DEPARTMENT OF PLANNING, INDUSTRY & ENVIRONMENT

Form and function of NSW intermittently closed and open lakes and lagoons

Implications for entrance management

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Contents

List of tables

List of figures

List of photos

About this document

This document provides a technical background to the factors controlling entrance dynamics of intermittently closed and open lakes and lagoons (ICOLLs), how entrance dynamics affect water quality and ecology, and the likely consequences of different management interventions.

The primary audiences are natural resource and flood risk managers, local and State government authorities and agencies, and water industry professionals. It provides a precis of the characteristic geomorphic, hydrological and ecological features common to ICOLLs, with a particular focus on the interactions between entrance dynamics and these features.

While we present conceptual models that convey some of the commonalities among ICOLLs, there is an underlying understanding that these systems are all unique due to their own blend of environmental factors, and consequently each will react a bit differently to outside influences.

NSW ICOLLs – a unique waterway type

Photo 1 **Tallow Creek in northern New South Wales**
Photo: A Ferguson/DPIE

'Intermittently closed and open lakes and lagoons' (ICOLLs) is a generic term for a distinct type of estuary with a tendency for the ocean entrance to close during periods of low freshwater inflow. ICOLLs are found in mid-latitude countries worldwide, including Australia, South Africa, and Mexico (McSweeney et al. 2017), and they account for more than 60% of the 184 estuaries along the NSW coast (Roper et al. 2011). NSW ICOLLs share a set of common morphological and hydrological attributes, however the relative size and expression of these attributes varies greatly among systems (Maher et al. 2011). This variability presents challenges in generating a universal understanding of the hydrological and ecological functions of ICOLLs, and in turn understanding the unique aspects of individual systems. However, the ubiquity of some features does allow a degree of generalisation about responses to external factors.

Urban areas along the NSW coast are often situated around ICOLLs, leading to a need for local councils to manage issues such as flooding and community perceptions of 'poor' water quality. Historically, these issues have been addressed by manipulating ICOLL entrances (e.g. artificial opening and berm alteration), either opportunistically or in compliance with State legislation. However, there is recognition that entrance manipulation can cause a range of unintended negative impacts and costs, which must be weighed against the real and perceived benefits of intervention. It is increasingly clear that a 'one size fits all' approach to entrance management is not appropriate for such highly diverse systems, and there is a need for a more tailored approach based on system-specific attributes.

The purpose of this document is to provide a review of the form and function of ICOLLs, factors that contribute to how entrances behave, and the acute and chronic effects of entrance management on hydrodynamics, habitats and biota. We provide guidance on ICOLL entrance management principles and strategies, consistent with the *Coastal Management Act 2016* and the NSW Coastal Management Manual, to facilitate informed decision-making which accounts for the unique properties of individual systems.

Conceptual model of NSW ICOLLs

The form and function of NSW ICOLLs stems from interactions between aspects of their regional setting (e.g. geology, climate and wave climate), which in turn influence the stage of sedimentary infilling, or 'geomorphic evolution' of the ICOLL basin (Roy et al. 2001). This section provides a brief overview of these factors and how they relate to ICOLL entrance dynamics and the types of functional zones and habitats present.

Geomorphic evolution

All NSW estuarine systems have undergone 'geomorphic evolution' which refers to the infilling of paleovalleys with Quaternary sediments since the end of the post-glacial marine transgression some 5000 years ago (Chapman et al. 1982). The stages of evolution for saline coastal lakes, from 'youthful' (coastal embayment) to 'mature' (completely infilled) are summarised in Figure 1 (Roy 1984; Roy et al. 1980). This conceptual model shows the formation of the different habitats that are recognisable to various degrees in all NSW ICOLLs. The present-day form of ICOLLs (i.e. the relative extent of these habitats) reflects the degree of natural infilling (i.e. maturity) which is dependent on the rate of terrigenous sediment supply and the morphology of the paleovalley – which controls the capacity for trapping these sediments. For example, prevalence of immature ICOLLs with large, deep central basins along the NSW South Coast reflects a combination of small catchments constrained by the close proximity of the Great Dividing Range to the coast, and generally low rainfall relative to the rest of the coast. In contrast, larger catchments and higher rainfall along the northern NSW coast has resulted in a predominance of large, mature riverine estuaries, with ICOLLs limited to smaller interdunal systems.

Geomorphic classification

NSW estuaries have previously been classified by Roy (1984) according to their entrance conditions as: drowned river valley estuaries, barrier estuaries, and saline coastal lakes. Drowned river valley estuaries are permanently open to the ocean with generally deep, subaqueous tidal deltas, while barrier estuaries and saline lakes exist behind coastal sand barriers that can impede the efficiency of the ocean entrance or cause it to close. Coastal sand barriers are common features along wave-dominated coastlines, where the littoral drift and build up of barrier sands exceeds the scouring actions of tide and fluvial discharges. ICOLLs are considered to belong to the saline coastal lake category of Roy (1984), and are included in the 'intermittent estuary' classification of Roy and Haines (Roy et al. 2001; Haines 2006). Some larger coastal lakes with intermittent entrances may also fit the barrier estuary classification (Roy 1984; Roy et al. 1980). More recently, the classification of NSW estuaries has been revised to recognise distinct subtypes of ICOLL within the wave-dominated, intermittent class based on flushing times, freshwater inflow relative to ICOLL volume, and water quality (Roper et al. 2011; Scanes P et al. 2020; Scanes P et al. 2017):

1. lakes
2. back dune lagoons (BDLs)
3. lagoons
4. creeks.

These ICOLL subtypes have distinct morphometric and hydrological characteristics that can be attributed to their stage of sedimentary infilling. According to the geomorphic evolution model (Figure 1), systems become shallower and more channelised ('linear') as they mature and the central basin infills. Channelisation can be approximated by the waterway perimeter divided by the waterway area (Figure 2), indicating that the geomorphic age of ICOLL subtypes from youthful to mature is generally lakes < BDLs < lagoons < creeks.

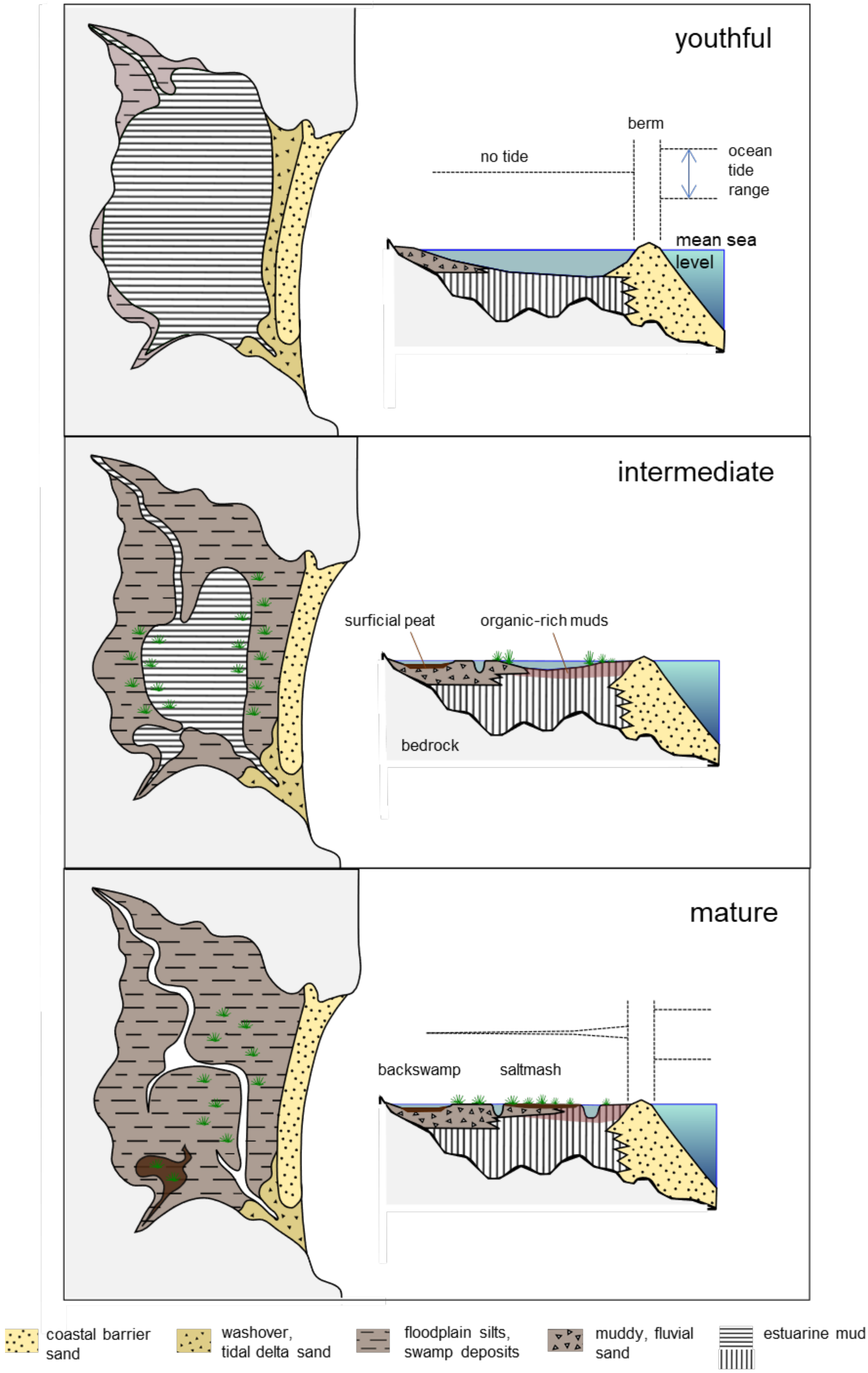


Figure 1 **Stages of infilling in the geomorphic evolution of a NSW ICOLL**

Adapted from Roy 1984.

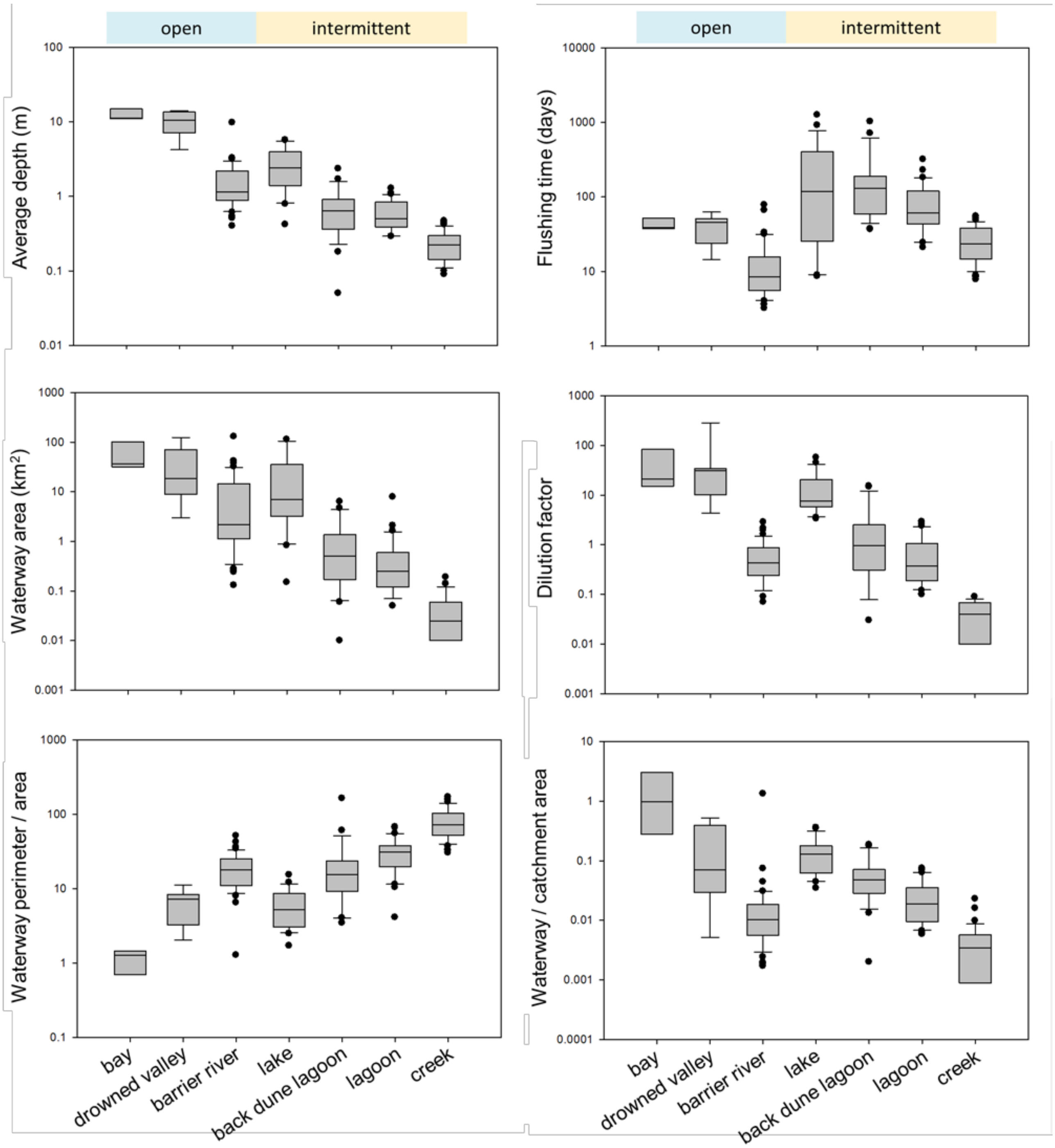


Figure 2 **Statistical summary of morphometrics and hydrology of the different estuary types in New South Wales**

Note: The ICOLL subtypes are grouped within the 'intermittent' entrance class.

ICOLL subtype classifications

The clear morphometric differences among ICOLL subtypes arising from their stages of geomorphic evolution has a range of implications for entrance dynamics, water quality, habitat distribution and ecological function. These implications will be further detailed in subsequent sections of this report, however it is pertinent at this stage to highlight the need for managers to account for these morphometric attributes when dealing with particular ICOLLs. Grouping ICOLLs in distinct subtypes with similar properties allows partitioning of variability in important drivers, because variability within subtypes is minimised and differences between subtypes are maximised (Roper et al. 2011). This classification allows for:

- increasing the understanding of ICOLL processes and functions
- avoiding making invalid comparisons between unlike systems
- identifying and prioritising conservation and management efforts
- guiding research.

A full list of NSW estuaries showing details of class, subtype and morphometrics is provided in Appendix A. Names of estuaries (e.g. Lake Wollumboola) are not a good indicator of their subtype classification (in this case, a back dune lagoon).

Distribution of ICOLL subtypes in New South Wales

ICOLLs account for 57%, 58% and 76% of the estuary systems in the northern, central and southern regions of New South Wales respectively (Figure 3). The distribution of ICOLL subtypes varies significantly among regions, reflecting factors such as geology and rainfall. Large lakes dominate in the central region, while lagoons are more prevalent in the northern region. The southern region has the highest occurrence of BDLs and creeks. More detail on the classification of individual ICOLL systems is provided in Appendix A.

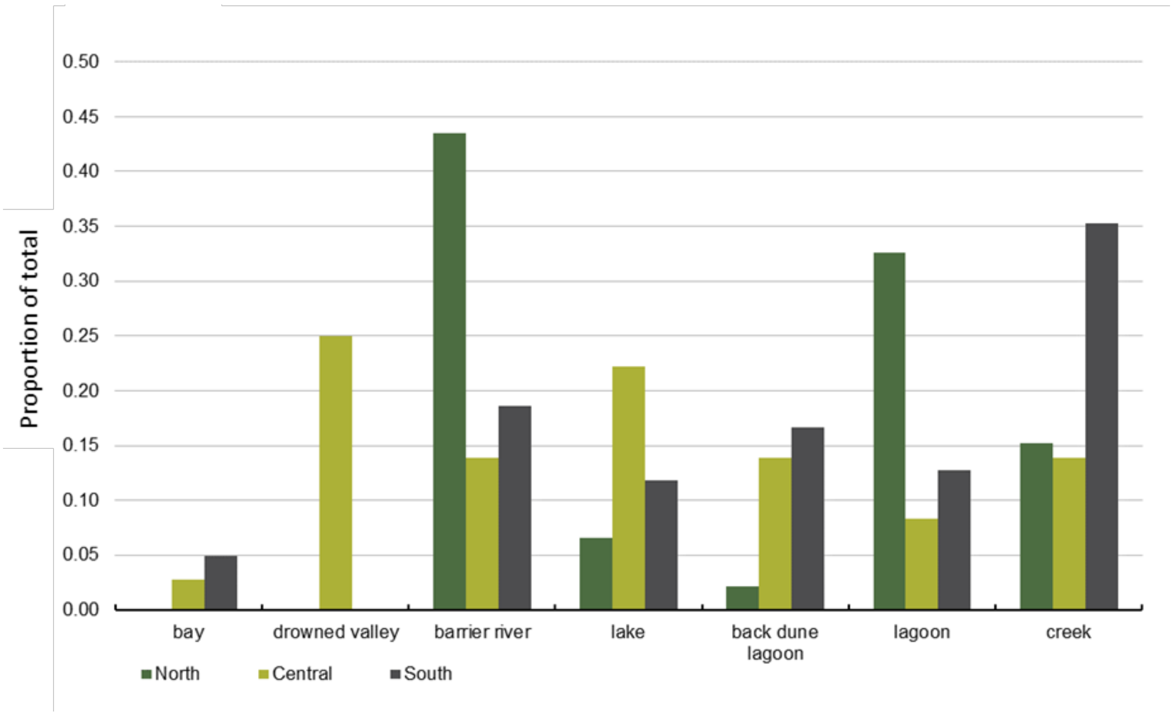


Figure 3 **Distribution of different estuary types among the northern, central and southern regions of the NSW coast**

Functional zones and habitats of ICOLLs

The habitat zonation used throughout this document is largely based on the distribution of depositional sedimentary environments common to NSW estuaries as proposed by Roy (Roy et al. 2001), with modifications to better describe some of the distinct aspects of ICOLLs. The distribution and characteristics of these zones are detailed in Figure 4 and Table 1. Each ICOLL will display its own unique mix of these environments (e.g. Table 2) according to factors such as geological setting (e.g. catchment size and lithology, paleovalley morphology), and latitude (rainfall, wave climate).

Shallow water shoals of the flood-tide delta reach are characterised as relatively 'active' (i.e. subject to high bed shear stress and mobilisation by tidal currents or wind-wave energy), or 'stable' (i.e. their depth and extent remains relatively constant over monthly to yearly timescales allowing colonisation by macrophytes). Within the basin, shallow water shoals are subject to significant wind-wave energy which tends to result in relatively sandy substrate as fine material is suspended and deposited in the deep basin.

While the ICOLL entrance is open, hydrological processes and water quality gradients are influenced by tidal exchange, freshwater runoff and groundwater inputs. Semidiurnal tidal influence tends to be greatly attenuated by frictional losses across the flood-tide delta shoals, with much larger tidal signals due to fortnightly tides (spring tide pumping) and sea level anomalies (see 'Water exchange due to tides', below, for more detail).

