4-8.

Table 4-8 Scoring guide for estuarine flora and fauna

Score	Description
5	Option results in a considerable reduction in the tidal range within the lake resulting in improvements to flora health and subsequently fauna health.
4	Option results in a minor reduction in the tidal range within the lake resulting in minor improvements to flora health and subsequently fauna health, or, Option results in the closure of the lake entrance to the ocean (ICOLL conditions) reducing further impacts and/or improving flora health and subsequently fauna health.
3 (business as usual)	No discernible change to the tides levels within the lake resulting in no change to the current impacts to flora and subsequently fauna.
2	Option results in a minor increase to the tidal range within the lake resulting in new impacts to flora health and subsequently fauna health.
1	Option results in a major increase to the tidal range within the lake resulting in new large scale impacts to flora health and subsequently fauna health.

4.4.8 Indigenous heritage (Criteria F)

For options where the training walls remain in place, WRL received advice that the impact of each option's footprint (e.g. where the rock or sand would be placed) should be considered in addition to changes to erosion which may impact heritage sites. That is, the protection of indigenous archaeological sites from erosion by placing rock directly in front of them may be less preferable than the current state (where unprotected sites may be exposed to erosion). On this basis:

- A score of 4 was given for options that reduce erosion indirectly by reducing tidal current speeds, and their footprint does not coincide with known indigenous archaeological sites (e.g. Option 11: Construction of an artificial reef seaward of the training walls and Option 14: Half tide rock weir all the way across the channel beneath the bridge).
- Conversely, a score of 2 was given for options that reduce erosion (by direct protection), but their footprint coincides with a known site(s) (e.g. Option 4: Place rock on the bed along the entire entrance channel (training walls to lake) to stabilise the channel bed and Option 5: Installing large deep structures along both sides of the entrance channel).
- A score of 3 was then given for options that did not change the present rate of erosion and their footprint does not coincide with known sites.
- A score of 1 was given for options where the training walls remain in place and the present rate of erosion is increased.
- Finally, a score of 5 was given for options where one or both training walls are removed (e.g. Option 44: remove both training walls (return to pre-2007 conditions) and Option 45: remove northern training wall only). It is uncertain whether implementing either of these options (intended to increase the supply of marine sediment into the entrance) would return the entrance to a target historical state within an acceptable timeframe. Indigenous archaeological sites may still be impacted by erosion following the removal of one or both training walls. It is envisioned that large scale sand nourishment would be required, in addition to either of these options, to achieve the target historical state in a guaranteed period.

The scoring guide for assessing how each option impacted on the values of the Indigenous community and changed the present impact on Indigenous heritage from erosion or the addition of structural/non-structural features is shown in Table 4-9.

Table 4-9 Scoring guide for Indigenous heritage

Score	Description
5	Option results in the lake entrance to the ocean returning to a more natural state (ICOLL conditions).
4	Training walls remain, option results in discernible reduction in erosion and option footprint does not coincide with known Aboriginal heritage items.
3 (business as usual)	Training walls remain, no discernible change to the present rate of erosion, option footprint does not coincide with known Aboriginal heritage items.
2	Training walls remain, option results in discernible reduction in erosion but option footprint coincides with a known Aboriginal heritage item(s).
1	Training walls remain, option results in discernible increase in erosion.

Scoring impacts on Indigenous heritage for the multi criteria assessment were informed by:

- An extensive AHIMS (Aboriginal Heritage Information Management System – Heritage NSW) search in the area (received by WRL via e-mail 3 May 2022)
- The foreshore and bed erosion assessment (Criteria A)
- The footprint of each option

It is acknowledged that:

- Knowledge and data about the locations and significance of Indigenous heritage along the entrance channel is limited
- Direct engagement with the Indigenous community was not undertaken as part of the Stage 1 assessment due to the extensive number of options being considered
- WCC and SCC will engage and consult with the Indigenous community during Stage 2 of the assessment

4.4.9 In-water recreation (Criteria G)

Since the entrance was permanently opened in 2007, tidal velocities in the entrance channel (particularly on large spring tides) have increased to speeds which may pose a risk to safety, particularly for some unpowered activities (e.g. swimming, canoeing/kayaking, stand-up paddle boarding, etc). Those options which do not change in-water access for any recreation activity but reduce tidal velocities (scored as 5 for major reduction and 4 for minor reduction) have been considered to improve in-water recreation in the entrance channel compared to the present “base case” (scored as 3).

A score of 2 was given to options which reduce tidal velocities but impede access under Windang Bridge or access to the lake. A new boat ramp would need to be constructed upstream of these options if they

were constructed (e.g. Option 14: Half tide rock weir all the way across the channel beneath the bridge and Option 15: Head loss structure at the western end of the entrance; near Bevans Island). A score of 2 was also given to options which increase tidal velocities.

Finally, a score of 1 was given to options (Options 44 and 45) which impede access to the ocean via the training walls. While this loss of ocean access was considered to be detrimental overall to in-water recreation, it is acknowledged that implementing these options would still have the benefit of reducing tidal velocities in the entrance channel.

The scoring guide for assessing how each option impacted on community recreational activities within Lake Illawarra is shown in Table 4-10. Tidal velocities within the entrance channel for relevant options were extracted from the numerical model.

Table 4-10 Scoring guide for in-water recreation

Score	Description
5	Option results in major reduction in tidal velocities without changing in-water access.
4	Option results in minor reduction in tidal velocities without changing in-water access.
3 (business as usual)	No discernible change to present tidal velocities and in-water access.
2	Option results in access under Windang Bridge being impeded, access to lake being impeded or increase in tidal velocities.
1	Option results in access to the ocean via training walls being impeded.