Table 1 ICOLL functional zones and their subenvironments

Functional zone	Subenvironments	Substrate types	Hydrological processes
Flood-tide delta reach	• 'Active' shoals • 'Stable' shoals • Tidal flats • Flood/ebb tide channels	Marine sands Aeolian sands Muddy sands	*Open*: tidal variation in water quality, exposure of shallow shoals *Closed*: water gradually mixes with basin due to wind; water depth varies as a function of freshwater inflows and evaporation
Central basin	• Deep basin floor • Shallow fringing shoals • Shorelines • Rocky shorelines • Reefs	Organic-rich mud Sandy mud Muddy sand	*Open*: main variation in depth and water quality due to sea level anomalies and spring tide pumping *Closed*: water quality gradients broken down by wind-driven mixing; water depth varies as a function of freshwater inflows and evaporation
Fluvial-influenced reach	• Levees • Distributary channels • Mid-channel shoals • Delta shoals • Riverine channel • Point bars • Mid-channel bars	Fluvial sand Muddy sand Sandy mud	*Open*: salinity gradients may form during runoff events *Closed*: water quality gradients broken down by wind-driven mixing; water depth varies as a function of freshwater inflows and evaporation
Alluvial plain (fringing wetlands)	• Floodplain • Saltmarsh • Backswamp • 'Swamp forest'	Silt Sand Clay Peat	*Open*: intermittent inundation during high sea level anomalies and spring tides *Closed*: intermittent inundation during rainfall events

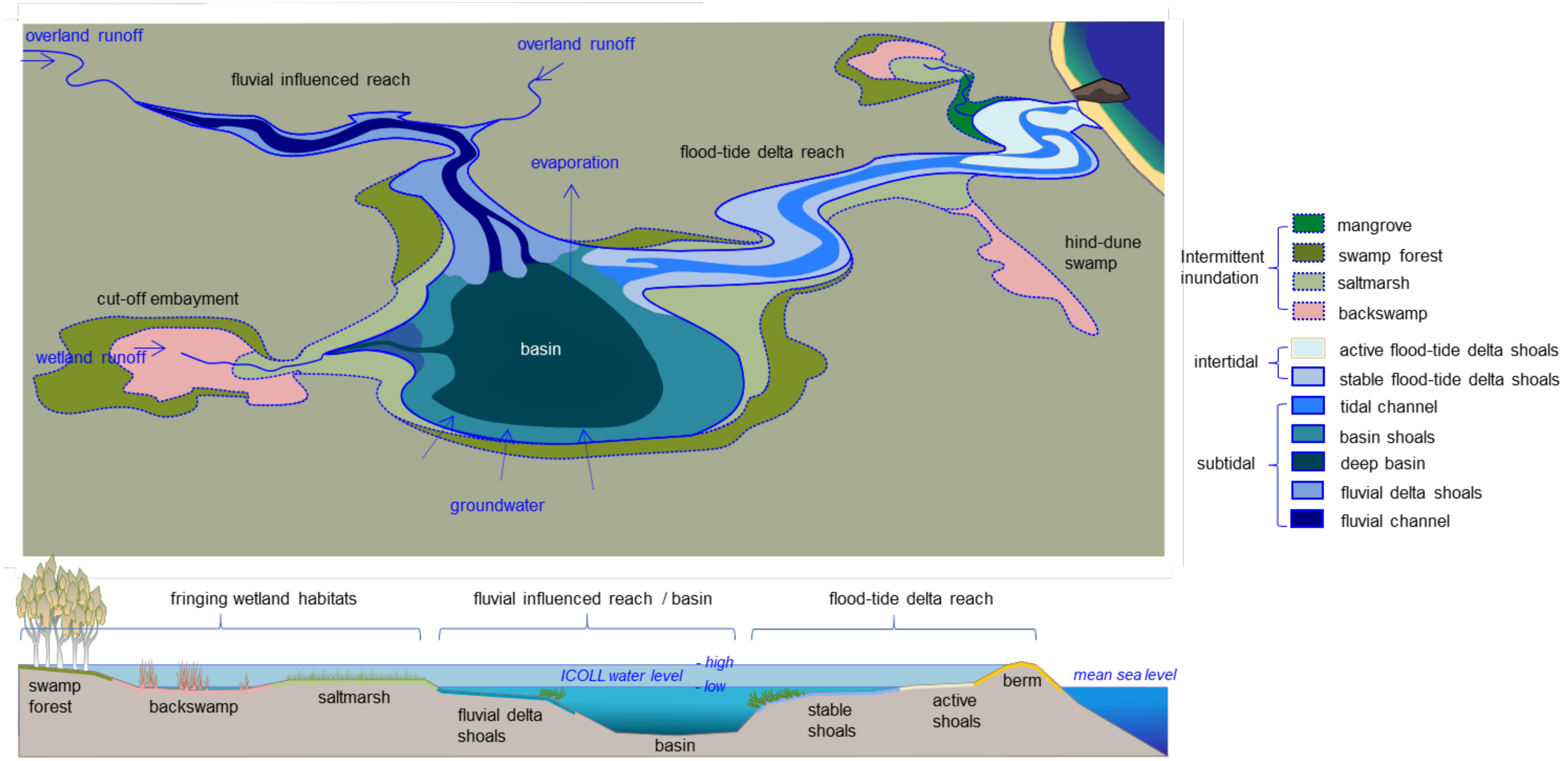


Figure 4 **Idealised ICOLL showing the distribution of key functional zones and subenvironments**

Table 2 Functional zone characteristics of ICOLL subtypes present in New South Wales

ICOLL subtype	Functional zones	Setting and entrance conditions
Lakes	• Youthful to intermediate • Extensive flood-tide delta • Deep central basin • Extensive fluvial reach • Limited alluvial plain and fringing wetlands	• Mainly occur in higher relief coastlines of the NSW south coast and central coast (many examples now have trained entrances) • Natural entrances predominantly open for more than 80% of the time, but depends on nearshore sand supply • Lake entrances in the lee of rocky headlands (e.g. Burrill Lake) close less frequently due to reduced wave influence (hence lower onshore sand transport and entrance infilling) compared to entrances on sandy coastlines (e.g. Lake Conjola) • 30% of lakes have training walls which prevent closure
Back dune lagoons	• Youthful to intermediate • Small flood-tide delta • Partially infilled shallow central basin • Infilled fluvial reach • Limited alluvial plain and fringing wetlands	• Generally form in smaller high-relief coastal catchments that limit alluvial floodplain development • Entrances predominantly closed for more than 80% of the time • Entrances tend to close rapidly after breakout due to small freshwater inputs relative to onshore sand supply • Significant groundwater influence likely
Lagoons	• Intermediate to semi-mature • Intermediate flood-tide delta • Open central basin with extensive shallow fringing shoals • Infilled fluvial reach with fluvial delta • Fringing wetlands confined by floodplain infilling	• Northern region examples tend to form in hind dune depressions of low-relief Holocene/Pleistocene barrier coastlines • Southern region examples similar to BDLs but with larger catchments • Entrances predominantly closed for more than 80% of the time, but this depends on nearshore sand supply
Creeks	• Semi-mature to mature • Intermediate flood-tide delta • Shallow linear central basin • Infilled fluvial reach • Extensive alluvial plain and fringing wetlands	• Generally form in hind dune depressions of low-relief Holocene/Pleistocene barrier coastlines of NSW north coast • Entrances predominantly closed for more than 80% of the time • Entrances tend to close rapidly after breakout due to small freshwater inputs relative to onshore sand supply • Groundwater influence likely • 10% of creeks have training walls

NSW climate – important driver of ICOLL dynamics

The defining characteristic of ICOLLs (i.e. an intermittently closed or open entrance) is in large part controlled by the highly variable rainfall climate of eastern Australia balanced against the persistent moderate- to high-energy coastal wave climate. The former is characterised by muted seasonal variability, high interannual variability, and long period (multidecadal) climatic cycles (Erskine & Warner 1978; Speers et al. 2011; Verdon et al. 2004). A nuanced understanding of the interactions among these temporal scales in rainfall variability is key to understanding ICOLL processes and managing community expectations around ICOLL water levels and entrance management.

Rainfall along the NSW coast

In general, NSW coastal rainfall is highest along the Tweed coast and decreases moving south, with the lowest annual rainfall occurring along the Merimbula region of the far South Coast (Figure 5). In addition to this latitudinal trend, there are parts of the coast that receive substantially less rainfall (e.g. the Clarence region).

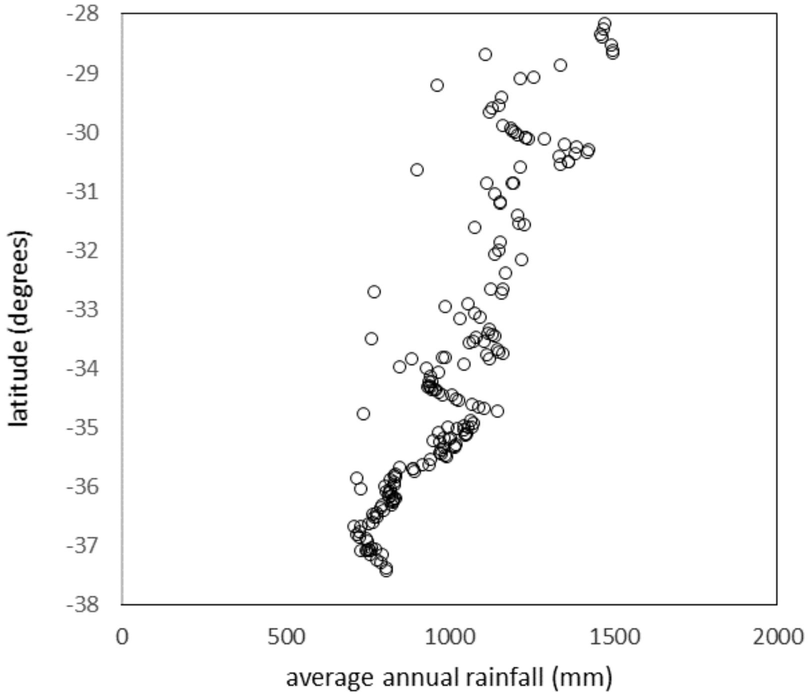


Figure 5 **Average annual rainfall for each of the 184 estuary catchments along the NSW coast**

Note: the average annual rainfalls presented in Figure 5 are derived from the weighted mean of all available rainfall stations within each of the 184 estuary catchments in New South Wales, and therefore integrate many more inland rainfall stations with lesser rainfall for the larger catchments (e.g. the Clarence River). Hence these catchments are estimated to receive less rainfall per unit area over the entirety of their extent.

Seasonal rainfall

There is a trend for highest rainfall totals during the late summer–autumn period along much of the NSW coast, with this pattern being strongest along the central to northern coastlines. The cumulative seasonal rainfall totals combined with lower evapotranspiration rates during autumn mean that ICOLL water levels are generally high and therefore approaching berm levels and potential breakout thresholds. Major rainfall events with the potential to trigger an entrance breakout tend to be episodic and can occur at any time of the year (e.g. September and October 2018 in Figure 6), however long-term statistics show these events are more likely to occur during late summer–autumn in association with major storm systems (e.g. east coast lows and cyclones).

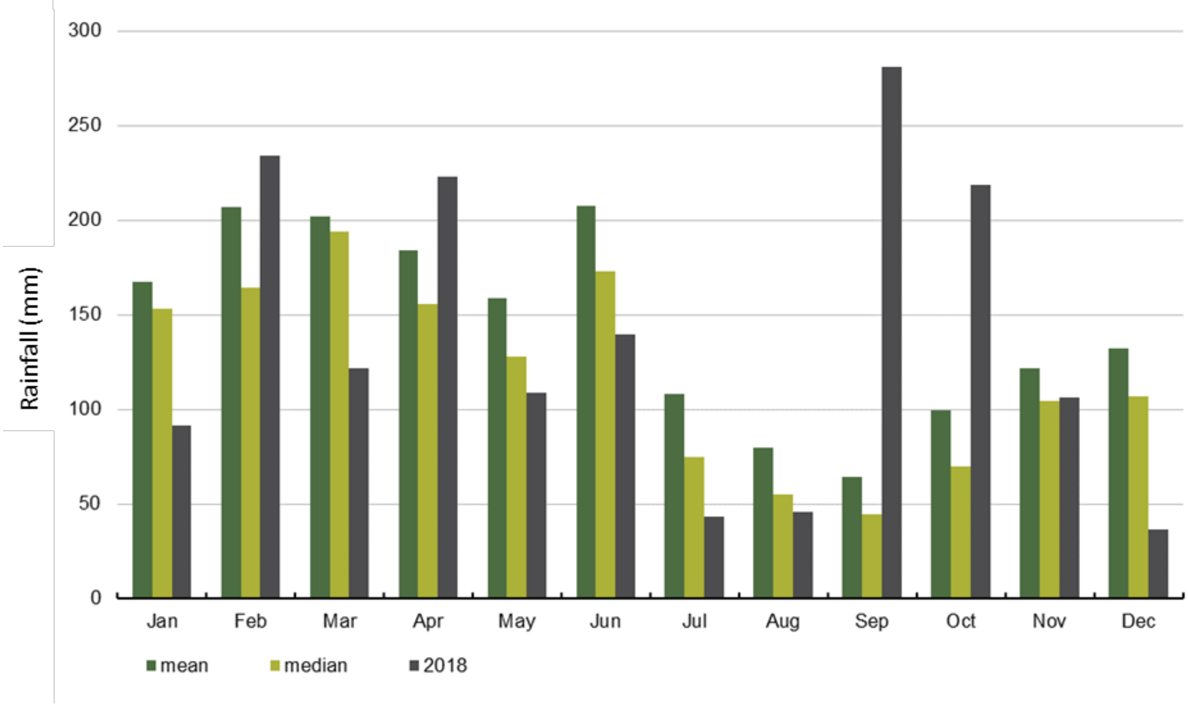


Figure 6 **Long-term rainfall statistics for Ballina Airport, showing the effects of two unseasonally high rainfall events during 2018**

Source: Bureau of Meteorology (BOM).

Interannual variability

Rainfall along the NSW coast exhibits high interannual variability over two- to five-year timescales due to the influences of fluctuations in the Southern Annular Mode (SAM), El Niño–Southern Oscillation (ENSO, Figure 7) and Indian Ocean Dipole (IOD). The SAM describes the north–south shift of a consistent band of westerly wind flows across the Southern Hemisphere that circle the South Pole. A shift towards the equator (negative phase) typically causes increased westerlies, unsettled weather, and storms in south-east Australia and New Zealand. In general, a sustained positive ENSO index (termed a La Niña event) results in above-average winter–spring rainfall along the NSW coastline and higher likelihood of cyclone formation in the Coral Sea.

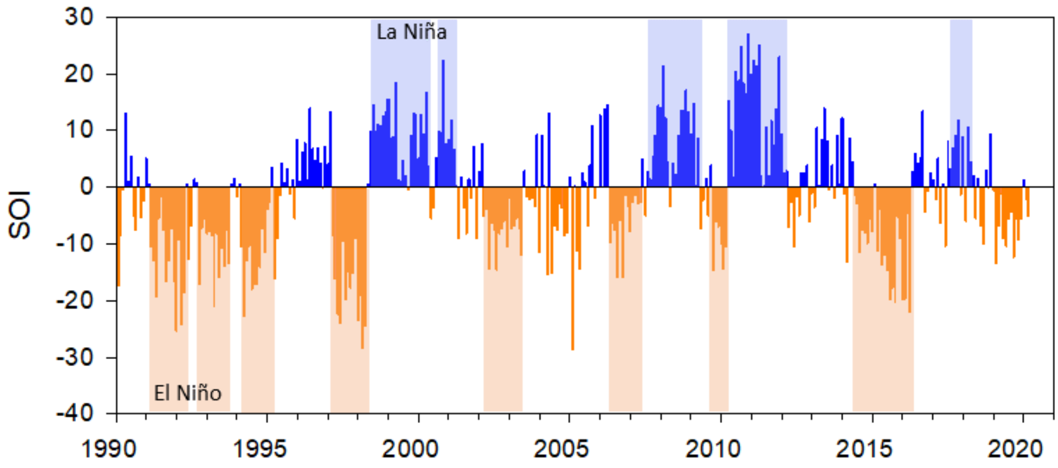


Figure 7 **Interannual variation in the Southern Oscillation index (SOI) since 1997**
Source: BOM.

A negative IOD event results in greater connectivity between moist air emanating from warm waters off north-west Australia and south-east Australia leading to an increased chance of rain, especially along the southern NSW coast. When La Niña and negative IOD events coincide, the chance of above-average rainfall is greatly increased.

Longer period climatic cycles

There is evidence of longer period climatic cycles affecting rainfall along the NSW coast. Bureau of Meteorology records since 1860 show that a 'severe' drought has occurred on average every 18 years (Figure 8), while an analysis of flood records from the Hawkesbury Nepean and Richmond rivers has demonstrated the occurrence of 50-year flood- and drought-dominated cycles (Erskine & Warner 1978). Multidecadal trends in rainfall are known to be linked to the Interdecadal Pacific Oscillation (IPO) which is an oceanographic/meteorological phenomenon that describes the differential between tropical and northern Pacific Ocean temperatures. A negative IPO phase (cooler tropics and warmer northern regions) is associated with above-average rainfall along the NSW coast and Victoria. The IPO has a period of roughly 20–30 years, and when a negative IPO phase coincides with a La Niña event, rainfall increases are further magnified (Verdon et al. 2004). There is also a clear latitudinal effect on multidecadal rainfall trends due to variable influences among the primary climatic drivers along the NSW coast (Figure 8).

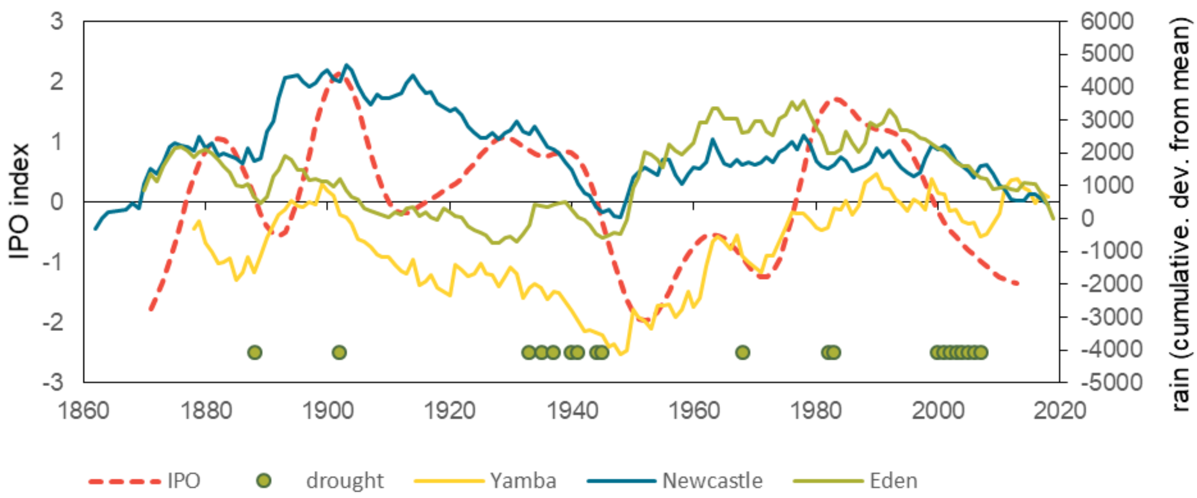


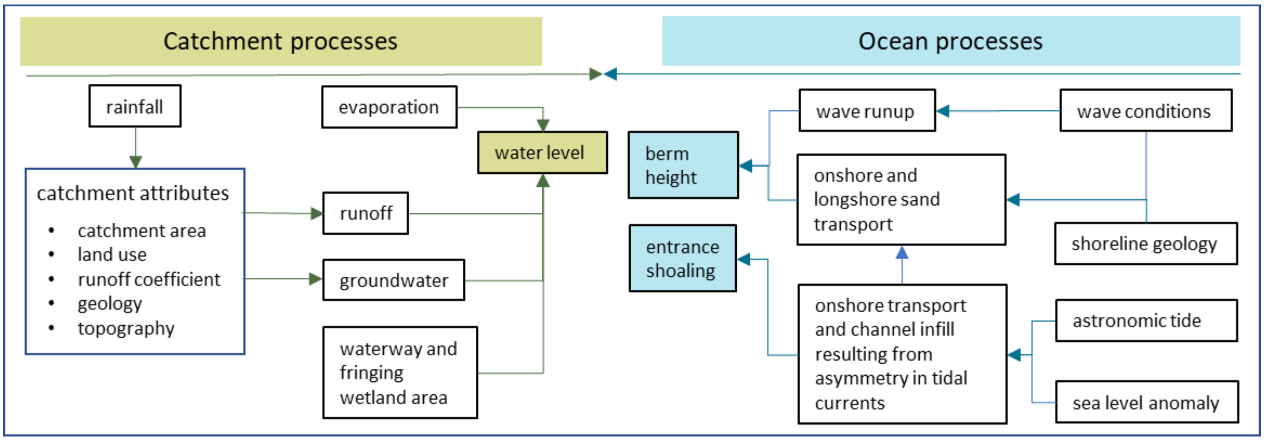
Figure 8 **Average annual Interdecadal Pacific Oscillation index[1] and cumulative deviation from the mean for annual rainfall totals at Yamba, Newcastle and Eden**

Also shown are major drought years for south-east Australia.