4.4.10 Foreshore recreation (Criteria H)

Those options which add new spaces and infrastructure that deliver foreshore recreation and amenity such as walking, other recreational activities on the foreshore, fishing access and access to the water for swimming (scored as 5 for substantial increase and 4 for discernible increase) have been considered an improvement compared to the present “base case” (scored as 3). Conversely, options which reduce existing spaces and infrastructure for foreshore recreation (scored as 2 for discernible reduction and 1 for substantial reduction) have been considered a deterioration. Scoring examples are provided below:

- 5 – Option 10: Construction of a staggered groyne field in the entrance channel
- 4 – Option 5: Installing large deep structures along both sides of the entrance channel
- 3 – Option 11: Construction of an artificial reef seaward of the training walls
- 2 – Option 49: Shorten training walls
- 1 – Option 20: Move one of the training walls to widen the distance between them

The scoring guide for assessing how each option impacted on foreshore open spaces and infrastructure that delivers recreation and amenity for the community around the Lake Illawarra entrance is shown in Table 4-11.

Table 4-11 Scoring guide for foreshore recreation

Score	Description
5	Option results in a substantial increase of open spaces and infrastructure that deliver recreation and amenity.
4	Option results in a discernible increase of open spaces and infrastructure that deliver recreation and amenity.
3 (business as usual)	Option does not change open spaces and infrastructure that deliver recreation and amenity.
2	Option results in a discernible reduction of open spaces and infrastructure that deliver recreation and amenity.
1	Option results in a substantial reduction of open spaces and infrastructure that deliver recreation and amenity.

4.4.11 Capital cost (Criteria I)

The scoring guide for assessing the capital cost of each option is shown in Table 4-12. The five bins for this criteria (i.e. each bin represents a capital cost range) and the ongoing costs criteria (Section 4.4.12) have been set to cover the full range of WRL's estimates across all options, with bin width increasing as cost increases.

Table 4-12 Scoring guide for capital cost

Score	Description
5 (business as usual)	The capital cost of the option is estimated to be less than $2M.
4	The capital cost of the option is estimated to be between $2M and $10M.
3	The capital cost of the option is estimated to be between $10M and $25M.
2	The capital cost of the option is estimated to be between $25M and $50M.
1	The capital cost of the option is estimated to be more than $50M.

The capital cost for the "base case" (Option 1 – business as usual) has been assumed to be zero for the purposes of the multi criteria assessment. See Appendix B for further details on key assumptions and inputs for each of WRL's preliminary capital cost estimates for the long-term management options considered.

Note that for those options shortlisted for further analysis, the associated capital cost estimates will be further reviewed during Stage 2 of the assessment.

4.4.12 Ongoing costs (Criteria J)

Preliminary estimates of the ongoing costs related to each long-term management option were prepared by WRL. The scoring guide for assessing the ongoing costs of each option is shown in Table 4-13.

Table 4-13 Scoring guide for ongoing costs

Score	Description
5 (business as usual)	The ongoing costs of the option are estimated to be less than $10k/year.
4	The ongoing costs of the option are estimated to be between $10k and $50k/year.
3	The ongoing costs of the option are estimated to be between $50k and $250k/year.
2	The ongoing costs of the option are estimated to be between $250k and $1M/year.
1	The ongoing costs of the option are estimated to be more than $1M/year.

The ongoing costs for the "base case" (Option 1 – business as usual) have been assumed to be zero for the purposes of the multi criteria assessment. That is, the ongoing costs of any option are in addition to any present ongoing costs of landowners (WCC, SCC, Crown Lands and TfNSW) in the entrance channel. Also, reductions in any present ongoing costs were not considered in this assessment because of the implementation of any option. See Appendix B for further details on key assumptions and inputs for each of WRL's preliminary estimates of ongoing costs for the long-term management options considered.

4.5 Results

To compare each of the long-term management options, the score for each criteria was multiplied by each criteria's weighting (Table 4-3) to obtain a total weighted score for each option (Figure 4.1). The results for the multi criteria analysis of the 35 options (sorted by increasing rank) are presented in Table 4-14. In these results, there were 17 options which ranked above the "base case" (Option 1 – business as usual).

As a sensitivity test, the management options were also assessed without criteria weightings (i.e. weighting of 1.00 for all 10 criteria). The full results of this unweighted multi criteria analysis are provided in Appendix C.

Table 4-14 Multi criteria analysis results (sorted by increasing rank)

Ref.	Management option	Criteria										Weighted Score	Rank
		Foreshore and bed erosion	Increasing tidal regime	Upstream flooding	Water quality	Estuarine flora and fauna	Indigenous heritage	In-water recreation	Foreshore recreation	Capital cost	Ongoing costs		
	Description	1.54	1.49	0.80	1.37	1.22	1.03	0.15	0.34	0.39	1.67		
15	Head loss structure (rock weir/concrete weir/wavescreen) at the western end of the entrance (near Bevans Island) + new boat ramp upstream	5	5	1	2	5	4	2	4	4	4	38.8	1
14	Half tide rock weir all the way across the channel beneath the bridge + new boat ramp upstream (flow control by choke point)	5	5	1	2	5	4	2	3	4	4	38.5	2
24	Porous wavescreen breakwater all the way across the channel beneath the bridge + new boat ramp upstream (head loss by choke point)	5	5	1	2	5	4	2	3	3	4	38.1	3
19	Move one of the training walls to narrow the distance between them (flow control by choke point)	4	4	1	3	4	4	4	5	3	5	37.8	4
7	Construct a lock system across the western end of the entrance to isolate Lake Illawarra (additional opportunities: walkway on top and turbines for hydropower)	5	5	3	2	5	4	2	5	2	2	36.6	5
10	Construction of a staggered groyne field in the entrance channel to reduce cross-sectional flow area (head loss by choke points)	4	4	1	3	4	4	4	5	4	4	36.6	6
12	Disguised gate structures across the channel beneath the bridge to fine tune flow (with scour protection of surrounds) (flow control by choke point)	5	5	2	2	5	4	2	3	1	3	36.4	7

Table 4-14 Multi criteria analysis results (sorted by increasing rank) (cont.)

Management option		Criteria											
		Foreshore and bed erosion	Increasing tidal regime	Upstream flooding	Water quality	Estuarine flora and fauna	Indigenous heritage	In-water recreation	Foreshore recreation	Capital cost	Ongoing costs	Weighted Score	Rank
Ref.	Description	1.54	1.49	0.80	1.37	1.22	1.03	0.15	0.34	0.39	1.67		
26	Retractable overshot weir that could be lowered during a flood (SmartGate / Thames Barrier) (flow control by choke point)	5	5	2	2	5	4	2	3	1	3	36.4	7
18	Large concrete culvert weir all the way across the channel beneath the bridge + new boat ramp upstream (flow control by choke point)	5	5	1	2	5	4	2	3	2	3	36.0	9
45	Remove northern training wall only	5	5	1	2	4	5	1	1	4	3	35.8	10
44	Remove both training walls (return to pre-2007 conditions)	5	5	1	2	4	5	1	1	3	3	35.4	11
49	Shorten training walls so that littoral sand starts infilling (maybe with a nourished shoal in the entrance to get started) (increase sediment supply into entrance channel)	4	5	1	3	5	4	5	2	4	2	35.1	12
48	Building a series of engineered, stabilised islands (perhaps protected by oyster bags/reefs) in the flood-tide delta (head loss by choke point)	5	5	1	2	5	4	2	5	2	2	35.0	13
21	Narrow the entrance throat by creating a wave trap beach and other engineered beaches within the channel on the northern side (flow control by choke point)	4	4	1	3	4	4	4	5	4	3	34.9	14

Table 4-14 Multi criteria analysis results (sorted by increasing rank) (cont.)

Ref.	Management option Description	Criteria Foreshore and bed erosion 1.54	Increasing tidal regime 1.49	Upstream flooding 0.80	Water quality 1.37	Estuarine flora and fauna 1.22	Indigenous heritage 1.03	In-water recreation 0.15	Foreshore recreation 0.34	Capital cost 0.39	Ongoing costs 1.67	Weighted Score	Rank
22	Place rock at several locations within the entrance channel to reduce the cross-sectional area at multiple locations (flow control by choke points)	5	5	1	2	5	4	5	3	1	2	34.4	15
23	Place rock on the bed over the first 250 to 500 m of the channel (seaward end) to reduce the cross-sectional area (head loss by choke point)	5	5	1	2	5	4	5	3	1	2	34.4	15
38	Planting large riparians trees and other vegetation on foreshores with no structural protection (reduce vulnerability to erosion)	4	3	3	3	3	3	3	4	5	4	34.3	17
1	Business as usual (follow existing investment spending rate on maintenance of bridge, foreshore and training walls)	3	3	3	3	3	3	3	3	5	5	34.1	18
50	Temporarily close the entrance (rock bags could be used), re-engineer the entrance channel with protection/nourishment and then re-open the entrance	5	5	1	2	5	4	2	3	3	1	33.1	19
11	Construction of an artificial reef or other structure seaward of the training walls to disturb the ebb tide jet and restrict the entrance (head loss by choke point)	4	4	2	3	4	4	4	3	2	2	32.6	20

Table 4-14 Multi criteria analysis results (sorted by increasing rank) (cont.)

Ref.	Management option	Criteria										Weighted Score	Rank
		Foreshore and bed erosion	Increasing tidal regime	Upstream flooding	Water quality	Estuarine flora and fauna	Indigenous heritage	In-water recreation	Foreshore recreation	Capital cost	Ongoing costs		
	Description	1.54	1.49	0.80	1.37	1.22	1.03	0.15	0.34	0.39	1.67		
34	Install aquaculture on the northern bank, downstream of the bridge (reduce vulnerability to erosion)	3	3	3	3	3	3	3	3	5	4	32.5	21
31	Construction of mangrove forest at the western end of the entrance to increase roughness (head loss via friction along a channel stretch)	5	5	1	3	5	2	2	4	2	1	32.3	22
33	Create intertidal/wetland area in the flood-tide delta with different zones for different ecosystem services (head loss via friction along a channel stretch)	5	5	1	3	5	2	2	4	2	1	32.3	22
32	Construction of oyster reefs at the western end of the entrance to increase roughness (head loss via friction along a channel stretch)	5	5	1	3	5	2	2	3	2	1	32.0	24
5	Stabilise the existing shoreline by installing large deep structures (e.g. concrete caissons) along both sides of the entrance channel to account for the assumed future channel deepening	4	3	3	4	3	2	3	4	2	3	31.8	25
3	Construction of groyne fields upstream (northern side) and downstream (southern side) of bridge to keep the main tidal flow away from existing banks	3	4	2	3	4	2	4	5	3	3	31.7	26

Table 4-14 Multi criteria analysis results (sorted by increasing rank) (cont.)

Ref.	Description	Criteria: Foreshore and bed erosion	Increasing tidal regime	Upstream flooding	Water quality	Estuarine flora and fauna	Indigenous heritage	In-water recreation	Foreshore recreation	Capital cost	Ongoing costs	Weighted Score	Rank
		1.54	1.49	0.80	1.37	1.22	1.03	0.15	0.34	0.39	1.67		
36	Periodically place sand between the training walls to shallow the entrance, repeat when eroded by tidal or flood velocities (increase sediment supply into entrance channel to increase head loss via friction)	2	5	1	2	5	4	5	3	4	2	31.0	27
37	Place a large volume of sand between the training walls to block the entrance, repeat when eroded by flood velocities (total closure)	2	5	1	2	4	4	1	3	4	2	29.1	28
40	Sand transfer in ongoing campaigns via dredging ship or truck movements (increase sediment supply into entrance channel to increase head loss via friction)	2	4	2	3	4	4	4	3	3	1	28.2	29
39	Rehabilitation of historical seagrass beds for stabilisation (head loss via friction along a channel stretch)	3	3	1	3	5	3	5	3	3	1	27.8	30
2	Construct a more efficient central channel (via internal training walls) to keep the main tidal flow away from existing banks	3	4	2	3	4	2	4	5	1	1	27.6	31
4	Place rock on the bed along the entire entrance channel (training walls to lake) to stabilise the channel bed	4	4	2	3	3	2	4	3	1	1	27.2	32

Table 4-14 Multi criteria analysis results (sorted by increasing rank) (cont.)