The occurrence of these longer period climatic cycles has significant implications for the dynamics of ICOLL entrances, particularly in systems with a low closure index, as the frequency of closure may closely align with decadal trends in drought occurrence. Climate change is likely to reduce overall rainfall totals, but increase the severity and frequency of major events. Extended entrance closures resulting from long-period climate cycles are likely to be outside the 'community memory' of conditions and so generate significant community pressure to fix perceived problems that have not been apparent before.

ICOLL entrance dynamics

The dynamics of ICOLL entrances (i.e. the proportion of time that systems remain closed and the frequency with which they may open and close) are determined by the interactions between the opposing forces of catchment and ocean processes on the movement and accumulation of sand at the flood-tide delta, entrance berm and nearshore (Figures 9 & 10).



[1] https://data.mfe.govt.nz/table/52591-annual-average-interdecadal-pacific-oscillation-index-18712013/.

Figure 9 **Conceptual diagram of the processes that control entrance dynamics in ICOLLs**

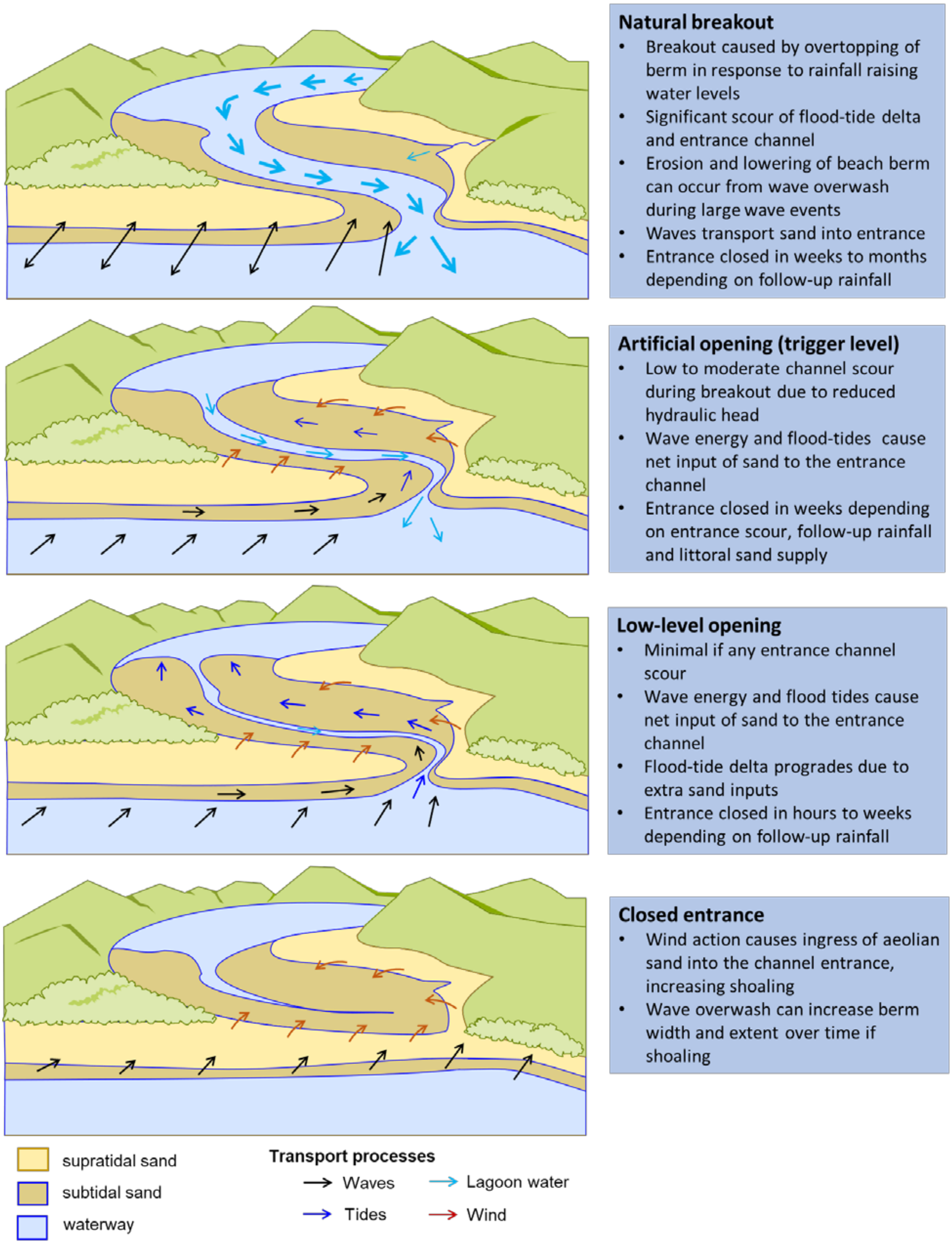


Figure 10 **Conceptual diagram of the processes that control entrance dynamics in ICOLLs**
Graphics: R Laine/DPIE

Entrance breakout

This section provides an overview of factors relevant to ICOLL entrance dynamics with respect to natural and artificial breakout regimes. Natural breakout is defined as entrance opening without any human intervention or modification of the berm, while artificial openings are defined as those resulting from direct mechanical channel dredging, or berm modification by activities such as ‘scraping’ to reduce berm height to a prescribed level.

Natural breakout

Under natural conditions, ICOLLs breakout over a relatively wide range of levels known as the ‘natural breakout range’. Natural breakout of ICOLLs occurs when either: 1) rainfall in the catchment causes ICOLL water levels to exceed the berm height leading to breaching and channel formation, or 2) occasionally in response to wave overwash during storms. The rise in ICOLL water levels depends on the total freshwater inputs divided by the total area of the receiving waterway and the area of fringing wetlands below the level of the berm (i.e. the flood storage, see Figure 11). The flood storage volume can be estimated as the sum of areas within discrete elevation ranges (i.e. ‘hypsometry’).

In cases where there has been no artificial reduction in berm height (e.g. through mechanical scraping), the berm can build up significantly, meaning that when overtopping occurs (either in response to large rainfall events or the gradual increase in water level in response to multiple smaller rainfall events) the large potential hydraulic head will result in significantly greater channel scour (see ‘Channel formation …’ below). Due to differences in wave runup, berms are typically higher on steep beaches with coarser sand as compared with fine-grained flatter beaches. ICOLLs on steep beaches therefore have greater head and scour potential (depending on berm width). The potential hydraulic head is defined here as the difference between ICOLL water level and mean sea level at the time of breakout. The actual hydraulic head is more dynamic, because in practice the sea level is variable over timescales of minutes to days due to interactions among factors such as state of tide, water level anomalies, wave runup, and setup (defined below as ‘storm surge’).

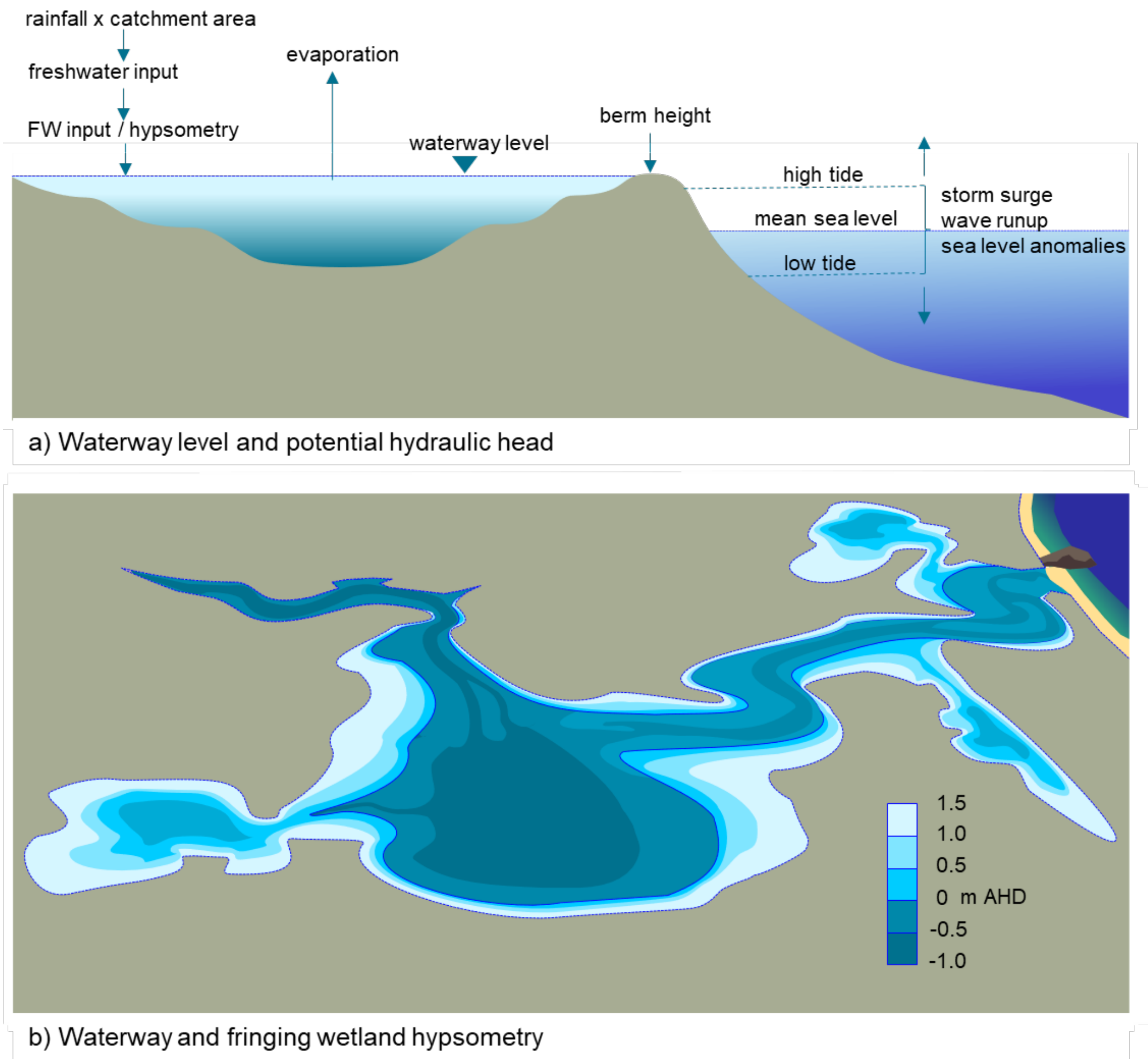


Figure 11 **Factors that determine the hydraulic head at the time of entrance breakout in ICOLLs**

Artificial opening

There are two modes of artificial entrance opening: high-level opening (seaward-directed hydraulic gradient between ICOLL and ocean), and low-level opening (landward-directed hydraulic gradient between ocean and ICOLL). In both cases, the opening level is generally below the mean natural breakout level and may in some cases be below the natural breakout range. Continued opening at artificially low levels can be expected to have a cascade of impacts on ICOLL hydrology and inundation regimes, with flow-on long-term modifications to vegetation communities and ecological processes.

High-level opening

High-level opening is most commonly undertaken in response to water levels rising above a critical ‘trigger level’ which is set in order to reduce flooding of specific properties and built assets (e.g. roads) within the catchment. Trigger levels for high-level opening are generally well below natural berm levels, meaning that hydraulic head and channel scour are much smaller than for natural breakouts.

Photo 2 **Mechanical opening of Lake Conjola on 10 February 2020**
Photo: D Wiecek/DPIE.

Low-level opening

Low-level opening refers to artificial openings executed during dry weather when ICOLL water levels are generally at or just below mean sea level, resulting in a small landward-directed hydraulic gradient. Low-level opening can be prompted in response to community perceptions about 'poor' water quality and is an attempt to promote the ingress of oceanic water. The general strategy is to excavate a 'dry notch' channel leaving a small plug at the ocean end. A breach is initiated by removing the plug once the ocean level on the incoming tide exceeds the ICOLL level, meaning the hydraulic head has become landward-directed (determined by the difference between high-tide level and ICOLL water level). If the surface area of the waterway is small enough, the ICOLL water level will equilibrate with the water level in the ocean at high tide. On the outgoing tide, the hydraulic head reverses and water flows out until the depth in the entrance channel reduces to the point where friction impedes flow and water is held back in the ICOLL.

Case study – Wonboyn Lake low-level opening

Based on 30- to 50-year timescales, the Wonboyn Lake entrance is open for more than 80% of the time, with a relatively efficient channel to the ocean (Figure 12a). However, during extended multiyear periods of drought which can occur every 15 to 20 years, the entrance channel can become filled with sand, as happened in October 2019 (Figure 12b). A four-month entrance closure led to an increase in lake salinity to 40 PSU (practical salinity unit) due to evaporation. A low-level opening was made on 11 February 2020 under pressure from the local community. The opening coincided with a major rainfall event, however runoff associated with this event did not raise lake levels prior to the opening. A 250-metre long channel was excavated and maintained by on-site excavators for 10 days, however entrance scour was minimal due to the small hydraulic head at the opening and the breach was weak (Figure 12c). After excavators left, the entrance rapidly infilled (Figure 12d) and closed approximately seven days later. Onsite data loggers showed that freshwater inputs lowered the salinity of surface waters while the impact of the low-level opening on water quality in the lake was imperceptible.

a) Wonboyn Lake – predominant state

b) Wonboyn Lake 25th Jan 2020 – extended drought

c) Excavation of the entrance channel 12th Feb 2020

d) Entrance channel just prior to closing 19th Feb 2020

Figure 12 Wonboyn Lake entrance in various conditions

a. Typical open entrance conditions in Wonboyn Lake. Photo: Google Earth; b. Closed entrance after extended drought. Photo: S Blanch; c. Ongoing excavation of channel to maintain an open entrance. Photo: R Duczynski; d) Entrance channel immediately prior to closure. Photo: R Duczynski

Channel formation during natural breakouts

Once initiated by overtopping of the berm during a natural breakout, the form of the channel progresses through a series of definable flow phases that take several hours to develop (Gordon 1981 & 1990; see Figure 13). In this model, the amount of channel scour is a function of depth and width which change as the channel develops, and discharge is determined by cross-section area of the channel and flow velocity. Due to the larger hydraulic head associated with natural breakouts (as described above), the channel scour through the berm and entrance shoals is greater in a natural breakout than from artificial breakouts, resulting in more sand being transported out of the entrance and moved offshore.

Channel formation during artificial openings

High-level opening

The initiation phase of channel formation is often short-circuited by the excavation of a pilot channel. The lower level of entrance breaching and smaller hydraulic heads result in less channel scour and a 'weak breach', meaning that less sand is moved offshore and the entrance is prone to rapid closure.

Low-level opening

The lack of a positive hydraulic head between the ICOLL and ocean means the normal channel development described above does not apply. The small and directionally oscillating hydraulic head (i.e. landwards at high tide and seawards at low tide) during a low-level opening results in minimal channel development and a very weak breach. Under these conditions the entrance will close quickly (usually within days, see Figure 12).

1. Initiation phase	2. Weir phase	3. River flow phase
Subcritical to critical flow F ~ 0.6–1 Overtopping occurs initially as a thin sheet flow. Small channel develops from the crest downslope towards the beach. As channel develops, critical flow develops causing standing waves.	**Supercritical flow** F > 1.0 This phase develops rapidly with the formation of a semicircular weir in the sand at the upstream end of the channel with a plunge pool. Downstream of the weir plunge/pool, a series of hydraulic jumps and associated steps in the channel develop. These features migrate upstream as phase progresses. Channel depth increases rapidly to its maximum, with channel width increasing more gradually.	**Subcritical flow** F < 1 Weir/plunge pool completes its upstream translation and disappears. A steadier flow regime establishes; however, scour of the channel continues at a lower rate as long as threshold conditions are exceeded. As hydraulic head approaches zero the ICOLL becomes tidally dominated.
Limiting factors • Rate of ICOLL water level rise • Berm width and cross-sectional geometry • Porosity of beach • Wave conditions	**Limiting factors** • Actual hydraulic head • Berm width and cross-sectional geometry • Extent of entrance shoals	**Limiting factors** • Lagoon and catchment size • Rainfall intensity and duration

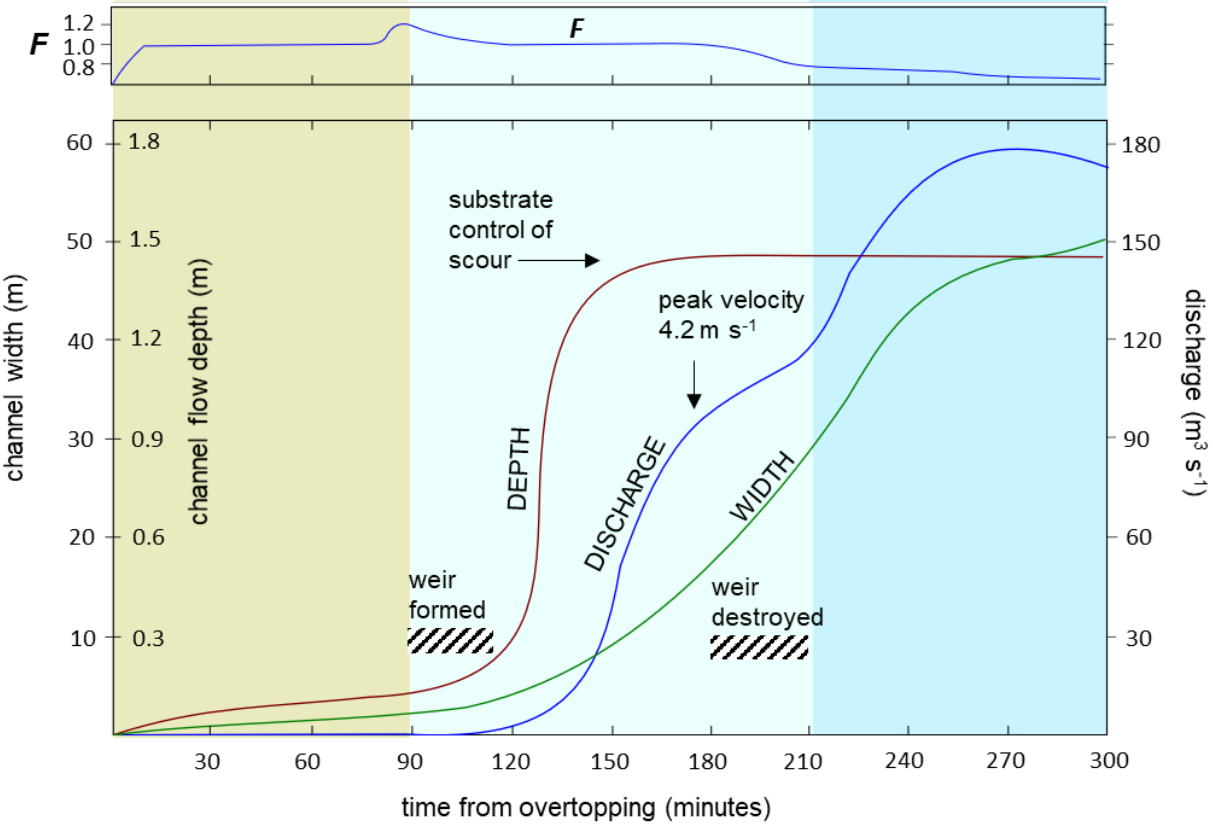


Figure 13 **Three phases of entrance breakout based on data from Dee Why Lagoon**

Source: Gordon 1981. F = Froude Number which describes the transitions between subcritical flows (flow velocity < wave velocity), and supercritical flows (flow velocity > wave velocity).

Photo 3 **Formation of a weir and plunge pool during an artificial opening of Durras Lake**
Photo: D Wiecek/DPIE.

Entrance closure

Natural closure processes

ICOLLs of the NSW coast, when open, are classified as being in an 'unstable shoaling mode' which means they will eventually close in the absence of human intervention. Closure occurs due to the inability of 'self-scouring' processes (freshwater inflows and tidal currents) to clear the entrance channel of sand in opposition to continual coastal processes (both alongshore and onshore transport) which act to move sand into the entrance. In general, the duration the entrance remains open depends on the tidal prism of the ICOLL and the gross sediment transport environment of the adjacent beach and nearshore zone. Major rainfall events help keep entrances open, while ocean storms with large waves potentially accelerate closure.

Tidal processes

Infilling of the entrance channel commences on the first flood tide following breakout, with entrained sand from the surf zone transported into the entrance by tidal currents and deposited in the entrance channel. The ability of ebb-tide currents to export sand from the entrance is limited by the characteristic tidal asymmetry (flood-tide flow velocity > ebb-tide flow velocity), resulting in a net import of sand from the ocean over the tidal cycle. The smaller sand transport potential (export) during ebb tides is exacerbated by the absence of sand entrainment due to wave action. As the entrance channel is increasingly blocked by sand, the degree of tidal asymmetry increases, further promoting the net ingress of sand.

Wave processes

Onshore asymmetry in sediment transport associated with wave-driven process results in the tendency to fill entrance channels and ultimately form a beach. Depending on swell direction and size, wave action during storms can result in the injection of large amounts of entrained sand directly into the entrance, thereby accelerating the action of tides in promoting closure. Once closed, wave runup builds the beach berm usually to some threshold height associated with the sediment characteristics and exposure of the site. During major storms wave overwash may increase berm width and the extent of entrance shoals. During periods of extended closure wind action may also add to berm levels and can also result in the deposition of aeolian sands in the channel and entrance shoals.

Limiting processes

The presence of headlands and rocky reefs can reduce wave influence and restrict or impede the longshore transport of sand, thereby reducing ingress of sand from the ocean and slowing the process of entrance closure. Large, long-period swell events associated with east coast lows (ECLs) and cyclones may result in significant beach erosion and offshore transport of sand from the beach and nearshore zone, reducing the amount of sand available for transport into the entrance.

Berm dimensions

The development of entrance berms after closure is highly variable among systems, depending on localised variation in physical factors such as coastline alignment, position of the entrance relative to geological obstructions (e.g. headlands), and grain size of sand within the local littoral sand compartment (Hanslow et al. 2000). Once an ICOLL entrance is closed, the berm height builds due to inputs of sand from wave and wind action. The height attained during the building period is determined by a number of factors including coastline orientation and the sand within the local compartment. Water level, wave height and period, along with beach slope, are major determinants of wave runup, which builds the beach berm. Berms are typically higher on exposed, steep beaches with coarser sand as compared with fine-grained flatter beaches. Berm width builds over time due to overwash during storms.

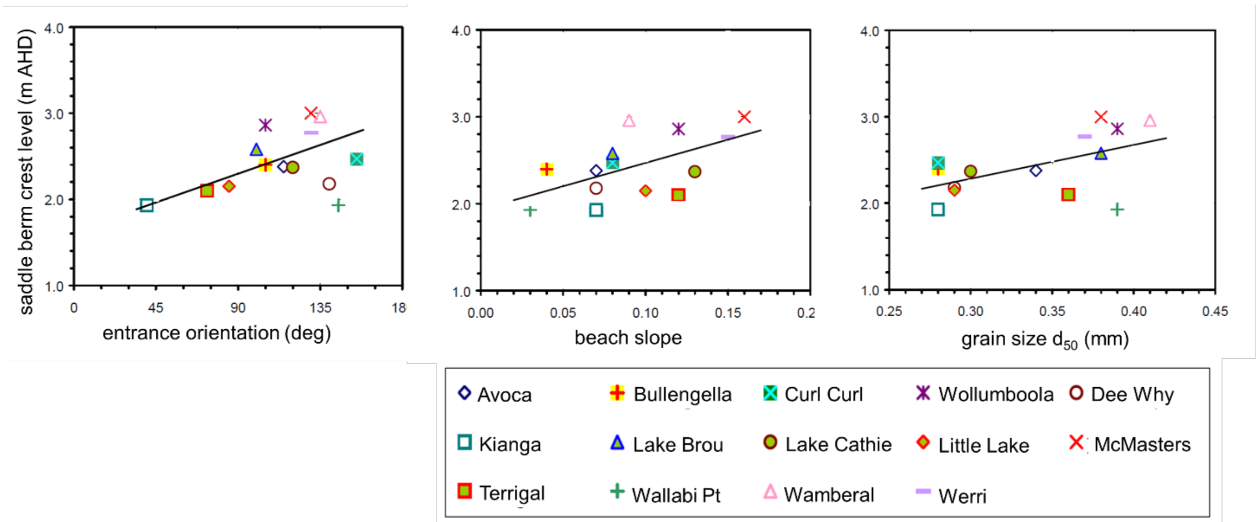


Figure 14 **Relationships between berm height, morphometrics and sand grain size**
AHD = Australian Height Datum; d_{50} = corresponding particle size when cumulative percentage reaches 50%
Source: Hanslow et al. 2000.

Entrance closure following artificial opening

High-level opening

The relatively weak breach behaviour and small channel scour associated with artificial opening at low trigger levels during wet weather means that more sand is carried into the entrance during subsequent flood tides than was scoured during the breakout. This results in a net accretion of sand in the flood-tide delta and entrance shoals. Frequent artificial opening at low trigger levels causes the entrance compartment to become progressively more clogged over time, making ongoing artificial opening increasingly ineffective as breaching velocities decrease with each operation. Eventually this effect can become so severe the entrance will close almost immediately after breaching (e.g. Terrigal Lagoon).

Low-level opening

The reversal of the hydraulic gradient (i.e. the ocean is higher than lake level) during dry weather means that sand will be carried into the entrance by flood-tide flow, with no scour and export of sand during the weaker ebb-tide flows. This will result in a potentially greater net import of sand from the ocean and an even more rapid entrance closure than described for wet weather openings.

Balance between entrance opening and closure

Entrance closure index

The frequency of breakout and the intervening period of entrance closure varies according to system type and depends on local variation in the entrance breakout and closure processes described above. In addition, long-period climatic cycles (e.g. ENSO, IOD, IPO) are important in determining the frequency and severity of large storm events (rainfall and wave conditions) and may therefore influence the frequency and duration of entrance closure over longer timescales, especially in larger ICOLLs (Haines 2006). Haines (2006) categorised 56 systems on the NSW coast in accordance with an entrance closure index (ECI) representing the proportion of time they tend to be closed to the ocean (Figures 15 and 16):

- **Closure index >0.6:** the entrance is closed for more than 60% of the time (e.g. Smiths Lake and Lake Wollumboola).
- **Closure index <0.2:** the entrance is open for most of the time (e.g. Narrabeen Lagoon and Wonboyn Lake). In the case of Narrabeen Lagoon, regular entrance clearance operations are carried out every four to five years which skews the natural ECI. Wonboyn Lake has required minimal intervention over the past three decades and was even classified as having a ‘permanently open entrance’ (WBM Oceanics Australia 2003). However, the dominance of drought conditions over the past 15 to 20 years has seen Wonboyn Lake naturally close more frequently.
- **0.2 < closure index < 0.6:** systems which are in between the first two, including Terrigal Lagoon and Lake Conjola. During the past two decades, concerns relating to flooding and water quality in these systems have resulted in repeated intervention in their entrances.

While all ICOLLs show a tendency to eventually close, there is substantial variation from system to system. Part of this variation can be explained by catchment size (and therefore total freshwater inflows), with smaller systems being predominantly closed and larger systems tending to be predominantly open (Hurrell & Web 1993). This general model is refined by considering the waterway to catchment area ratio (e.g. Figure 2), which accounts for the relative impact of freshwater inflows on water levels within the ICOLL (Haines 2006). Further refinement is made by considering the angle of entrance exposure to prevailing wave climate, which impacts the longshore supply of marine sand. Finally, the presence of geomorphic and human-made controls (e.g. headlands, bedrock, groynes) that interrupt coastal processes (e.g. waves and longshore sand drift) can explain entrance behaviour in some systems.

Closure index of ICOLL subtypes

The ECIs for systems analysed by Haines (2006) have been grouped according to the ICOLL subtype classification (Figure 15). The mean ECIs for these subtypes are consistent with both the geomorphic evolution model (which states that entrances tend to be more open as systems mature), and the first-order model described above (that catchment size is a primary driver of entrance conditions). The interaction between these models accounts for the similarity in ECI between BDLs (younger systems with larger catchments) and creeks (more mature systems with smaller catchments). Overall, ECIs of ICOLL subtypes are best described by variability in catchment size (freshwater inflow).

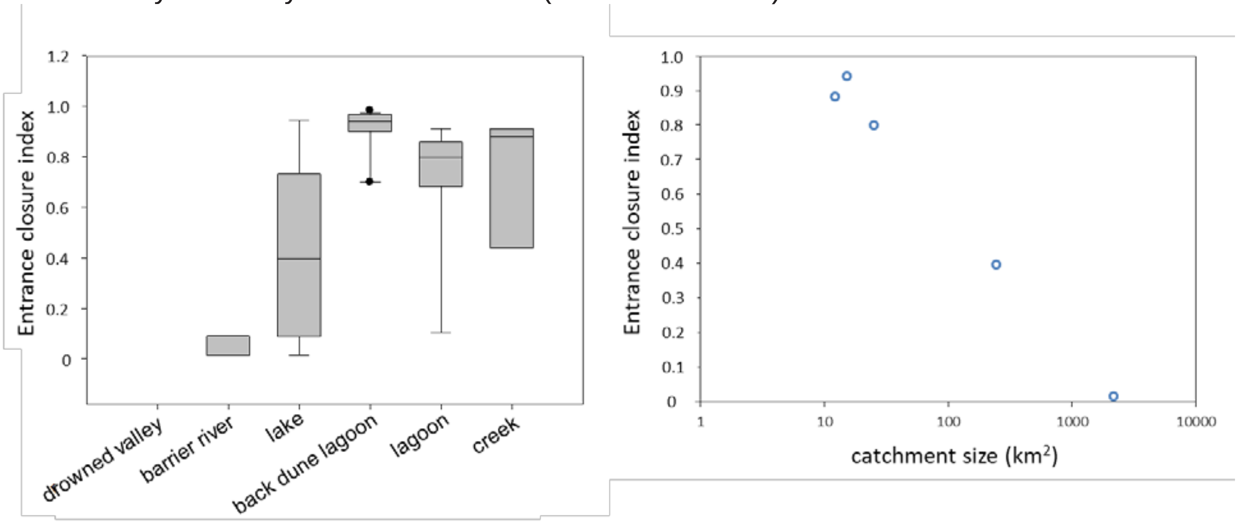


Figure 15 **Entrance closure indexes**

ECIs for the ICOLL subtypes (left), and the relationship between catchment size and ECI (medians of all cases within each subtype) (right).

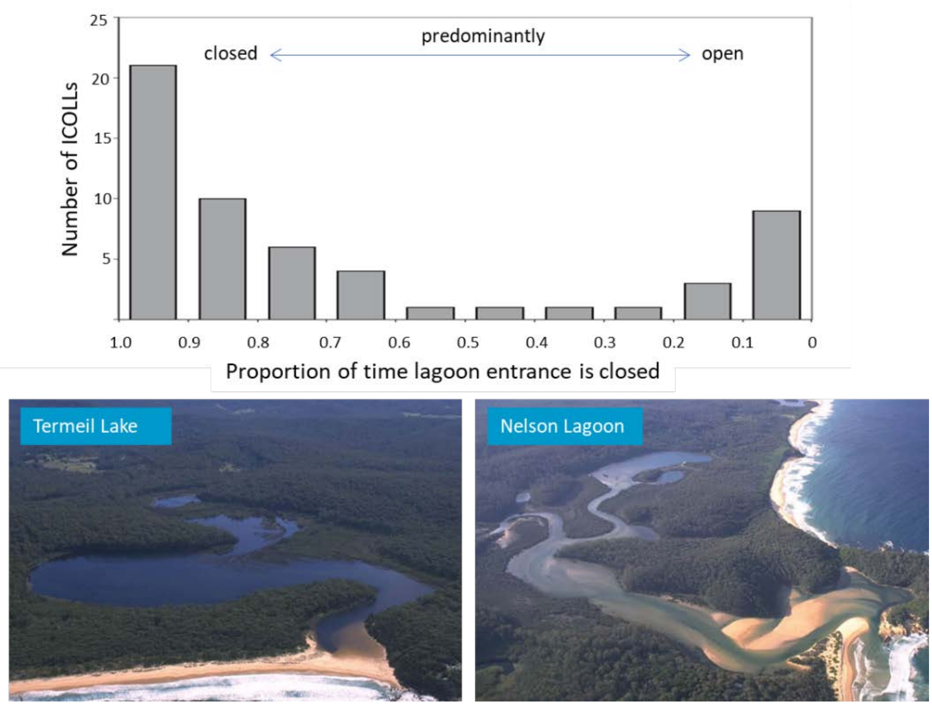


Figure 16 **Frequency analysis of NSW ICOLLs**

Frequency analysis based on the proportion of time their entrance is closed (top), and examples of ICOLLs which are rarely open (Termeil Lake; bottom left) and rarely closed (Nelson Lagoon; bottom right).

Water exchange due to tides

Photo 4 **Tuross Lakes entrance showing tidal exchange**
Photo: D Wiecek/DPIE

Astronomic tides

Tides in ICOLLs are subject to a range of changes compared with the ocean. These include reductions in tidal range, an increase in tidal lag or phasing, tidal distortion, elevation of half tide levels or tidal pumping, and amplification of fortnightly tides. The astronomic (semidiurnal) tidal behaviour inside ICOLLs is influenced by the dampening of tidal flows due to bottom friction across the entrance and flood-tide delta. In general, ocean tide ranges are significantly reduced by the flood-tide delta, and tidal ranges in the ICOLL basin are usually an order of magnitude smaller than the adjacent ocean. The main diurnal and semidiurnal tidal constituents are typically significantly reduced compared with the ocean while the lunisolar synodic fortnightly constituent (MSf) grows. The difference in frictional resistance across the entrance between spring and neap tides (due to depth) can cause an obvious fortnightly cycle in daily-mean water levels (known as ‘spring tide pumping’). This phenomenon is also known as a fortnight tide and can be equal to or greater than semidiurnal tides in many ICOLLs. ICOLLs which are mainly open can be tidal for years, while other ICOLLs may be tidal only for weeks following breakout. ICOLLS with progressively closing entrances display rapid decrease in tide range as the entrance shoals.

Effects of sea level anomalies

The mean sea level along the NSW coast experiences significant variations due to the effects of coastal-trapped waves, storm surges and changes in barometric pressure due to the passage of high and low pressure systems. The combined effect of these factors is known as mean sea level anomalies. These commonly result in water level variations of around 20 to 30 centimetres and occasionally up to 50 centimetres in ocean levels along the NSW coast, with concurrent influences on ICOLL water levels when the entrance is open. Changes (anomalies) in mean sea level commonly account for the greatest water level variation in ICOLLs over and above the effects of semidiurnal and fortnightly tides (Figure 17).

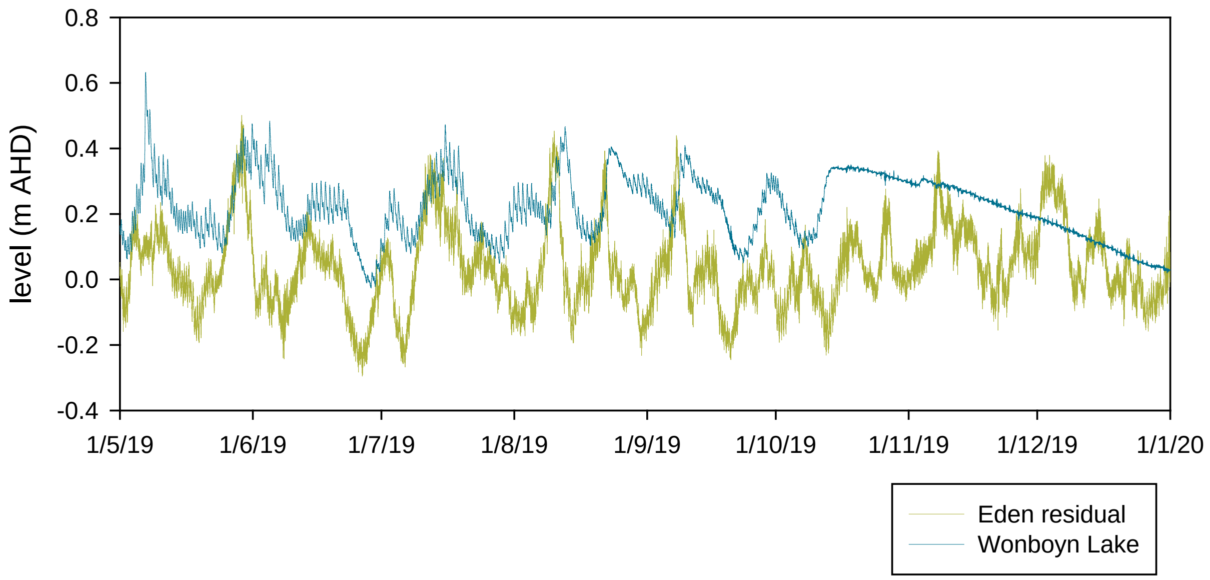


Figure 17 **Close coupling between Wonboyn Lake water levels and mean sea level residual at Eden**

Source: MHL. Note: mean sea level residual referred to here is the 15-minute actual level minus predicted tide for the Eden gauge, termed the 'Eden residual'.

Tidal flushing

Water exchange with the ocean due to tidal flushing in ICOLLs can occur only while entrances remain open. The volume that can enter and leave in a tidal cycle (tidal prism) is determined by the size of the channel and usually is only a few percent of the ICOLL volume. Incoming oceanic water mixes with ICOLL water due to advection–dispersion processes, which are driven by factors including tidal velocities, wind-wave currents, and interaction with bathymetry and channel features. Typically only a small fraction of the tidal prism (the total volume of water entering and leaving the ICOLL over a tidal cycle) exchanges with water in the ICOLL basin, and in most cases mixing only occurs at the flood-tide front, with most of the water that comes in on the incoming tide simply going back out on the falling tide. The mixing and exchange of oceanic and ICOLL water is also highly dependent on density effects due to temperature and salinity. For example, cooler more saline water entering during flood tides will tend to plunge to the ICOLL floor, promoting stratification and further minimising mixing. The net result is the amount of dilution and replacement of ICOLL water by tides is far less than commonly believed by communities.

Case study – modelled simulation of tidal flushing in Wonboyn Lake

Two-dimensional hydrodynamic modelling was undertaken by Environment, Energy and Science (within the Department of Planning, Industry and Environment) to assess the impacts of a low-level opening on salinity distribution in Wonboyn Lake (Figure 18). The lake salinity at the start of the simulation was set at 39 PSU throughout the system (conditions that existed in early January 2020) and the channel was held open for the duration of the simulation. Ocean salinity was held constant at 35 PSU throughout the simulation. The plot in Figure 18 shows the salinity distribution on Day 90 after the simulated low-level entrance opening. Even with ideal entrance channel conditions (i.e. no infilling), it can be seen that tidal flushing occurred only in the lower reaches of the flood-tide delta channel, with salinity throughout the bulk of the system remaining above 38 PSU.

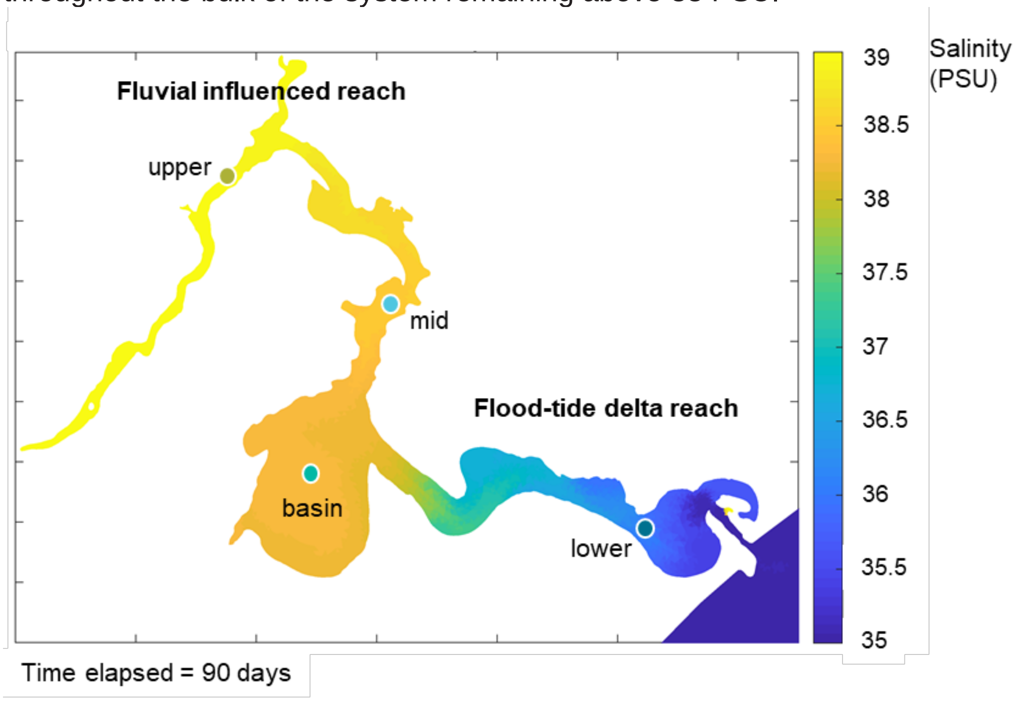


Figure 18 **Modelled effects of an idealised entrance opening on salinity distributions in Wonboyn Lake**
Source: Shivanesh Rao/DPIE. Also shown are upper, mid, basin and lower symbols indicating site locations for water quality profiles shown in Figure 26.