Ref.	Management option Description	Criteria Foreshore and bed erosion 1.54	Increasing tidal regime 1.49	Upstream flooding 0.80	Water quality 1.37	Estuarine flora and fauna 1.22	Indigenous heritage 1.03	In-water recreation 0.15	Foreshore recreation 0.34	Capital cost 0.39	Ongoing costs 1.67	Weighted Score	Rank
28	"Sand shifter" network to capture littoral drift on Windang Beach (similar to Noosa) and/or sand deposited on the flood-tide delta to be pumped back into the entrance (increase sediment supply into entrance channel to increase head loss via friction)	2	4	2	3	4	3	4	3	3	1	27.2	33
29	Actively dredge sand from the flood-tide delta and place it back into the entrance in an ongoing fashion to restrict tidal flows (increase sediment supply into entrance channel to increase head loss via friction)	2	4	2	3	4	3	4	3	3	1	27.2	33
20	Move one of the training walls to widen the distance between them (reduce tidal velocities by increasing flow area)	1	1	4	4	1	1	2	1	3	5	24.1	35

5 Review of multi criteria analysis results

The top 11 options (identified in Table 4-14) were considered by the PCG at a meeting on 8 December 2022 as candidates for the shortlist of long-term management options for Stage 2 of the study. Table 5-1 shows a summary of key results for the top 11 management options by identifying:

- Options which were assessed to have major improvements (score of 5) for both primary project objectives of reducing erosion and the tidal regime (denoted with a tick)
- Options which scored poorly (score of 1) for upstream flooding impacts (denoted with a cross)
- Estimated capital cost range for each option

Table 5-1 Multi criteria analysis key results (summary of top 11 management options)

Ref.	Management option Description	Best score (5) for erosion and tidal regime	Worst score (1) for flooding	Capital cost range
15	Head loss structure at the western end of the entrance + new boat ramp upstream (Figure 2.9)	✓	×	$2M to $10M
14	Half tide rock weir beneath the whole bridge + new boat ramp upstream (Figure 2.8)	✓	×	$2M to $10M
24	Porous wavescreen breakwater beneath the whole bridge + new boat ramp upstream (Figure 2.13)	✓	×	$10M to $25M
19	Move one of the training walls to narrow the distance between them (Figure 2.10)		×	$10M to $25M
7	Construct a lock system across the western end of the entrance (Figure 2.4)	✓		$25M to $50M
10	Staggered groyne field in the entrance channel (Figure 2.5)		×	$2M to $10M
12	Disguised gate structures beneath the whole bridge to fine tune flow (Figure 2.7)	✓		$25M to $50M
26	Retractable overshot weir that could be lowered during a flood (Figure 2.14)	✓		$25M to $50M
18	Large concrete culvert weir beneath the whole bridge + new boat ramp upstream (Figure 2.8)	✓	×	$25M to $50M
45	Remove northern training wall only (Figure 2.17)	✓	×	$2M to $10M
44	Remove both training walls (return to pre-2007 conditions) (Figure 2.16)	✓	×	$10M to $25M

Following discussion of the MCA results by the PCG, five of the top 11 management options were removed as candidates for the shortlist for Stage 2 of the study. Table 5-2 records these five long-term management options and the rationale of the PCG for not considering them further.

Table 5-2 Top 11 management options not adopted for Stage 2 shortlist

Management option		Rationale for not considering further
Ref.	**Description**	
19	Move one of the training walls to narrow the distance between them	This option only had minor improvements for the primary objectives (reducing erosion and tidal regime), scored poorly for upstream flooding impacts and had a higher capital cost estimate compared to the other top 11 options which scored similarly for the erosion-tide-flooding criteria (Option 10: staggered groyne field in the entrance channel).
7	Construct a lock system across the western end of the entrance	This option was not supported because of negative impacts on in-water recreation, negative impacts on fish passage and a high capital cost estimate.
26	Retractable overshot weir that could be lowered during a flood	This option was not supported because of its very high capital cost estimate.
18	Large concrete culvert weir beneath the whole bridge + new boat ramp upstream	This option comprising concrete is similar to Option 14 (rock weir beneath the whole bridge), however it was considered less preferable because it would be comparatively less adaptable in the future, provide negligible ecological habitat and had a higher capital cost estimate.
45	Remove northern training wall only	This option was not supported because, when compared to Option 44 (remove both training walls: return to pre-2007 conditions), there was less understanding of the likely response of the entrance channel to its implementation.

Of the remaining six of the top 11 management options, two of the options were combined and two of the options were modified to arrive at an agreed shortlist of five options for Stage 2 of the study. These shortlisted options (with accompanying notes from the PCG discussions) are shown in Table 5-3 and Figure 5.1. Note that while all five options are shown Figure 5.1 for illustrative purposes, it is envisaged that only one of these options would be implemented in the future.

Table 5-3 Agreed shortlist of management options for Stage 2

Shortlisted management option description	Notes
Head loss structures at the western end of the entrance across all three channels	This description is based on a modified version of Option 15 (head loss structure at the western end of the entrance + new boat ramp upstream). Head loss structures were included for all three channels to prevent additional erosion occurring in the smaller channels. The new boat ramp was also omitted with the aspiration that in-water access to the lake for recreation will not be impeded.
Variable depth rock weir beneath Windang Bridge	This description is based on a modified and combined version of Option 14 (half tide rock weir beneath the whole bridge + new boat ramp upstream) and Option 24 (porous wavescreen breakwater beneath the whole bridge + new boat ramp upstream). The “half tide” description was removed, and “variable depth” text added to give flexibility to optimising the geometry. The new boat ramp was also omitted with the aspiration that in-water access under Windang Bridge for recreation will not be impeded.
Rock weir beneath Windang Bridge with gate structures to fine tune flow	This description is based on a modified version of Option 12 (disguised gate structures beneath the whole bridge to fine tune flow). Inclusion of gates was considered advantageous for future flow adaptability, but the text was changed so that the gates would only be used beneath part of Windang Bridge (to reduce the capital cost) with the remaining sections to be built as a rock weir.
Staggered groyne field in the entrance channel	This description is unchanged from Option 10.
Remove both training walls (return to pre-2007 conditions)	This description is unchanged from Option 44.



Figure 5.1 Agreed shortlist of management options for Stage 2

6 Summary

A specialist project team consisting of WRL and MHL, was engaged by WCC, on behalf of a project control group consisting of WCC, SCC and DPE, to develop and assess a list of 50 long-term management options for the Lake Illawarra entrance channel. The primary objectives of these options were to reduce foreshore and bed erosion and mitigate the increasing tidal regime as these key criteria inform/influence the remaining criteria.