Effects of artificial entrance opening on tidal exchange

High-level opening

The relative weak breach behaviour and small channel scour associated with artificial opening at low trigger levels means that tidal attenuation across the entrance shoals is likely to be greater than that following natural breakout events. The clogging of the entrance compartment with successive artificial openings over time will worsen this effect, reducing ICOLL tidal prism and potential flushing.

Low-level opening

The same effects described for high-level artificial opening apply, but with even greater dampening effects on tidal exchange. The significant tidal attenuation across the entrance shoals means that tidal prisms are a very small fraction of ICOLL volume, therefore the potential for tidal exchange is minimal. Community pressure for dry weather artificial opening is more likely to be associated with hypersaline conditions within the ICOLL due to evaporation over a prolonged period of entrance closure. In these cases, the relatively less saline flood-tide water will push over the top of ICOLL water, with most of the flood-tide water exiting the system on the subsequent ebb tide (see ‘ICOLL water quality’ below).

Training walls

Permanent opening to the ocean can be achieved by the construction of entrance training walls, which is usually done for various reasons including improved navigation, and to address perceived ‘poor’ water quality issues. Notable examples of training walls constructed on large coastal lakes include Wallis Lake, Lake Macquarie, Lake Wagonga and Lake Illawarra. In all these examples there have been ongoing negative effects on geomorphic, hydrodynamic, water quality and ecological features (seagrass, mangroves) associated with the modification of coastal processes (Nielsen & Gordon 2008; Duchatel et al. 2014; Wiecek et al. 2016). The training of these systems is known to have triggered long-term (multicentennial) entrance scour processes which have caused significant issues to date. These include scour and subsidence of bridge foundations requiring major stabilisation works, bank erosion and major failure of waterway infrastructure, increases in tide range, and increased inundation of streets and walkways in foreshore towns, among others.

Case study – Lake Illawarra training wall

Figure 19 **Lake Illawarra ICOLL**

Unmodified entrance to Lake Illawarra ICOLL in 1936 (top left), and the impacts of subsequent entrance works between 2001 and 2007.

The relatively recent construction of entrance training works on Lake Illawarra provides a clear example of the various impacts on hydrodynamics, water quality and ecology due to entrance interventions. Prior to entrance works, the entrance channel was highly shoaled and broke out to either the north or south of Windang Island as illustrated in the oblique 1936 aerial photo in Figure 19. Internal training walls aimed at constraining the entrance channel and improve hydraulic conveyance were completed in 2001, followed by a connection to Windang Island via a rockwall, and finally twin entrance breakwalls and dredging completed in 2007. These works have fixed the entrance location and initiated an unstable scouring mode within the entrance channel of the lake.

The Lake Illawarra entrance works have caused fundamental changes to the lake tidal regime (Figures 20–22), which have in turn resulted in a cascade of impacts including destabilisation of the Windang Bridge pylons; smothering of benthic habitats by prograding flood-tide delta sands; erosion of foreshore infrastructure and cultural assets; loss of seagrass, fringing saltmarsh and wetland habitats (Figure 23); changes to water quality; and changes to invertebrate, fish and bird ecology (Wiecek et al. 2016).

Natural tidal regime

Prior to entrance works, tides in Lake Illawarra were dominated by a combination of sea level anomalies and the spring-neap cycle, with a much lesser signal due to semidiurnal tides. Barometric tides (i.e. changes in mean sea level due to the passage of weather systems etc.) also had a significant effect.

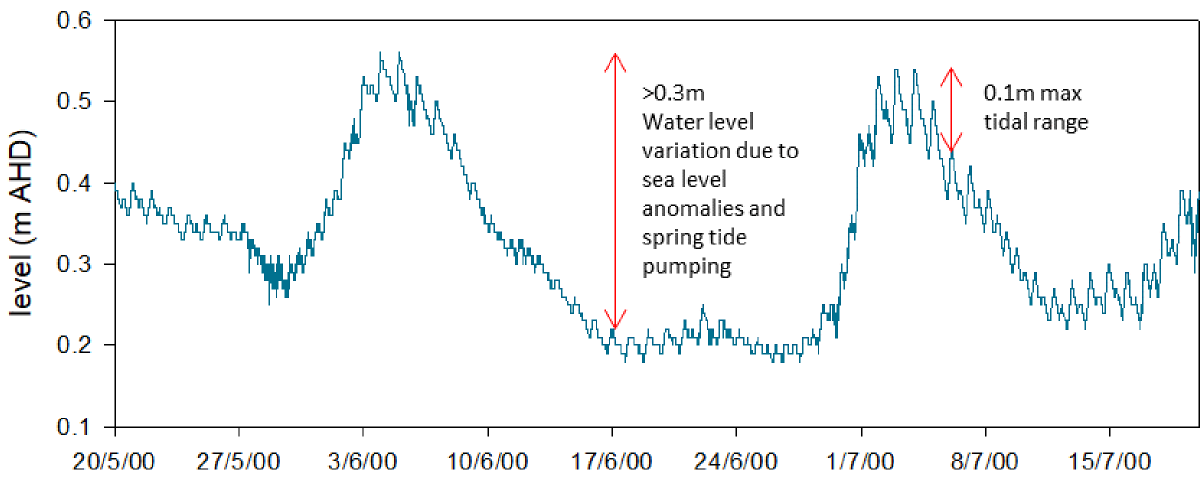


Figure 20 **Tidal variation at Koonawarra Bay in Lake Illawarra prior to entrance works**

Modified tidal regime

After the completion of entrance works, the increase in hydraulic efficiency of the entrance caused a significant increase in the semidiurnal tidal range and tidal current velocities.

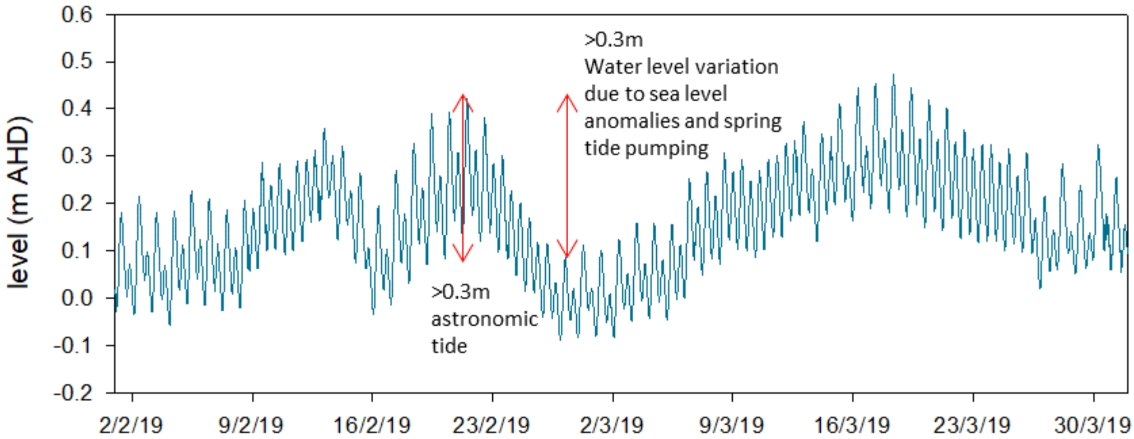


Figure 21 **Tidal variation at Koonawarra Bay in Lake Illawarra after the entrance works**

Changes in mean water level

Probably the most significant change due to the training walls is a net lowering of mean water levels by ~15 centimetres. While this change appears modest, it has translated to significant changes in the inundation of low-lying fringing habitats and flow-on effects on ecological communities.

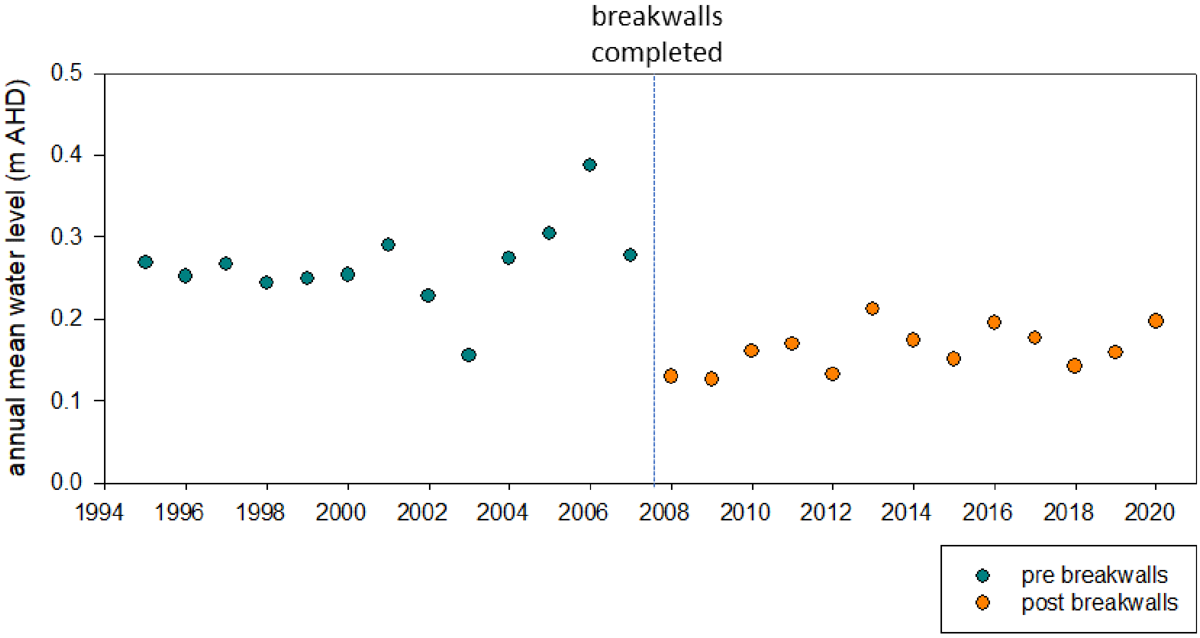


Figure 22 **Mean annual water level in Lake Illawarra prior to and after construction of entrance breakwalls**

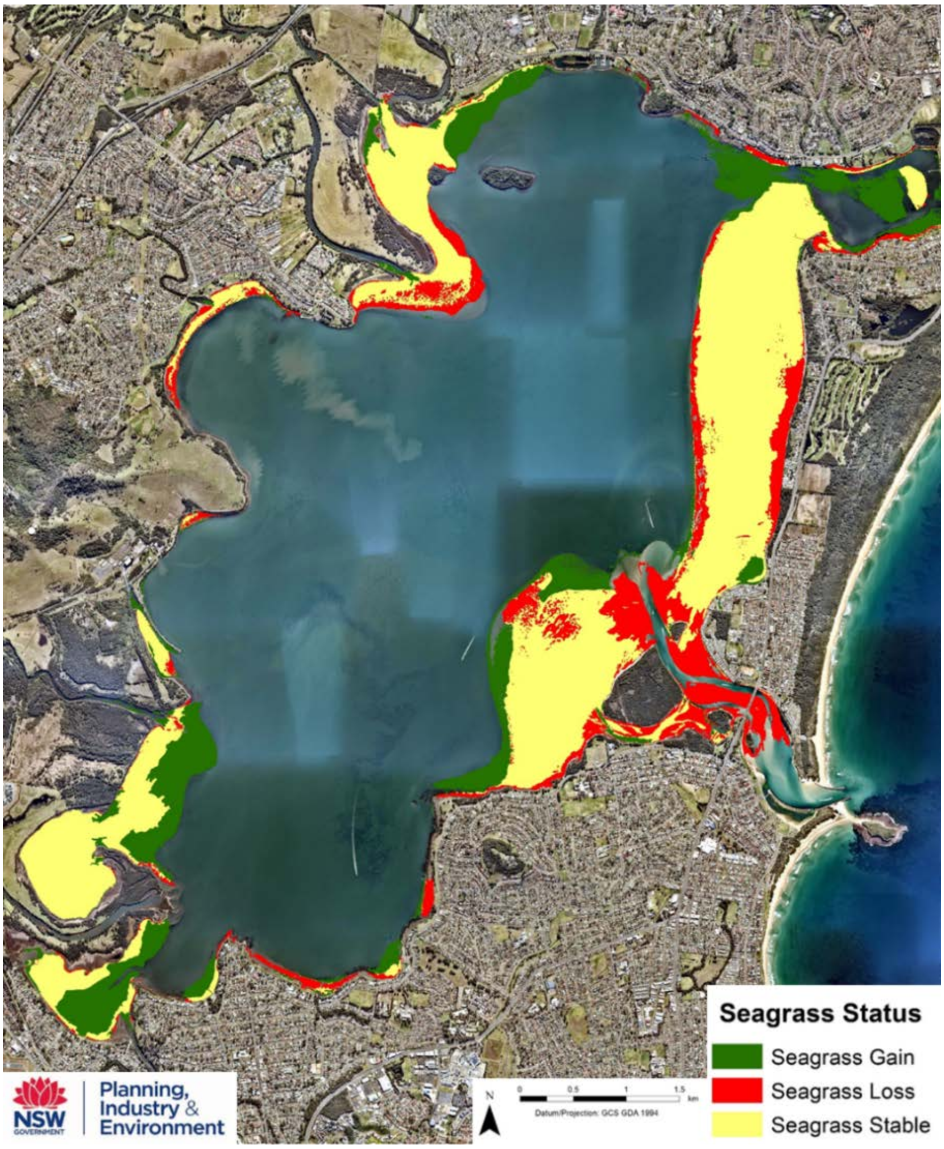


Figure 23 **Changes in seagrass coverage since building of breakwalls in Lake Illawarra**

ICOLL water quality

Natural variation

Water quality in ICOLLs is highly variable in space and time due to the combined effects of antecedent rainfall (and any entrained contaminants), entrance dynamics, a tendency to stratify under some conditions, and the influence of groundwater inputs from surrounding low-lying catchments. It is difficult to define a ‘characteristic’ water quality for ICOLLs due to the variable influences of many factors among systems. However, a relatively common property among smaller systems is the influence of tannin-rich groundwater and wetland runoff inputs, as indicated by the high concentrations of dissolved organic matter (measured as fluorescent dissolved organic matter [fDOM]) and total nitrogen concentrations (Photo 5, Figure 24). Tannins are responsible for the ‘tea-like’ brown water dominating these systems and should be regarded as a natural attribute of the system.

While water quality variation may appear extreme relative to permanently open tidal systems, in many cases this variation should be considered natural and an integral part of the greater coastal ecosystem. A statistical analysis of surface water quality from ICOLLs with small catchment disturbance across New South Wales indicates the expected ranges in main water quality variables, highlighting the relatively large range and need for ICOLL-specific health thresholds (Table 3). It should be noted that the variability indicated in Table 3 and Figure 24 is due to a combination of temporal (flow and season) factors as well as variation among systems within the ICOLL 'category'. Mid-sized coastal lagoons tend to have greater ranges in water quality parameters than larger systems which are buffered against large variations by their size and volume, and creeks where water is displaced frequently.

Photo 5 **Tannin-rich water in Tallow Creek**
Photo: A Ferguson/DPIE.

Table 3 **Statistical summary of physico-chemical water quality in NSW ICOLLs, 2007 to 2020**

	percentiles									
	Min	1st	5th	20th	50th	80th	95th	99th	Max	Range
Temperature (^{0}C)	11.0	11.5	14.9	19.8	23.1	25.7	28.3	30.0	31.6	20.6
Salinity (PSU)	0.1	0.3	2.0	15.1	26.9	35.0	40.2	52.5	67.0	66.7
DO (mg L^{-1})	0.2	3.1	4.8	6.3	7.5	8.9	10.3	13.1	14.0	13.8
DO (% sat)	3	37	62	84	98	113	132	178	253	251
pH	4.7	5.0	7.1	7.9	8.5	9.1	9.4	10.4	10.8	6.1
Turbidity (NTU)	0.0	0.1	0.1	0.5	1.5	4.2	10.3	18.3	32.4	32.4

Note: PSU = Practical Salinity Units; DO = dissolved oxygen; % sat = percent saturation;
NTU = Nephelometric Turbidity Units

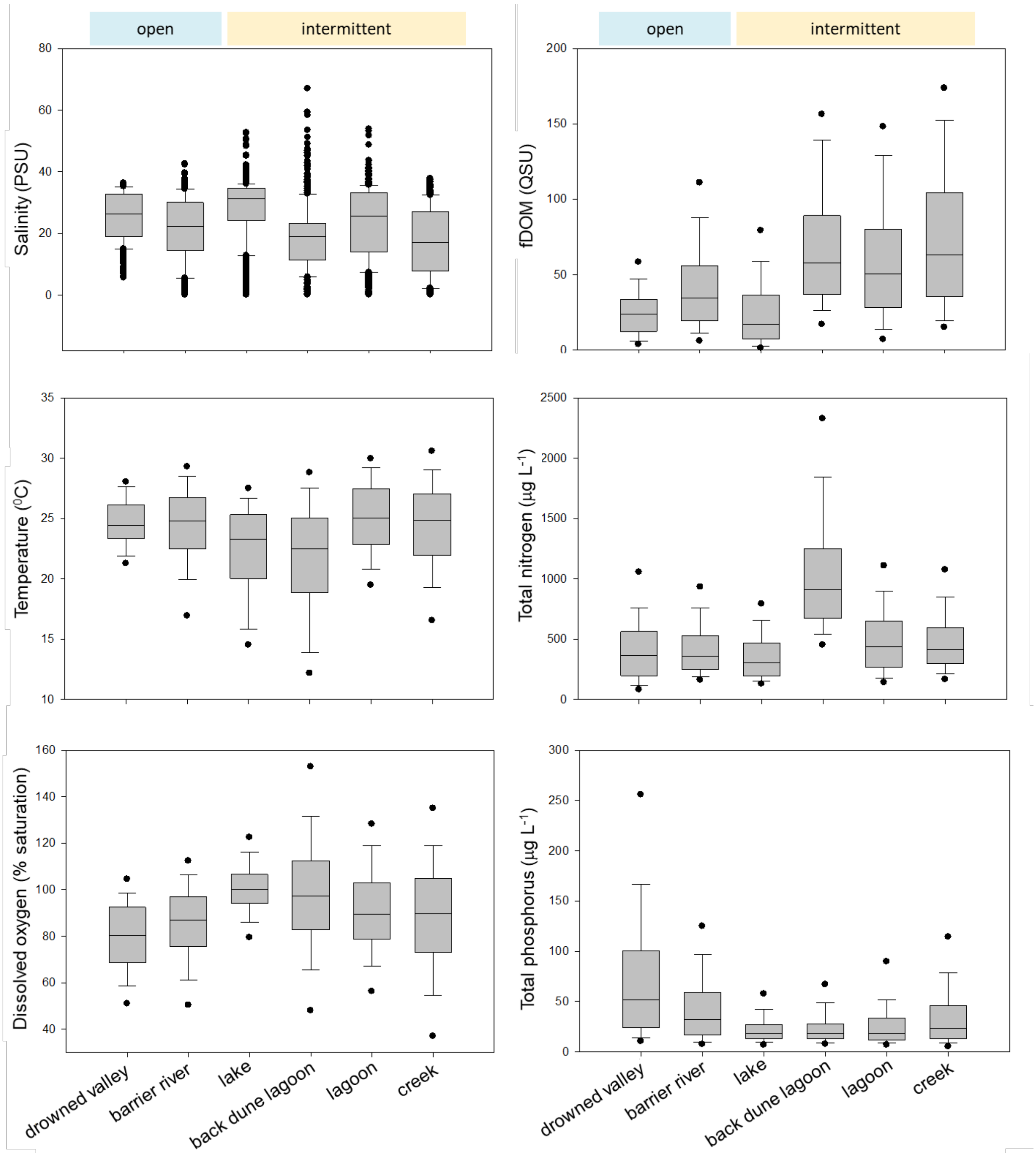


Figure 24 **Water quality statistics for NSW estuaries including the different ICOLL subtypes**

Water quality changes after freshwater inputs

Rainfall events result in freshwater inputs (overland flow and groundwater) lowering salinity and delivering nutrients, suspended sediments and pathogens. In smaller coastal lagoons, water quality is also significantly influenced by tannin-rich groundwater inputs from low-lying wetlands which can be acidic and low in dissolved oxygen. If entrance breakout occurs, smaller coastal lagoons tend to drain completely (see example for Dee Why Lagoon below), while in larger or deeper coastal lakes only the surface water layer drains, leaving behind commonly hypoxic water trapped in deeper parts of the central basin (‘decanting’) (Wiecek

2001; Wilson et al. 2002). Decanting carries a significant risk of fish kills occurring, even in natural breakout situations. In general, the occurrence of fish kills is highly unpredictable, however the accuracy of risk assessment is greatly improved by high-quality real-time water quality data leading up to breakout. A significant mitigating factor is the size of the rainfall event (and hence freshwater inputs) that initiates breakout: larger events will tend to cause greater flushing of hypoxic waters with overland runoff, and will also result in greater channel scour allowing fish easier passage to the ocean.