Initially, two gateways were used to check if each option had a well-worn legislative pathway to progress an option and that it would not impact on stability of Windang or Warilla Beaches. Application of these gateways eliminated 15 of the options.

Each of the remaining 35 options were assessed using multi criteria analysis (which was informed by numerical modelling of the options) considering the following 10 criteria:

A. Risk reduction effectiveness: foreshore and bed erosion
B. Mitigation of increasing tidal regime
C. Upstream flooding
D. Water quality
E. Estuarine flora and fauna
F. Indigenous heritage
G. In-water recreation
H. Foreshore recreation
I. Capital cost
J. Ongoing costs

Weightings were assigned to each of these by comparing each criteria to one another (i.e. pairwise comparisons) to establish the relative importance of one criteria over another using the Analytic Hierarchy Process (Saaty, 1980; Goepel, 2018). Scoring guides were developed whereby for each long-term management option being assessed, a score of 1 to 5 was assigned for each criteria. A score of 1 was considered least favourable for the objectives/values of the criteria and a score of 5 was considered most favourable. Finally, the score for each criteria was multiplied by each criteria's weighting to obtain a total weighted score for each option, which enabled all options to be ranked.

The top 11 ranked options from the results of the multi criteria analysis were then reviewed by the project control group. Following this review, some of the top 11 options were removed and the descriptions of others were modified to arrive at the following agreed shortlist of five options for Stage 2 of the study:

- Head loss structures at the western end of the entrance across all three channels
- Variable depth rock weir beneath Windang Bridge
- Rock weir beneath Windang Bridge with gate structures to fine tune flow
- Staggered groyne field in the entrance channel
- Remove both training walls (return to pre-2007 conditions).

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Appendix A Pairwise comparisons for weighting criteria for multi criteria analysis

During the workshop with WCC, SCC and DPE staff on 25 November 2021, each of the 10 criteria were compared to all other criteria and a consensus intensity of importance (score of 1 to 9; see Table 4-2) assigned. Each of the 45 pairwise criteria comparison results are shown in Table A-1.

Table A-1 Criteria comparisons from workshop on 25 November 2021

Criteria 1 Ref.	Criteria 1 Name	Criteria 2 Ref.	Criteria 2 Name	More important criteria	Intensity of Importance
A	Foreshore and bed erosion	B	Increasing tidal regime	A Foreshore and bed erosion	2
A	Foreshore and bed erosion	C	Upstream flooding	A Foreshore and bed erosion	4
A	Foreshore and bed erosion	D	Water quality	A Foreshore and bed erosion	2
A	Foreshore and bed erosion	E	Estuarine flora and fauna	E Estuarine flora and fauna	2
A	Foreshore and bed erosion	F	Indigenous heritage	F Indigenous heritage	2
A	Foreshore and bed erosion	G	In-water recreation	A Foreshore and bed erosion	9
A	Foreshore and bed erosion	H	Foreshore recreation	A Foreshore and bed erosion	5
A	Foreshore and bed erosion	I	Capital cost	A Foreshore and bed erosion	5
A	Foreshore and bed erosion	J	Ongoing costs	J Ongoing costs	2
B	Increasing tidal regime	C	Upstream flooding	B Increasing tidal regime	3
B	Increasing tidal regime	D	Water quality	- Equal	1
B	Increasing tidal regime	E	Estuarine flora and fauna	- Equal	1
B	Increasing tidal regime	F	Indigenous heritage	B Increasing tidal regime	2
B	Increasing tidal regime	G	In-water recreation	B Increasing tidal regime	8
B	Increasing tidal regime	H	Foreshore recreation	B Increasing tidal regime	6
B	Increasing tidal regime	I	Capital cost	B Increasing tidal regime	9
B	Increasing tidal regime	J	Ongoing costs	J Ongoing costs	2
C	Upstream flooding	D	Water quality	D Water quality	2
C	Upstream flooding	E	Estuarine flora and fauna	E Estuarine flora and fauna	2
C	Upstream flooding	F	Indigenous heritage	F Indigenous heritage	2

Table A-1 Criteria comparisons from workshop on 25 November 2021 (cont.)

Criteria 1 Ref.	Criteria 1 Name	Criteria 2 Ref.	Criteria 2 Name	More important criteria		Intensity of Importance
C	Upstream flooding	G	In-water recreation	C	Upstream flooding	8
C	Upstream flooding	H	Foreshore recreation	C	Upstream flooding	6
C	Upstream flooding	I	Capital cost	C	Upstream flooding	4
C	Upstream flooding	J	Ongoing costs	J	Ongoing costs	2
D	Water quality	E	Estuarine flora and fauna	D	Water quality	2
D	Water quality	F	Indigenous heritage	D	Water quality	2
D	Water quality	G	In-water recreation	D	Water quality	9
D	Water quality	H	Foreshore recreation	D	Water quality	7
D	Water quality	I	Capital cost	D	Water quality	3
D	Water quality	J	Ongoing costs	J	Ongoing costs	2
E	Estuarine flora and fauna	F	Indigenous heritage	E	Estuarine flora and	2
E	Estuarine flora and fauna	G	In-water recreation	E	Estuarine flora and	5
E	Estuarine flora and fauna	H	Foreshore recreation	E	Estuarine flora and	4
E	Estuarine flora and fauna	I	Capital cost	E	Estuarine flora and	2
E	Estuarine flora and fauna	J	Ongoing costs	J	Ongoing costs	2
F	Indigenous heritage	G	In-water recreation	F	Indigenous heritage	5
F	Indigenous heritage	H	Foreshore recreation	F	Indigenous heritage	2
F	Indigenous heritage	I	Capital cost	F	Indigenous heritage	2
F	Indigenous heritage	J	Ongoing costs	-	Equal	1
G	In-water recreation	H	Foreshore recreation	H	Foreshore recreation	5
G	In-water recreation	I	Capital cost	I	Capital cost	5
G	In-water recreation	J	Ongoing costs	J	Ongoing costs	5
H	Foreshore recreation	I	Capital cost	I	Capital cost	2
H	Foreshore recreation	J	Ongoing costs	J	Ongoing costs	2
I	Capital cost	J	Ongoing costs	J	Ongoing costs	5

The 45 pairwise comparisons shown in Table A-1 were then used to build the decision matrix shown in Table A-2. Table A-2 contains the same data as Table A-1 but is presented in Saaty's (1980) standard matrix format which compares the criteria in each row (i) with the criteria in each column (j). The diagonal in this matrix is 1 because this compares each criteria against itself. If the row (i) value in each cell is more important it will have the intensity of importance from Table A-1. However, if the column (j) value in each cell is more important, the value will be the reciprocal of the intensity of importance from Table A-1. That is, cell values in the upper right triangular matrix (above the diagonal) are the reciprocal of cell values in the lower left triangular matrix (below the diagonal).

Table A-2 Summary of pairwise comparisons (Saaty (1980) decision matrix)

		Foreshore and bed erosion	Increasing tidal regime	Upstream flooding	Water quality	Estuarine flora and fauna	Indigenous heritage	In-water recreation	Foreshore recreation	Capital cost	Ongoing costs
		A	B	C	D	E	F	G	H	I	J
Foreshore and bed erosion	A	1	2	4	2	1/2	1/2	9	5	5	1/2
Increasing tidal regime	B	1/2	1	3	1	1	2	8	6	9	1/2
Upstream flooding	C	1/4	1/3	1	1/2	1/2	1/2	8	6	4	1/2
Water quality	D	1/2	1	2	1	2	2	9	7	3	1/2
Estuarine flora and fauna	E	2	1	2	1/2	1	2	5	4	2	1/2
Indigenous heritage	F	2	1/2	2	1/2	1/2	1	5	2	2	1
In-water recreation	G	1/9	1/8	1/8	1/9	1/5	1/5	1	1/5	1/5	1/5
Foreshore recreation	H	1/5	1/6	1/6	1/7	1/4	1/2	5	1	1/2	1/2
Capital cost	I	1/5	1/9	1/4	1/3	1/2	1/2	5	2	1	1/5
Ongoing costs	J	2	2	2	2	2	1	5	2	5	1

The online software tool developed by Goepel (2018) for the Analytic Hierarchy Process (Saaty, 1980) was used to undertake the eigenvector calculations to determine the weightings for each criteria based on the decision matrix in Table A-2. The resulting criteria weightings are shown in Table A-3 (unsorted) and in Table A-4 (sorted by increasing rank).

Finally, to estimate the consistency of the consensus criteria scoring (intensities of importance) from the workshop, the consistency ratio (CR) was also calculated using the same software. For the Analytic Hierarchy Process, if the consistency ratio is less than 10%, then the ratio indicates a reasonable level of consistency in the pairwise comparisons, but once the CR is greater than 10%, it shows that the pairwise comparisons are inconsistent in judgment. The CR for the decision matrix for the Lake Illawarra criteria was found to be 9.8% indicating a reasonable degree of robustness to the consensus scoring (intensities of importance).

Table A-3 Summary of criteria weightings (unsorted)

Ref.	Name	Weighting	Rank
A	Risk reduction effectiveness: foreshore and bed erosion	1.54	2
B	Mitigation of increasing tidal regime	1.49	*3*
C	Upstream flooding	0.80	*7*
D	Water quality	1.37	4
E	Estuarine flora and fauna	1.22	5
F	Indigenous heritage	1.03	6
G	In-water recreation	0.15	10
H	Foreshore recreation	0.34	9
I	Capital cost	0.39	8
J	Ongoing costs	1.67	1

Table A-4 Summary of criteria weightings (sorted by increasing rank)

Ref.	Name	Weighting	Rank
J	Ongoing costs	1.67	1
A	Risk reduction effectiveness: foreshore and bed erosion	1.54	2
B	Mitigation of increasing tidal regime	1.49	3
D	Water quality	1.37	4
E	Estuarine flora and fauna	1.22	5
F	Indigenous heritage	1.03	6
C	Upstream flooding	0.80	7
I	Capital cost	0.39	8
H	Foreshore recreation	0.34	9
G	In-water recreation	0.15	10

Appendix B Assumptions for preliminary cost estimates

B1 General

The cost estimates developed for the 35 long-term management options which passed the two gateways should be considered preliminary only. It is noted that the cost estimates were intended for comparison between the options (e.g. assigning a score of 1 to 5) and were not prepared to the level of detail of a tender submission. WRL has not had any engagement with contractors and materials suppliers (e.g. quarries) in this area. Cost estimates will be revised in greater detail in Stage 2 for those options which are shortlisted for further analysis.

Other than consideration of capital construction cost and ongoing maintenance costs, the assessment was technical in nature and did not examine economic benefits (such as the value of the protected assets). The assessment also did not consider changes to ecosystem services.

Material quantities for the options were derived by WRL from the geometry included in the numerical model. Unit and bulk rates for materials were determined from information available to WRL from similar projects in Australia.

Note that these costs are quoted exclusive of Goods and Services Tax (GST) in 2022 AUD$.

Given the extensive variety of options that were required to be costed for the multi criteria analysis, only those assumptions which are common to many of the options have been described below.

B2 Capital cost

B2.1 Structural components

For options which include rock armour (assumed density 2.65 t/m^3), the cost for supply (including delivery) and placement of rock with land-based construction (e.g. groynes) has been assumed to be $100 per tonne. For those options which require water-based construction from a barge (e.g. rock weir, artificial reef), the cost for supply and placement of rock has been assumed to be $400 per tonne.

B2.2 Sand nourishment

For options which include sand nourishment, the cost for supply and distribution of the sand has been assumed to be $20 per m^3.

B2.3 New boat ramp

Options which will impede in-water access under Windang Bridge or access to the lake will require a new boat ramp to be constructed upstream of these options. A cost of $1.6M has been assumed for the construction of a new boat ramp.

B2.4 Detailed design and approvals

Depending on the type of each option, the cost for detailed design, environmental assessments, heritage assessments and approvals has been assumed to be between $100,000 and $500,000. The only exception to this is Option 38: Planting large riparians trees and other vegetation on foreshores with no structural protection (reduce vulnerability to erosion) which had assumed cost for this component of $10,000.