Tidal influence commences with the influx of oceanic water once water levels in the ICOLL are low enough. This causes an overall increase in salinity and stratification in deeper parts of the system. In some situations, oceanic water can react with acidic runoff from low-lying wetlands causing rapid deoxygenation events and fish kills. Salinity increases in the flood-tide delta reach while the entrance remains open, with conditions at the time of closure providing the starting point for water quality over the subsequent closed entrance period. Under closed conditions, oxygen and temperature stratification can develop, and evaporation can significantly increase salinity and lower water levels in shallow systems.

Stratification

Salinity or temperature stratification (or both) can develop in ICOLLs which can influence the development of hypoxia and algal blooms. Oceanic water entering during flood tides while the entrance is open, or alternatively due to wave overtopping of the entrance berm, can push underneath less dense fresh or brackish ICOLL water and flow into the basin. Vertical mixing is impeded without tidal flows while the entrance is closed, and the more saline bottom water becomes trapped in the basin. Oxygen consumption due to the breakdown of organic matter in basin sediments can result in hypoxia or anoxia of bottom waters and promote the recycling of bio-available nutrients from the sediments, which in turn, can stimulate algal blooms in surface waters (Figure 25). Stratification is most likely to occur in systems with deep central basins, but is also observed in much shallower systems like Tallow Creek on the NSW North Coast.

Lateral water quality gradients

Estuarine water quality gradients between freshwater and ocean-end members that are common to permanently open systems are rarely observed in ICOLLs due to a combination of generally small and episodic freshwater inputs coupled with the absence of tidal mixing during periods of entrance closure. In addition, wind-driven mixing tends to homogenise the surface water layer thereby breaking down any gradients that may have developed during open entrance periods. The most prevalent lateral water quality gradients in ICOLLs are developed due to the decoupling of nearshore environments from the ICOLL basin due to barrier effects associated with macrophytes and macroalgae. This effect is commonly observed in Tuggerah Lakes, where the presence of contiguous dense seagrass beds approximately 50 metres offshore serves to concentrate stormwater pollutants in the nearshore zone. This results in extremely poor water quality that is distinct from the greater lake basin.

Effects of artificial entrance opening on water quality

High-level opening

If opening occurs in response to relatively small rainfall events, the risk of decanting surface water without sufficient catchment inflow to flush hypoxic bottom waters from the system is high (Figure 25), thereby greatly increasing the risk of fish kills. More frequent opening at low-level triggers will result in ‘marinisation’ characterised by higher and more stable salinities. Artificial openings at moderate levels with no follow-up rainfall can result in subsequent poor water quality, as occurred at Tilba Tilba Lake in summer 2019–20 following an illegal opening.

Low-level opening

As outlined above, tidal prisms and exchange potential are low in ICOLLs. Therefore, water quality in the ICOLL basin will not be significantly altered by dry weather opening. Low-level opening will only impact water quality in the lower flood-tide delta reach during incoming tides. Sediment, nutrient, debris and faecal contamination all come into lagoons from their catchment. Opening of lagoon entrances will not improve water quality while catchment sources remain active.

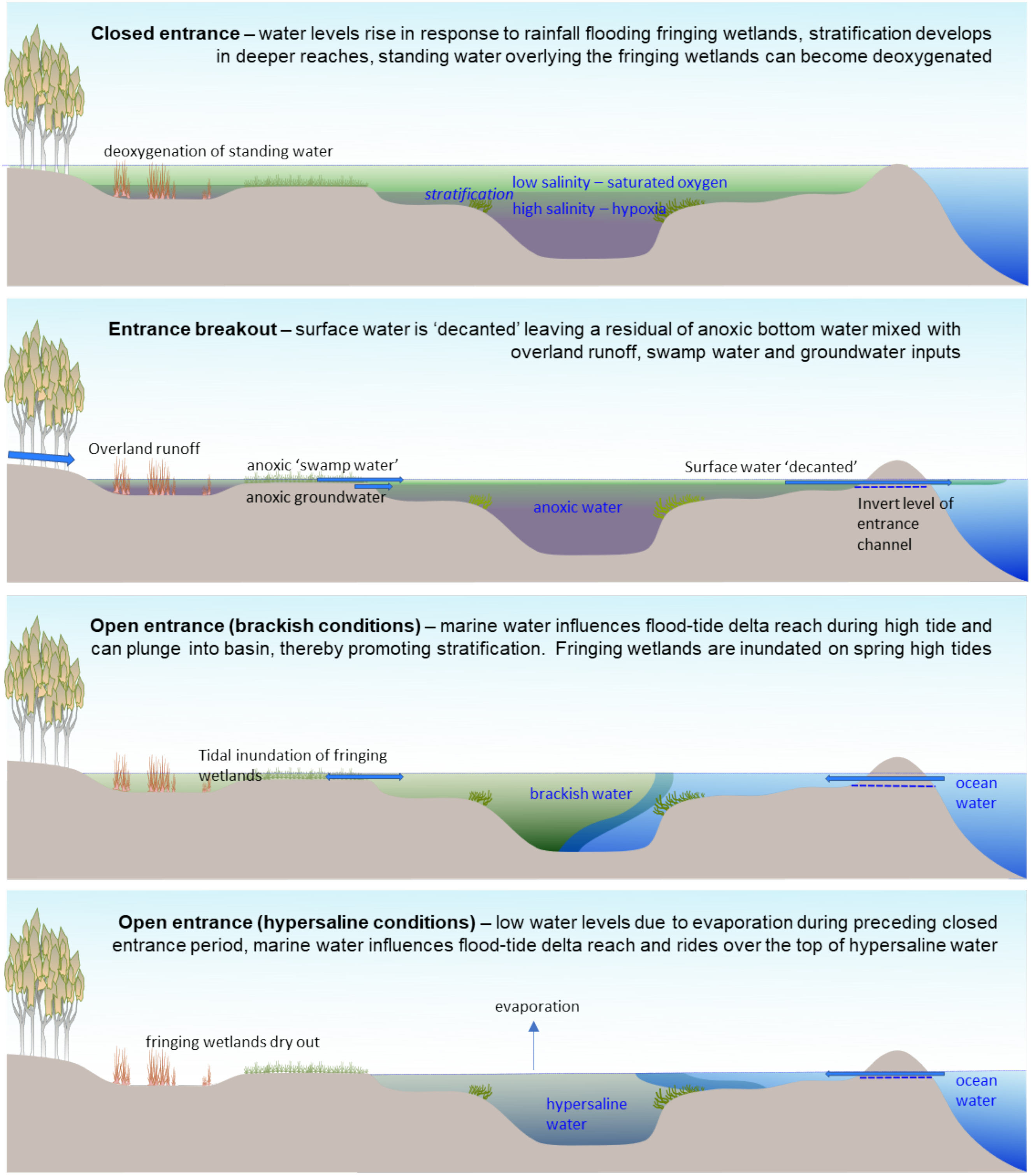


Figure 25 Conceptual model of key phases in ICOLL water quality

Case study – water quality dynamics in Wonboyn Lake

Environment, Energy and Science responded to community concerns about water quality in Wonboyn Lake following the 2019–20 bushfires, which burnt more than 93% of the catchment, by deploying a combination of automated loggers and boat-based sampling. Water quality time series and depth profiles (Figure 26) highlight the evolution of salinity and oxygen stratification in response to rainfall after the 2019–20 bushfires. Salinity stratification develops in response to freshwater inflows, followed by the development of hypoxia in bottom waters due to the breakdown of pyrogenic detritus. A phytoplankton bloom developed on 19 February 2020 (as indicated by the rapid increase in dissolved oxygen) in response to an improvement in light climate and high nutrient concentrations resulting from the pyrogenic material.

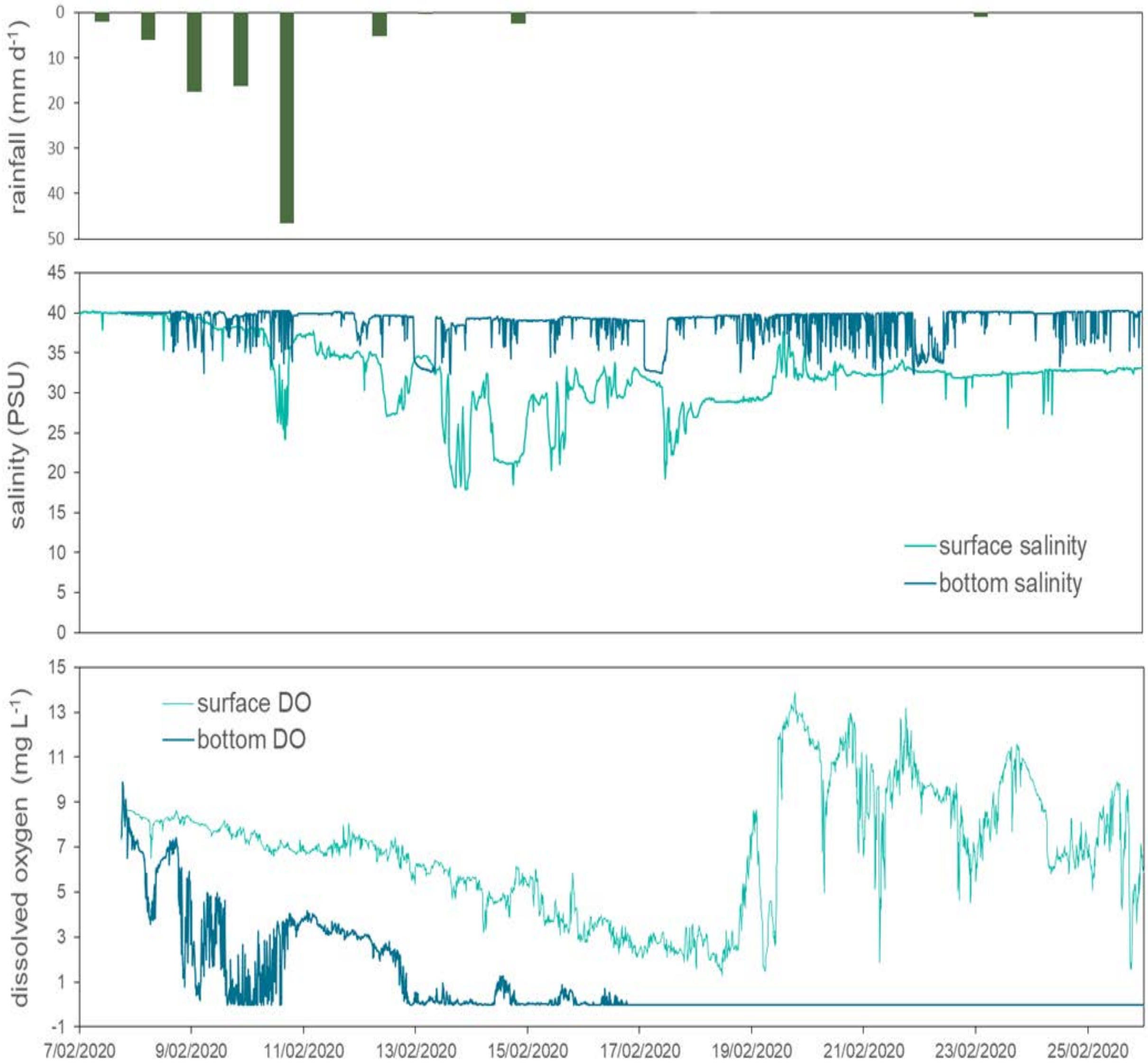


Figure 26a **Timeseries of surface and bottom water quality in the basin of Wonboyn Lake following the 2019–20 bushfires, showing variations.**

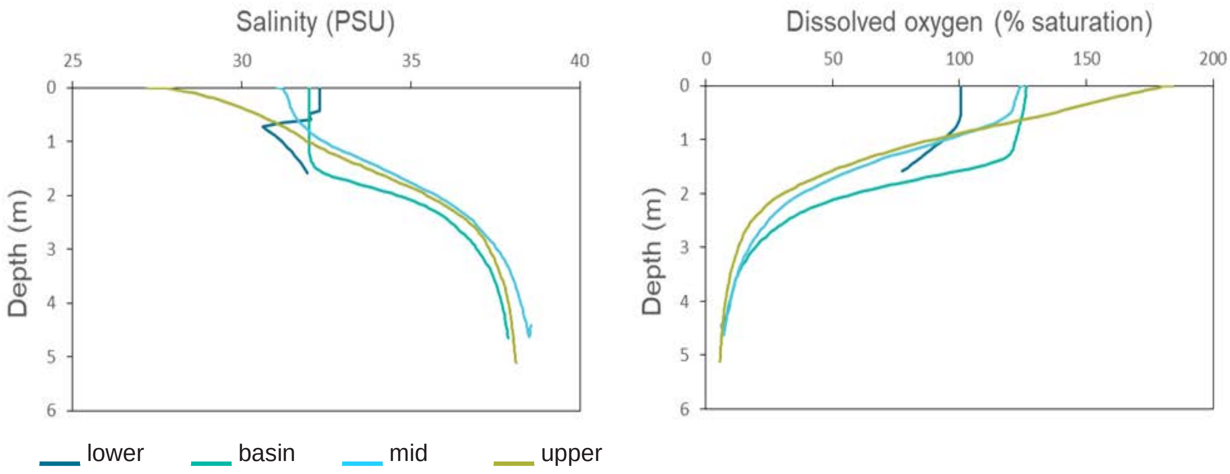


Figure 27b **Water quality depth profiles taken on 22 February 2020 at four sites in Wonboyn Lake, showing variation.**

Site locations for water quality profiles are shown in Figure18.

Water quality monitoring considerations

Routine monitoring

Routine monitoring allows characterisation of system-specific water quality variation during dry weather times and provides tracking of eutrophication risk indicators (e.g. nutrients, chlorophyll-a) associated with catchment pollutant inputs. With appropriate and timely interpretation, routine data can also provide information on system status (e.g. degree of stratification, hypoxia etc.) leading up to entrance breakout. Care should be taken in establishing routine sites to ensure they are representative of broad 'functional zones' within the ICOLL (e.g. flood-tide delta reach, main basin, etc.). These zones must first be delineated by boat-based, spatially intensive water quality surveys under different conditions (e.g. predominant wind directions, seasonal, high to low water levels). These surveys can also use physico-chemical depth profiles to determine the tendency for stratification in the system. If routine monitoring is to be undertaken by collecting shore-based grab samples at sites, care must be taken to ensure that localised effects (e.g. shallow water heating or cooling, presence of macrophytes and macroalgae, etc.) do not unduly influence the ability of the site to represent the broader functional zone.

Event-based monitoring

Event-based monitoring involves more intensive sampling (temporal or spatial, or both) to provide more detailed information about rapidly evolving water quality dynamics throughout the ICOLL in response to major rainfall events, as well as the quality of freshwater inputs to the system. More intensive monitoring can be triggered once water levels reach a prescribed threshold in order to assess risks associated with artificial entrance opening. As with routine monitoring, care is required to ensure the monitoring strategy and site selection are appropriate for meeting stated aims and fully characterising water quality trends. If stratification and 'decanting' upon breakout is a major known risk, it is critical that event-based monitoring includes physico-chemical profiles at key locations.

Telemetered onsite loggers

Telemetered onsite loggers are a powerful monitoring approach that allows managers to track the evolution of physico-chemical water quality parameters in near real-time (see data from Wonboyn Lake, above). There have been ongoing improvements in new sensors for dissolved nutrients, however the detection limits and precision of these sensors are generally not appropriate for the characteristically low nutrient concentrations in ICOLLs. Aside from appropriate site selection (see above for routine and event-based monitoring), there are two major issues with the deployment of onsite loggers: 1) biofouling, and 2) stratification. Biofouling refers to the growth of invertebrates and algae on sensors during deployment, which results in significant impairment of sensor function and calibration drift. This requires regular (fortnightly or less) servicing, cleaning and calibration of sensors, and correction of data for drift over the deployment period.

An alternative and preferable solution is to deploy sensors in a remote sampling setup that limits exposure to ICOLL water to the time while readings are being made. In systems prone to stratification, careful consideration must be given to sensor deployment and data interpretation. If sensors are deployed at a fixed distance from the bottom, readings will potentially be made from above and below the halo or thermocline as water level varies (either due to tide or freshwater inputs) making interpretation of data extremely difficult. If only one multiprobe sensor array is available, it is preferable that it is deployed on a float at a fixed depth from the surface. Ideally surface and bottom reading should be made simultaneously using either two multiprobe arrays, or a remote sampling setup with multidepth sampling capability.

ICOLL habitats

Photo 6 Fringing habitats and exposed entrance shoals in Lake Wollumboola
Photo: A Ferguson/DPIE

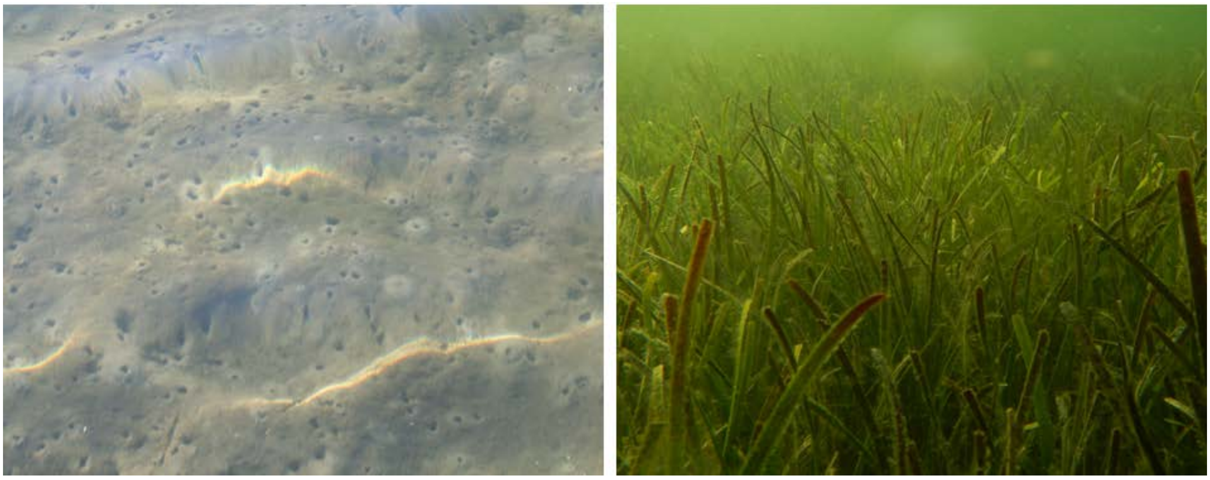
Benthic and fringing wetland habitats

ICOLLs support a range of benthic and fringing wetland habitats (see Figure 4), with the relative extent and nature of these habitats varying according to system type, freshwater inflows and entrance status. The benthic habitats are broadly characterised by sediment type, stability, overlying water depth, and exposure frequency. Fringing wetland habitats exist in low-lying landscape features formed by the gradual infilling of shallow waterway areas since the end of the post-glacial marine transgression, approximately 5000 years ago (Roy 1984). The transitions between different fringing habitats and their relative extents are largely controlled by small variations in elevation and inundation frequency. Infilling and erosion processes continue to modify the characteristics and boundaries of ICOLL habitats.