B2.5 Contingency

A contingency sum of 15% has been added to the sub-total costs. This is based on standard industry practice for preliminary design estimates of this nature.

B2.6 Contractor profit

A profit of 10% for the primary contractor has been allowed for in addition to all other costs.

B2.7 Training wall removal

The construction of the training walls completed in 2007 was estimated to cost $11.6M (LIA, 2011). Based on a Consumer Price Index (CPI) rise of 33.4% between March 2008 and March 2022 (ABS, 2022), the replacement cost of the breakwaters in 2022 AUD$ is estimated to be $15.5M (including contingency and contractor profit).

There is limited literature available regarding the cost to remove coastal structures. However, an artificial surfing reef (“Pratte’s Reef”), comprising sand filled geotextile containers, in California (USA) began construction in 2000 and was removed in 2010. The total cost to remove this reef was nearly identical to the construction cost (Leidersdorf, et al., 2011).

Cognisant of this example and considering that armour rock for the Lake Illawarra entrance training walls is understood to have been supplied as a by-product from nearby road construction at a reduced rate, the estimated costs for removing both training walls have been assumed to be 100% of the 2022 replacement cost. With allowance for detailed design of the removal process and approvals, the capital cost to remove both training walls (Option 44) is estimated to be $15.7M.

Since there is a greater volume of armour rock in the northern training wall compared to the southern training wall, the capital cost to remove the northern training wall only (Option 45) has been assumed to be $9.5M on a pro-rata basis (60% of the 2022 replacement cost for both training walls plus allowance for detailed design and approvals).

B3 Ongoing costs

B3.1 Structural components

The average annual cost for maintenance of options comprising rock armour has been estimated to be approximately 1% of the initial capital cost to supply and place the rock (Gordon, 1989).

B3.2 Sand nourishment

The average annual cost to maintain any nourishment sand placed in the Lake Illawarra estuary has been estimated to be approximately 17% of the initial capital cost to supply and distribute the sand. This is based on the observed rate of erosion of existing sand in the channel between March 2016 and December 2021.

B3.3 ICOLL management

For those options (Options 44 and 45) which could result in a closed entrance to the ocean again (i.e. return to an ICOLL state by removal of one or both training walls), the average annual cost for management of the entrance (e.g. managing the beach berm to facilitate opening at lower than natural levels at a desired location, artificial opening) has been estimated to be $50,000 per year.

Appendix C Multi criteria analysis results (unweighted)

As a sensitivity test, the management options were assessed without criteria weightings (i.e. weighting of 1.00 applied for all 10 criteria). The results of this unweighted multi criteria analysis are provided in Table C-1. In these unweighted results, there were eight options which ranked above the “base case” (Option 1 – business as usual). Each of these eight options were also ranked above the “base case” for the weighted MCA results (Table 4-14).

Out of the top 11 options from the weighted results (Table 5-1), the following six options were ranked below the “base case” in the unweighted MCA results (Table C-1):

- Option 12: Disguised gate structures beneath the whole bridge to fine tune flow
- Option 18: Large concrete culvert weir beneath the whole bridge + new boat ramp upstream
- Option 24: Porous wavescreen breakwater beneath the whole bridge + new boat ramp upstream
- Option 26: Retractable overshot weir that could be lowered during a flood
- Option 44: Remove both training walls (return to pre-2007 conditions)
- Option 45: Remove northern training wall only

Table C-1 Unweighted multi criteria analysis results (sorted by increasing rank)

Ref.	Management option	Criteria										Unweighted Score	Rank
		Foreshore and bed erosion	Increasing tidal regime	Upstream flooding	Water quality	Estuarine flora and fauna	Indigenous heritage	In-water recreation	Foreshore recreation	Capital cost	Ongoing costs		
	Description	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00		
10	Construction of a staggered groyne field in the entrance channel to reduce cross-sectional flow area (head loss by choke points)	4	4	1	3	4	4	4	5	4	4	37.0	1
19	Move one of the training walls to narrow the distance between them (flow control by choke point)	4	4	1	3	4	4	4	5	3	5	37.0	1
15	Head loss structure (rock weir/concrete weir/wavescreen) at the western end of the entrance (near Bevans Island) + new boat ramp upstream	5	5	1	2	5	4	2	4	4	4	36.0	3
21	Narrow the entrance throat by creating a wave trap beach and other engineered beaches within the channel on the northern side (flow control by choke point)	4	4	1	3	4	4	4	5	4	3	36.0	3
7	Construct a lock system across the western end of the entrance to isolate Lake Illawarra (additional opportunities: walkway on top and turbines for hydropower)	5	5	3	2	5	4	2	5	2	2	35.0	5
14	Half tide rock weir all the way across the channel beneath the bridge + new boat ramp upstream (flow control by choke point)	5	5	1	2	5	4	2	3	4	4	35.0	5
38	Planting large riparians trees and other vegetation on foreshores with no structural protection (reduce vulnerability to erosion)	4	3	3	3	3	3	3	4	5	4	35.0	5

Table C-1 Unweighted multi criteria analysis results (sorted by increasing rank) (cont.)

Ref.	Management option Description	Criteria Foreshore and bed erosion 1.00	Increasing tidal regime 1.00	Upstream flooding 1.00	Water quality 1.00	Estuarine flora and fauna 1.00	Indigenous heritage 1.00	In-water recreation 1.00	Foreshore recreation 1.00	Capital cost 1.00	Ongoing costs 1.00	Unweighted Score	Rank
49	Shorten training walls so that littoral sand starts infilling (maybe with a nourished shoal in the entrance to get started) (increase sediment supply into entrance channel)	4	5	1	3	5	4	5	2	4	2	35.0	5
1	Business as usual (follow existing investment spending rate on maintenance of bridge, foreshore and training walls)	3	3	3	3	3	3	3	3	5	5	34.0	9
24	Porous wavescreen breakwater all the way across the channel beneath the bridge + new boat ramp upstream (head loss by choke point)	5	5	1	2	5	4	2	3	3	4	34.0	9
3	Construction of groyne fields upstream (northern side) and downstream (southern side) of bridge to keep the main tidal flow away from existing banks	3	4	2	3	4	2	4	5	3	3	33.0	11
22	Place rock at several locations within the entrance channel to reduce the cross-sectional area at multiple locations (flow control by choke points)	5	5	1	2	5	4	5	3	1	2	33.0	11
23	Place rock on the bed over the first 250 to 500 m of the channel (seaward end) to reduce the cross-sectional area (head loss by choke point)	5	5	1	2	5	4	5	3	1	2	33.0	11

Table C-1 Unweighted multi criteria analysis results (sorted by increasing rank) (cont.)

Ref.	Management option Description	Criteria Foreshore and bed erosion 1.00	Increasing tidal regime 1.00	Upstream flooding 1.00	Water quality 1.00	Estuarine flora and fauna 1.00	Indigenous heritage 1.00	In-water recreation 1.00	Foreshore recreation 1.00	Capital cost 1.00	Ongoing costs 1.00	Unweighted Score	Rank
34	Install aquaculture on the northern bank, downstream of the bridge (reduce vulnerability to erosion)	3	3	3	3	3	3	3	3	5	4	33.0	11
36	Periodically place sand between the training walls to shallow the entrance, repeat when eroded by tidal or flood velocities (increase sediment supply into entrance channel to increase head loss via friction)	2	5	1	2	5	4	5	3	4	2	33.0	11
48	Building a series of engineered, stabilised islands (perhaps protected by oyster bags/reefs) in the flood-tide delta (head loss by choke point)	5	5	1	2	5	4	2	5	2	2	33.0	11
11	Construction of an artificial reef or other structure seaward of the training walls to disturb the ebb tide jet and restrict the entrance (head loss by choke point)	4	4	2	3	4	4	4	3	2	2	32.0	17
12	Disguised gate structures across the channel beneath the bridge to fine tune flow (with scour protection of surrounds) (flow control by choke point)	5	5	2	2	5	4	2	3	1	3	32.0	17
18	Large concrete culvert weir all the way across the channel beneath the bridge + new boat ramp upstream (flow control by choke point)	5	5	1	2	5	4	2	3	2	3	32.0	17

Table C-1 Unweighted multi criteria analysis results (sorted by increasing rank) (cont.)

		Criteria											
	Management option	Foreshore and bed erosion	Increasing tidal regime	Upstream flooding	Water quality	Estuarine flora and fauna	Indigenous heritage	In-water recreation	Foreshore recreation	Capital cost	Ongoing costs	Unweighted Score	Rank
Ref.	Description	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00		
26	Retractable overshot weir that could be lowered during a flood (SmartGate / Thames Barrier) (flow control by choke point)	5	5	2	2	5	4	2	3	1	3	32.0	17
45	Remove northern training wall only	5	5	1	2	4	5	1	1	4	3	31.0	21
5	Stabilise the existing shoreline by installing large deep structures (e.g. concrete caissons) along both sides of the entrance channel to account for the assumed future channel deepening	4	3	3	4	3	2	3	4	2	3	31.0	21
50	Temporarily close the entrance (rock bags could be used), re-engineer the entrance channel with protection/nourishment and then re-open the entrance	5	5	1	2	5	4	2	3	3	1	31.0	21
44	Remove both training walls (return to pre-2007 conditions)	5	5	1	2	4	5	1	1	3	3	30.0	24
31	Construction of mangrove forest at the western end of the entrance to increase roughness (head loss via friction along a channel stretch)	5	5	1	3	5	2	2	4	2	1	30.0	24
33	Create intertidal/wetland area in the flood-tide delta with different zones for different ecosystem services (head loss via friction along a channel stretch)	5	5	1	3	5	2	2	4	2	1	30.0	24

Table C-1 Unweighted multi criteria analysis results (sorted by increasing rank) (cont.)

Ref.	Management option	Criteria										Unweighted Score	Rank
		Foreshore and bed erosion	Increasing tidal regime	Upstream flooding	Water quality	Estuarine flora and fauna	Indigenous heritage	In-water recreation	Foreshore recreation	Capital cost	Ongoing costs		
	Description	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00		
39	Rehabilitation of historical seagrass beds for stabilisation (head loss via friction along a channel stretch)	3	3	1	3	5	3	5	3	3	1	30.0	24
40	Sand transfer in ongoing campaigns via dredging ship or truck movements (increase sediment supply into entrance channel to increase head loss via friction)	2	4	2	3	4	4	4	3	3	1	30.0	24
2	Construct a more efficient central channel (via internal training walls) to keep the main tidal flow away from existing banks	3	4	2	3	4	2	4	5	1	1	29.0	29
28	"Sand shifter" network to capture littoral drift on Windang Beach (similar to Noosa) and/or sand deposited on the flood-tide delta to be pumped back into the entrance (increase sediment supply into entrance channel to increase head loss via friction)	2	4	2	3	4	3	4	3	3	1	29.0	29
29	Actively dredge sand from the flood-tide delta and place it back into the entrance in an ongoing fashion to restrict tidal flows (increase sediment supply into entrance channel to increase head loss via friction)	2	4	2	3	4	3	4	3	3	1	29.0	29
32	Construction of oyster reefs at the western end of the entrance to increase roughness (head loss via friction along a channel stretch)	5	5	1	3	5	2	2	3	2	1	29.0	29

Table C-1 Unweighted multi criteria analysis results (sorted by increasing rank) (cont.)

Ref.	Management option	Criteria										Unweighted Score	Rank
		Foreshore and bed erosion	Increasing tidal regime	Upstream flooding	Water quality	Estuarine flora and fauna	Indigenous heritage	In-water recreation	Foreshore recreation	Capital cost	Ongoing costs		
	Description	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00		
37	Place a large volume of sand between the training walls to block the entrance, repeat when eroded by flood velocities (total closure)	2	5	1	2	4	4	1	3	4	2	28.0	33
4	Place rock on the bed along the entire entrance channel (training walls to lake) to stabilise the channel bed	4	4	2	3	3	2	4	3	1	1	27.0	34
20	Move one of the training walls to widen the distance between them (reduce tidal velocities by increasing flow area)	1	1	4	4	1	1	2	1	3	5	23.0	35