Flood-tide delta shoals

Shallow-water sand shoals of flood-tide deltas support an array of primary producers, invertebrates, fish and bird life. The entrance shoals tend to be shallower and may be exposed during entrance breakout and subsequent low tides. Entrance shoals also actively migrate due to scouring after entrance breakout and tidal currents while the entrance remains open (Figure 27). Despite good light climate, entrance shoals are generally not stable enough to support seagrasses, but do support high benthic microalgae production and invertebrate communities (Ferguson et al. 2003; Gladstone et al. 2006). Further upstream of the entrance, flood-tide delta shoals tend to be more stable and commonly support extensive seagrass meadows (Ferguson et al. 2018). While these shoals are dominated by sand, the dampening effect of seagrass on currents and wind-wave energy promotes the trapping of particulate organic matter and fines, thereby increasing the content of these in sediments.

a. Active flood-tide delta shoals. Mobile sands support benthic microalgae production



b. Stable flood-tide delta shoals. More stable sands support benthic microalgae, seagrass and diverse invertebrate fauna

Figure 28 Examples of a. active (mobile) and b. stable shoal habitats
Photos: R. Duczynski; A Ferguson

Fluvial and basin shoals

Shoals fringing the basin and the fluvial-influenced reach are formed by the deposition of sediments derived from catchment runoff as well as aeolian sand deposition on the seaward fringes of the ICOLL basin. These shoals tend to have higher fine sediment factions and organic matter contents than flood-tide delta shoals, however there is generally spatial variation in grain size according to shoreline aspect and exposure to prevailing wind fetches (Ferguson et al. 2013). Variable combinations of wind-driven sediment resuspension and high tannin concentrations in ICOLL basins can reduce light penetration, resulting in poorer benthic light climate than in the flood-tide delta reach. Light limitation in conjunction with reducing sediment redox conditions can limit seagrasses at their lower depth range (Ferguson et al. 2017; Ferguson et al. 2016). Seagrasses are dominated by *Zostera muelleri* in most ICOLL systems, with the exception of back dune lagoons which have significant areas of *Ruppia megacarpa* on shoals influenced by fresh water from groundwater and fluvial inputs (Ferguson et al. 2018).

Deeper benthic habitats

Deep-basin and fluvial-channel sediments tend to receive less bed shear stress due to wind waves and currents than shallower benthic environments and are therefore net depositional environments with high fine-sediment and organic-matter contents. Deep benthic habitats are generally light limited and do not support primary production by seagrasses, but in some cases can support limited benthic microalgal production. Remineralisation of deposited organic matter by bacteria in deep benthic habitats can result in deoxygenation of bottom waters especially where temperature or salinity stratification impedes vertical mixing (Cook et al. 2010).

Fringing wetlands

Saline fringing wetlands in NSW estuaries include both mangrove and saltmarsh, although the mixture of these varies depending on the estuary type (Creese et al. 2009). While mangroves are dominant in total area across some estuary types, they are largely absent from ICOLLs where saltmarsh is the dominant fringing wetland type (Hughes et al. 2019; Roper et al. 2011).

Coastal saltmarsh in the NSW North Coast, NSW Sydney Basin and NSW Southeast Corner Bioregions was declared an endangered ecological community (EEC) in 2004 under the *Threatened Species Conservation Act 1995*. It remains listed as an EEC under the current *Biodiversity Conservation Act 2016*.

Saltmarsh species can thrive in upper intertidal areas largely due to their competitive advantage as halophytes and their tolerance to anaerobic soils. Within an individual wetland, different saltmarsh species are often arranged in zones or mosaics that reflect consistent elevation with respect to water level (Adam et al. 1988). Species composition is determined by the inundation regime (frequency, duration and depth of inundation), the soil salinity and its aerobic condition (Hughes et al. 2019).

Unlike estuaries with permanently open entrances, saltmarsh in ICOLLs is positioned with respect to a complex inundation regime that is tidal when the entrance is open and dominated by catchment inflows when the entrance is closed. The mix of saltmarsh species in an ICOLL is expected to also reflect this complex inundation regime. Altering the inundation regime through a significant change to the entrance opening regime can potentially result in a change to the position and mix of saltmarsh species and to saltmarsh dieback.

ICOLLs also include freshwater wetlands, often dominated by Casuarina and Melaleuca species. Some, such as Coastal Swamp Oak Floodplain Forest, are also listed EECs. These wetlands are situated at higher elevations than saltmarsh or further up freshwater creeks feeding into the ICOLL. Just as the position and extent of saltmarsh is strongly influenced by the entrance opening regime, so too is the position and extent of freshwater wetlands. Increasing the frequency or duration (or both) of ICOLL opening from its natural regime increases the marinisation of the system, potentially resulting in dieback of the freshwater wetlands through salinisation and their transition to more salt-tolerant species.

Given that ICOLL wetlands are predominantly EECs, it is critical to ensure that ICOLL management actions minimise the disturbance to these important habitat areas.

a. Inundation of saltmarsh in Coila Lake **b. *Juncus* marsh/casuarina complex, Belongil Creek**

c. Flooded lake fringes following rainfall in Lake Inness

Figure 29 **Examples of fringing wetland habitats in ICOLLs**
Photos: a. D Wiecek; b. A Ferguson; c. J Schmidt

Habitat mapping

Estuarine macrophyte mapping was completed for 154 NSW systems based on 2005 coverage and is now integrated with detailed bathymetric, topographical and habitat information (Creese et al. 2009). A complete set of maps (1:25000 scale) are available as GIS layers for the entire NSW coast from the upper tidal limit of estuaries to the three nautical mile limit: Mapping the habitats of NSW estuaries (Figure 29).

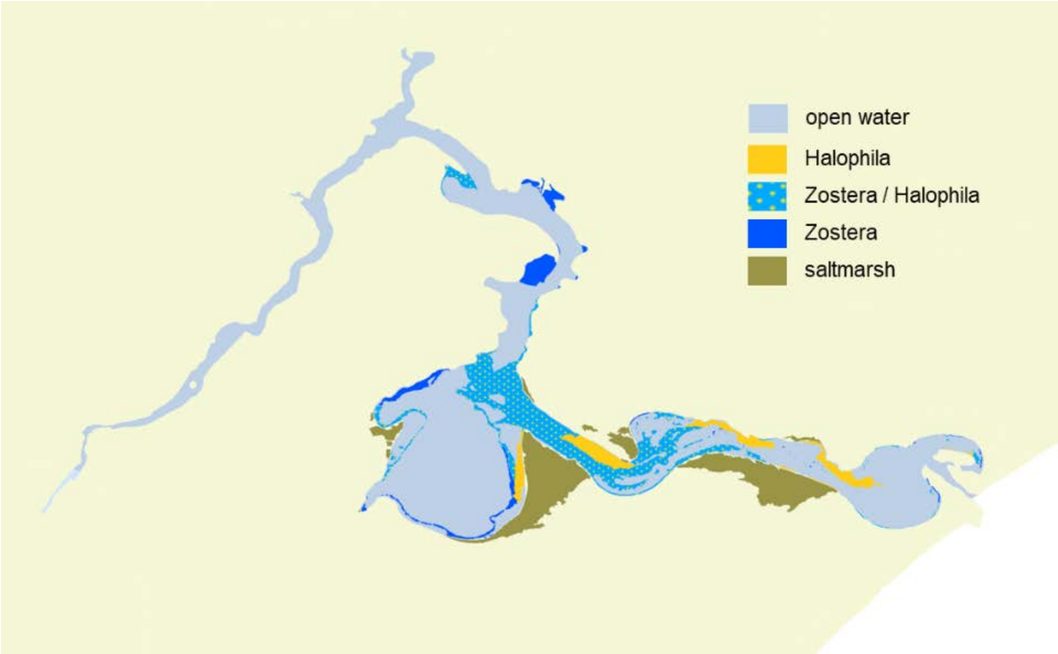


Figure 30 **Example of NSW Government estuarine habitat mapping for Wonboyn River**

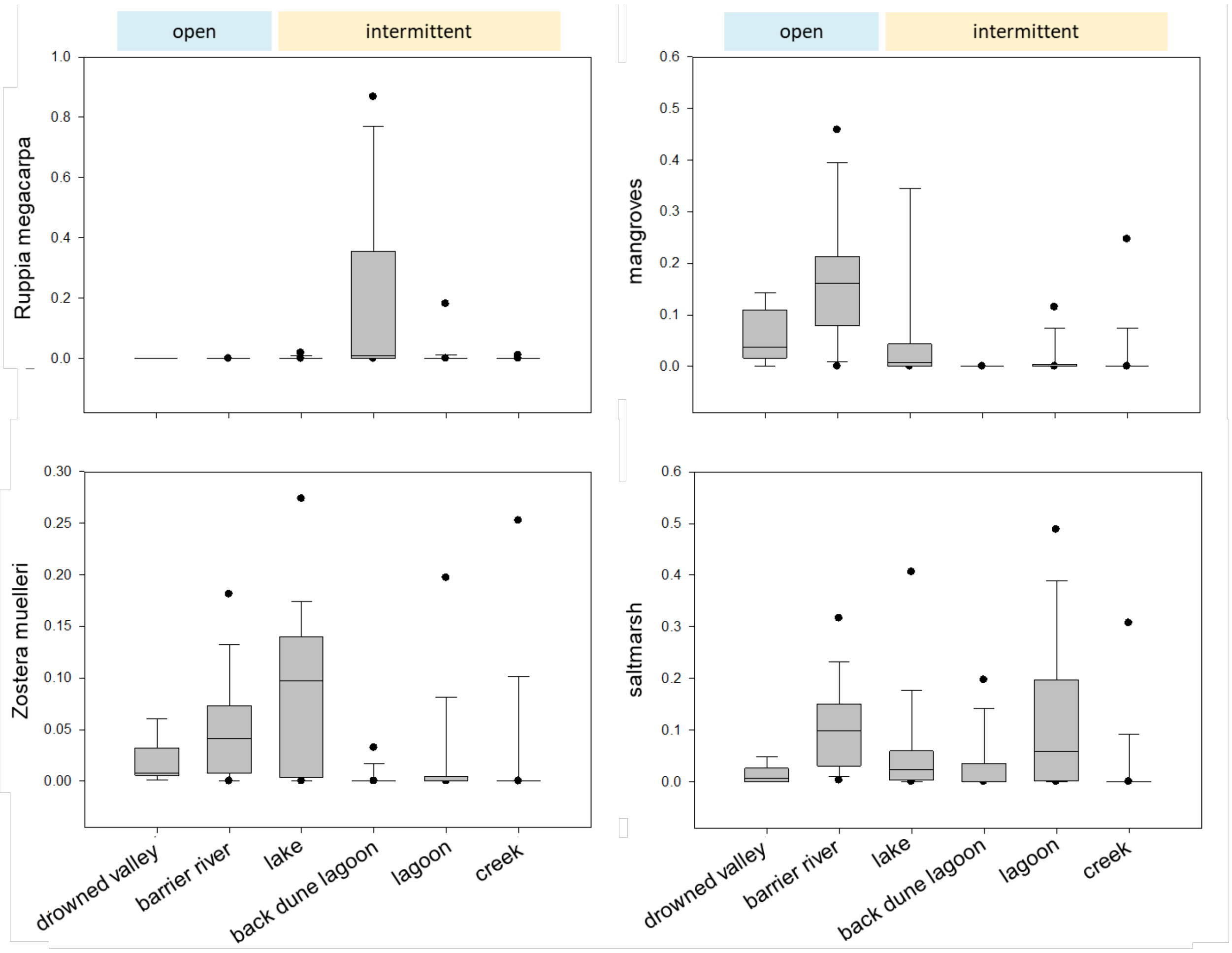


Figure 31 **Proportion of waterway area occupied by *Ruppia*, *Zostera*, mangroves and saltmarsh in NSW estuaries**
Data from Creese et al. 2009

Impacts of system drainage following breakout

In extremely shallow lagoons and creeks with a largely infilled basin, entrance breakout can cause almost complete drainage of the system resulting in exposure of benthic habitats and a range of pressures including temperature extremes, desiccation, and oxidation of potential acid sulfate sediments (Figure 31; see also the Lake Cathie and Lake Innes case study). Exposure of sediments and macrophytes can cause strong odours due to the production of hydrogen sulfide during the anaerobic breakdown of stranded organic material. Drainage of ICOLLs and associated pressures arising from entrance breakout can be considered a natural phenomenon in an undisturbed system (Scanes P et al. 2020), however where the adjacent low-lying catchment has been modified by artificial drainage, pressures can be significantly augmented by the export of acid runoff and anoxic groundwaters (Aaso 2019). In larger systems breakout can result in significant shallowing of shoal environments causing heat and exposure stress to seagrass habitats, as happened in Durras Lake in 2011 (Scanes P et al. 2020).

Figure 32 Complete drainage of Dee Why Lagoon following entrance breakout

Source: GoogleEarth.

Effects of artificial opening on benthic and fringing habitats

High-level opening

More frequent opening at low-level triggers or below the natural breakout range will have the net effect of lowering the mean water level within the ICOLL and changing the inundation regimes of fringing wetlands. This can greatly reduce the extent and usage of low-lying fringing swamps as benthic habitat, and ultimately lead to shifts in vegetation type and ecosystem function. Shoal habitats will be shallower, with habitat value for larger fish potentially reduced. More frequent drainage of sediments may result in increased exposure to the various stresses outlined above. Marinisation may also occur, with increased salinities and more regular tidal ranges and inundation periods favouring the expansion of mangroves at the expense of other vegetation types (e.g. freshwater wetlands).

Low-level opening

In cases where ICOLL water level exceeds mean sea level, the system will drain, thereby reducing benthic habitat.

Case study – Lake Cathie and Lake Innes

Prior to 1933, Lake Innes was a perched freshwater lake and swamp habitat. It was separated by a Holocene sand ridge from Lake Cathie, which was an ICOLL with a shallow lake basin and shallow sinuous drainage system (Figure 32). An artificial connection was made between the lakes in 1933. Although the intention was to drain Lake Innes for agricultural production, this proved impossible as the bed of Lake Innes was only slightly above sea level and therefore too low for effective drainage. Instead, the artificial channel converted Lake Innes from the largest freshwater lake in New South Wales to a saline estuarine habitat. This caused shoreline recession, the dieback of fringing swamp forests and freshwater reed habitats, and a cascade of unintended changes to the geochemistry of the lakebed sediments which caused a range of chronic downstream impacts.

Sea water introduced abundant marine sulfate into the lake system. During dry periods, evaporation causes a prevalence of hypersaline conditions in Lake Innes, which, coupled with high-sediment organic-matter contents, promoted the formation of sulfidic sediments (containing pyrite and monosulfides) across the lake basin bed. These sediments are precursors to acid sulfate soils and can become exposed when the entrance is breached or during extended drought when water levels drop due to evaporation (Figure 33a). Exposure to air causes oxidation of sulfidic sediments and the formation of acid, with associated release of metals and metalloids.

An artificial entrance breach was made in July 2018 resulting in drainage of the lake to 0.1 metre Australian Height Datum (AHD). Subsequent drought conditions over the following year saw water levels in the lake drop to historically low levels, thereby exposing up to 900 hectares of sulfidic sediments to oxidation (Aaso 2019).

A series of rainfall events filled the lake in early 2020, prompting an artificial entrance opening on 23 May 2020 as water levels reached the local flooding threshold of 1.6 metres AHD. Drainage of the ICOLL system after the entrance breach caused a massive export of dissolved reduced iron (Fe^{2+}) from sulfidic sediment pore waters which rapidly oxidised to particulate iron oxides (orange-coloured ‘iron floc’), smothering sediments throughout the system (Figure 33c).

This case study highlights the potential long-term chronic and acute impacts associated with artificial entrance opening in ICOLLs, especially in the presence of large-scale drainage and geochemical alterations to adjacent low-lying swamp habitats that enhance the hydrological coupling between these environments and the ocean entrance.

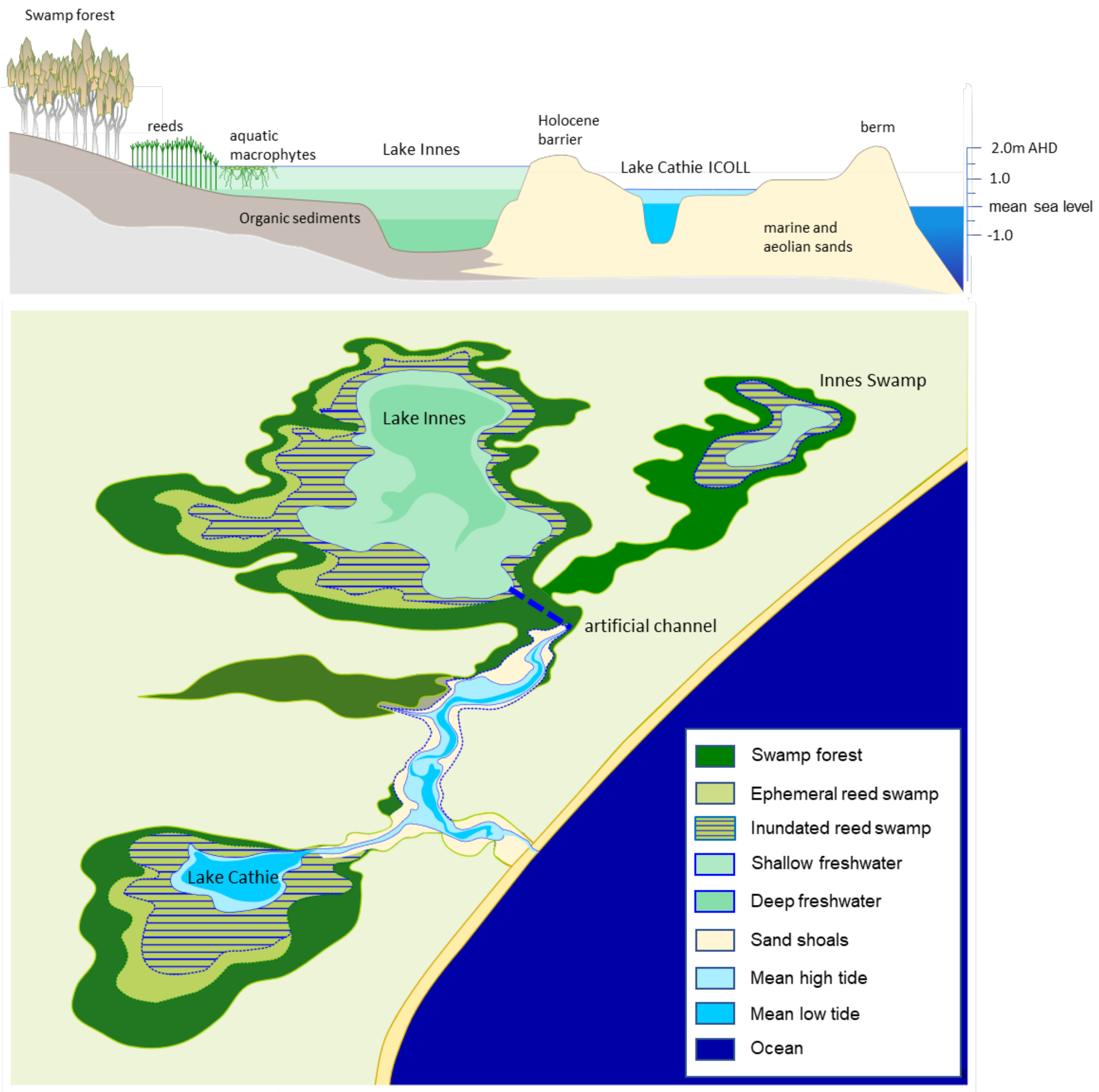


Figure 33 **Conceptual diagram of the Lake Innes and Lake Cathie system prior to the construction of the artificial channel**

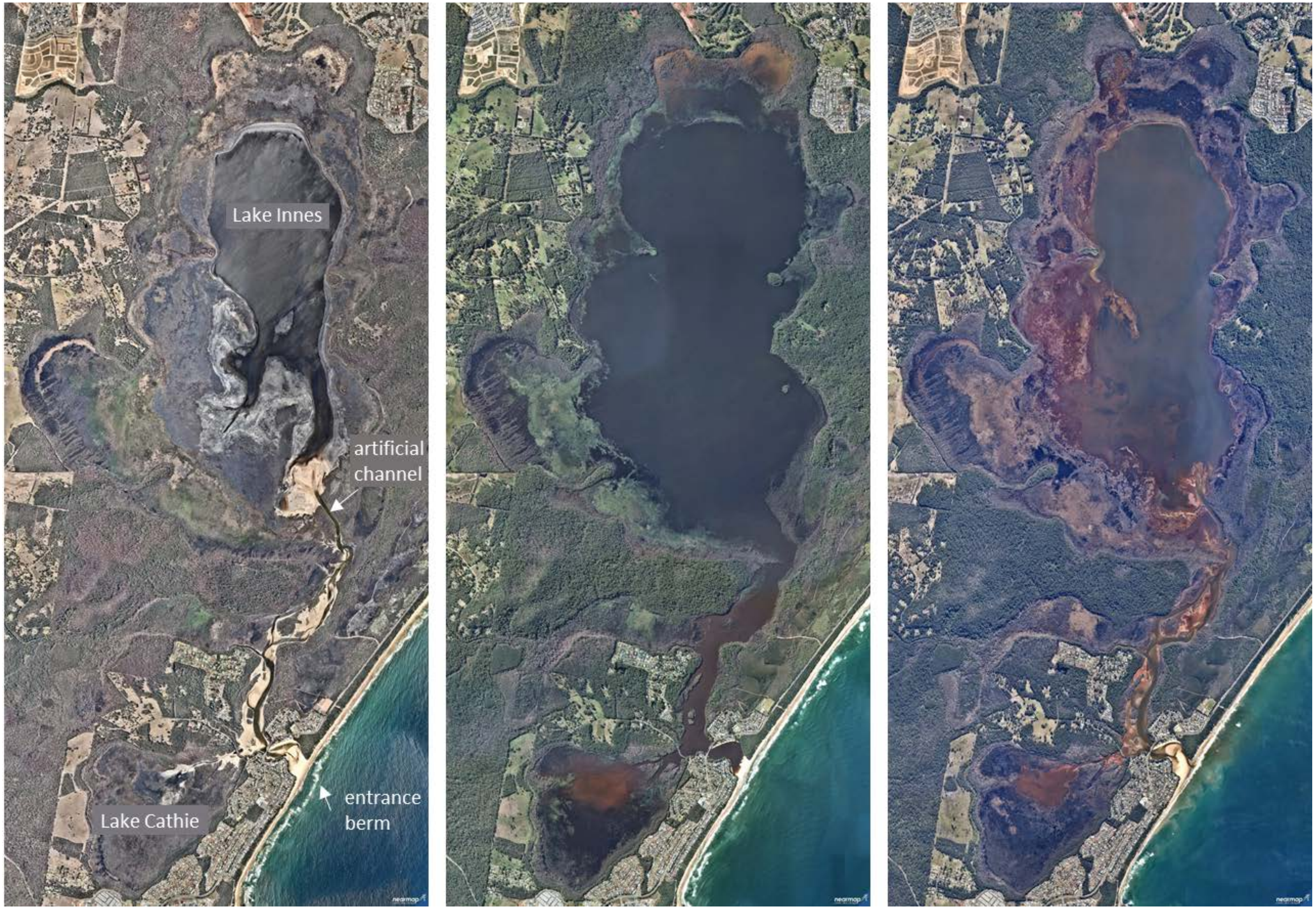


Figure 34 The Lake Cathie – Lake Innes system (l to r) Water levels: drought, -0.5 m AHD; lake full, 1.6m; lake drained, 0.3 m AHD

Images show the drainage of Lake Innes due to the impacts of the artificial channel connecting the lakes (source: Nearmap). The massive production of orange-coloured iron floc following an artificial opening event is evident in image on the right.

Pelagic habitats

Pelagic habitats in ICOLLs are highly dynamic due to the naturally variable water quality and water levels. Key attributes of pelagic habitat variability include:

- Wind mixing tends to reduce estuarine gradients in surface waters.
- The development of salinity and associated oxygen stratification can limit the habitat value of hypoxic bottom waters, and also result in negative feedbacks to benthic environments.
- ICOLLs influenced by tannin water inputs are characterised by high light attenuation which can limit benthic productivity in deeper benthic habitats of the basin.
- Salinity is highly variable over tidal cycles while the entrance is open, and over month to year timescales depending on the frequency and duration of openings.

Hypersalinity due to evaporation during periods of extended entrance closure can reduce dissolved oxygen availability and cause a range of physiological stresses for some biota (Tweedley et al. 2019).

Effects of artificial opening on pelagic habitats

High-level opening

More frequent opening at low-level triggers increases the likelihood of 'decanting' and associated extreme water quality events such as hypoxia. The net lowering of mean water level reduces the diversity of pelagic habitats. Marinisation will favour more marine species.

Low-level opening

Net reduction in the ICOLL water level could reduce pelagic habitat.

ICOLL biota

Fish

ICOLLs provide a range of habitats for fish fauna, including shallow-water shoals and seagrass, periodically flooded fringing wetlands, and deeper basins. All of these habitats are subject to high temporal variability in water quality imposed by freshwater inflows, intermittent entrance opening, and evaporation. In general, it is thought that system morphology, individual hydrological characteristics, and local climatic regimes are the primary determinants of fish abundance, diversity and community structure in ICOLLs (Jones 2003). However existing research has revealed few, if any, consistent patterns in species recruitment, diversity, and abundance, either between locations within ICOLLs, among ICOLLs regionally, or between seasons and years. This highlights a critical need to better understand the relationships between fish ecology and ICOLL processes.

Observations suggest that prawns and certain fish species (e.g. mullet and bream) can grow to large sizes in closed ICOLLs which may enhance the survival and reproductive success of these individuals once breakout occurs and they are released to coastal waters. (For more information see the fact sheet Sea Mullet (Mugil cephalus), Industy and Investment NSW 2010.) It is notable that the frequency of natural breakout is more likely to be greater in autumn, aligning with the annual northbound migration of many fish species to their winter spawning grounds (Harding et al. 2019; Pollock 1982; Smith & Deguara 2002). Furthermore, numerous observations describe the congregation of large mullet and other species at ICOLL entrances during heavy rainfall periods in anticipation of an entrance breakout.

Fish usage of seagrass habitats

A comprehensive survey of seagrass habitats in NSW south coast ICOLLs (Jones & West 2005) described a diverse and variable fish fauna, comprising a 'core' set of species that were found in all systems. It is considered that seagrasses provide a valuable recruitment and nursery habitat for a range of marine and estuarine species. There were no consistent spatial trends in fish assemblages within or between systems, which is thought to reflect the general lack of water quality gradients during periods of entrance closure. Interannual variation in abundance and diversity was higher than both spatial and seasonal variation, which is thought to be driven by the effects of rainfall variation in response to ENSO events.

Fish usage of flooded wetland habitats

The inundation of fringing wetlands occurs in two discrete modes: sporadic flooding due to spring tides while the entrance is open, and for extended periods while the entrance is closed. A distinct shift in fish assemblages occurs between these two flooding modes, related to changes in hydro-period and food availability within the flooded zone, and physico-chemical water quality within the wider system (Becker & Laurenson 2008).

Fish usage of deep-water habitats

The extent of deeper water habitats associated with ICOLL basins varies widely among systems according to factors such as morphology and size of the system. Less is known about fish assemblages of these habitats; however, it is likely they are highly variable and characterised by a range of migratory estuarine and marine species depending on entrance conditions and recruitment history.

Recruitment

Fish recruitment to open ICOLLs is highly complex, being dependent on factors such as:

- frequency, size and duration of opening
- fish assemblages in the nearshore zone adjacent to the entrance at the time of the opening
- the mode of recruitment (larval, adult or internal).

A study of commercial fish species abundance and diversity in NSW South Coast ICOLLs (Jones & West 2005) revealed that processes responsible for widespread increases in recruitment were large-scale, and not restricted to the life histories of individual species or to a particular area. It was hypothesised that interannual rainfall variation may be an important factor in driving both ICOLL processes (e.g. freshwater inflows and breakout frequency) and fish

Pelagic recruitment occurs after opening as larvae move into estuaries during flood tides (Bennett 1989; Griffiths 1999; Pollard 1994; Potter & Hyndes 1999; Young et al. 1997) – in this case, the assemblage is highly dependent on the time of opening, what larvae are available at that time and the frequency, size and duration of opening. The assemblage is also influenced by the presence of species that can complete their life cycle in an estuary.

Fish have been observed to frequently move in and out of an ICOLL when the entrance is open and tidal (Becker et al. 2016a), with most of the movement occurring at peak flow. Fish do not always move with the current in an ICOLL entrance. Becker et al. (2016b) showed that approximately 68% of fish moved with the current and 32% against the current. In the above-mentioned study, approximately three times more fish were recorded moving into the estuary than leaving, with movement significantly greater on neap tides. The movement and usage patterns of many species throughout closed ICOLLs are largely unknown (Becker 2016a), however small and large fishes are commonly observed to be abundant in the entrance region of closed ICOLLs (Becker et al. 2011).

Effects of artificial opening on fish

The impacts of artificial opening on fish processes are not fully understood due to an incomplete knowledge of the ecological function of ICOLLs in general, and how the function of individual ICOLLs may contribute to the ecology of fish along the NSW coast. More frequent opening at low-level triggers may be expected to have a range of acute and chronic impacts including:

- increasing the acute risks of extreme water quality events such as hypoxia and associated fish kills
- interrupting natural ecological cycles whereby juvenile fish and prawns are released to the coastal waters prematurely
- reducing fish and prawn productivity due to higher predation of juveniles and lower reproductive success.

Impacts on pelagic and benthic habitats (described above) may result in both positive and negative impacts across the range of fish species using ICOLLs. Smaller resident species may suffer a decline in habitat, while larger, migratory predators may benefit from more frequent opening and tidal exchange.

Birds

ICOLL habitats support a vast array of different bird species (Figure 34). Waterbirds using ICOLLs and their fringing wetlands for part or all of their life cycles include diverse species predominantly from six major groups (Kingsford 2013):

- grebes (Podicipediformes)
- ducks, geese and swans (Anseriformes)
- pelicans and cormorants (Pelecaniformes)
- egrets, ibises and spoonbills (Ciconiiformes)
- cranes, rails and crakes (Gruiformes)
- shorebirds or waders (Charadriiformes).

They fall into three main categories:

- **Colonial nesting waterbirds** require substantial floods to support large breeding events in floodplain wetlands. They include egrets, ibises, pelicans, cormorants and herons.
- **Non-colonial waterbirds**, including resident shorebird species, generally don't congregate to breed but are still dependent on wetlands for nesting and feeding habitat in which to raise their young. They include waterfowl, grebes, crakes, rails and waterhens.
- **Migratory waterbirds**, such as migratory shorebirds, use a range of wetlands to rest, feed and breed during their annual long journeys between wetlands in Australia and their breeding sites in the northern hemisphere.

Various raptor species also rely on food sources from ICOLL habitats including white-bellied sea-eagles, black-shouldered kites, swamp harriers, and brahminy kites.

The values of fringing wetland and aquatic habitats varies as a function of ICOLL water levels, meaning that opportunities for birds are constantly changing over seasonal to interannual timescales. Significant knowledge gaps exist in the understanding of basic life history and movement patterns of many NSW waterbirds, particularly for cryptic species (Kingsford 2013). In addition, a detailed knowledge of usage connectivity between neighbouring systems is lacking which may be critical for addressing bird conservation in relation to ICOLL entrance management.

Effects of artificial opening on birds

The impacts of artificial opening on birds are not fully understood due to an incomplete knowledge of the ecological function of ICOLLs, and in particular the invertebrate and fish foodwebs that constitute major food sources for birds. More frequent opening at low-level triggers will potentially benefit some bird groups (e.g. intertidal waders) over others that require extensive inundation of fringing wetland habitats. Longer term shifts in habitat types may occur (e.g. seagrass losses, replacement of saltmarsh by mangroves, shoreline recessions, etc.) with flow-on effects for birds. Mechanical and noise disturbance of nesting and roosting habitats for shorebirds (e.g. little tern) may occur due to the operation of machinery undertaking entrance-opening and berm-scraping works. The initiation of mass fish movements and potential fish kills associated with artificial opening may present brief opportunities for birds such as pelicans and cormorants.

Figure 35 ICOLL habitats for waterbirds

ICOLL waterways and their fringing wetlands provide a wide array of habitats for waterbirds including invertebrate feeders (bottom row) and hunters (top row). Little terns do not feed within ICOLLs; however, entrance berms are a preferred nesting habitat.

Climate change

The emerging impacts of climate change will have multiple implications for the dynamics of ICOLL entrances and their management, as well as the ecological function of ICOLL systems. The primary climate change impacts considered here are sea level rise (SLR), changes to the frequency and severity of storm events, and latitudinal migration of marine species.

Hydrodynamic and geomorphic effects of climate change

The entrance berm height is related to wave runup processes which are controlled by ocean water level, wave height, direction and period, and beach slope. Any increase in average ocean water level through SLR will also increase the average berm height. SLR will cause general beach recession along the coast accompanied by landward and upward translation of the berm (Haines & Thom 2007; Hanslow et al. 2000). This will result in higher ICOLL water levels, and increased inundation of low-lying fringing environments. The impact on foreshore wetlands will be either drowning, aggradation in place at the same pace as sea level rise, or migration of these habitats laterally and upslope (Hanslow et al. 2018).

The impact of SLR on flooding due to catchment runoff is complex. Hydrodynamic modelling of Shoalhaven ICOLLs[2] that included raised sea level boundaries suggests that increases to peak flood levels during catchment runoff events are much less than the amount of SLR applied, and that effects are concentrated at the seaward end of the entrance channel without influencing basin levels which are primarily a function of the total volume of water flowing into the basin. These results highlight the need for further detailed analysis of the interactions between flooding and SLR.

In theory the average depth of the marine delta (berm plus the ebb-tidal shoals) should also be related to sea level, thus this may also aggrade with SLR if sufficient sand is available, however the timescale of this response is unclear and is likely to lag the sea level change. Any lag in marine delta response would likely result in an increase in tide range and tidal prism while the entrance is open as entrance attenuation will be reduced.

Climate change may also affect climate patterns including extreme events like droughts and floods. In New South Wales, modelling suggests an overall decrease in annual average rainfall but rainfall extremes are projected to increase, especially during summer–autumn months (see the Department's AdaptNSW website: Climate Projections for your region). This will change the entrance closure index for many ICOLLs with flow-on effects to all parts of the system since they are highly dependent on the entrance condition.

Climate change may affect the intensity, frequency and duration of ECLs with implications for wave overwash and entrance dynamics as well as water level variability. Climate modelling projects a decrease in the number of small to moderate ECLs in winter, and little change in these storms during the summer. However, extreme ECLs in the warmer months may increase in number but extreme ECLs in cool seasons may not change. Projected future changes in ECLs are smaller than the natural variability we see in ECLs over the past few hundred years.

Longer interceding periods of drought will increase the duration of entrance closure in many ICOLLs.

[2] Undertaken as part of flood studies and floodplain risk management studies.

Ecological effects of climate change

Fish population dynamics (e.g. recruitment, growth, survival, abundance) and reproduction (e.g. maturity, fecundity, spawning) are influenced by a range of environmental factors (e.g. temperature, salinity, dissolved oxygen) that are highly likely to be affected by climate change. Changes to environmental cues associated with altered entrance dynamics may affect recruitment and usage of ICOLLs (Gillanders et al. 2011).

Temperature and acidity of NSW estuaries are increasing at rates up to an order of magnitude higher than predicted by global ocean and atmospheric models (Scanes E et al. 2020). The rate of increase is highest in shallow systems, therefore more mature lagoons and creeks are at greatest risk.

The southward migration of tropical fish and invertebrate species may have competitive impacts on local species (Vergés et al. 2019).

Changing environmental and hydrological factors will affect habitats and food resources within ICOLLs. Increased water levels will cause shifts in benthic and fringing vegetation habitats. The expression of these changes will be highly system-specific and will interact with other land-use pressures (Gillanders et al. 2011).

Entrance management in ICOLLs

Photo 7 **Tallow Creek and fringing wetland habitats**
Photo: A Ferguson/DPIE

Overview

Management objectives for the NSW coast are outlined in the Coastal Management Act which aims to facilitate management consistent with the principles of ecologically sustainable development for the social, cultural and economic wellbeing of the people of the State. The Act aims to:

- protect and enhance natural coastal processes and coastal environmental values
- support social and cultural values including Aboriginal peoples’ customary use
- recognise the economic importance of the coast
- promote sustainable land-use planning and decision-making
- mitigate current and future risks from coastal hazards including climate change
- promote integrated and coordinated coastal planning
- support public participation in coastal management.

The Act sets up a process to develop coastal management programs (CMPs) which set the long-term strategy for the coordinated management of land within the coastal zone with a focus on achieving the objects the Act. Guidance on this process is outlined in the Coastal Management Manual (OEH 2018). The development of an entrance management plan becomes a key means of achieving sustainable management of estuaries which close intermittently.

Entrance management in ICOLL systems must make trade-offs to balance the imperatives of maintaining ecosystem processes, protecting assets, and managing community expectations. An overarching principle for management should be the recognition of ICOLLs as a unique system type that does not conform to morphological, hydrological, and ecological paradigms established for other estuary types. A subsidiary to this is the recognition of the wide range of NSW systems within the 'ICOLL' classification. More targeted and effective management decisions can be made by understanding the interactions between system-specific attributes, local coastal processes, and hydrological factors in controlling entrance dynamics, and the acute and chronic impacts of different entrance management actions on water quality, habitats and ecology.

Management strategies should include both short-term and long-term actions to achieve overall goals. Longer term actions should include measures to avoid or reduce the factors leading to the need for entrance management, for example:

- avoiding new development in hazardous areas and areas vulnerable to sea level rise
- encouraging the raising or relocation of houses, roads and other assets over time to reduce existing risk
- improving the water quality of inflows from the catchment through riparian rehabilitation and use of water-sensitive urban design.

Measures to increase public knowledge of ICOLL processes and the benefits of ecologically sustainable management may also be beneficial to dispel common misperceptions. Shorter term actions could involve implementing interim entrance breakout guidelines which meet stringent risk minimisation criteria relating to flooding, as well as avoiding acute impacts on ecosystems. These may need to be supported through enhanced monitoring of key water quality risk factors.

System-specific management models

Conceptual models

A sound and well-articulated understanding of individual ICOLL systems is required for the identification of system-specific risk factors and indicators associated with entrance management practices. Conceptual models (either flow diagrams like Figure 9 or cartoons like Figure 25) are useful for organising existing information on the ICOLL in a relational manner as well as identifying key knowledge gaps. Models should be based on the appropriate ICOLL subtype (Table 2, Appendix A), and characterise the main functional zones (e.g. Table 1). Conceptual models are also a key step underpinning the development of monitoring strategies and mechanistic models (e.g. hydrodynamic models) of the system. Finally, conceptual models are a useful educational tool for improving the understanding of ICOLL processes among stakeholders and the general community (e.g. the Tuggerah Lakes Estuary Management Plan video presentation[3])

Data requirements

Baseline data required for characterisation of ICOLL functional zones and model development includes:

- bathymetry
- distribution of aquatic macrophytes

[3] Tuggerah Lakes Estuary Management Plan video presentation, Central Coast Council 2020.

- sediment quality (grain size and organic matter content)
- high-resolution elevation mapping (e.g. light detection and ranging [LiDAR]) of fringing wetlands and floodplain)
- distribution of fringing wetland communities
- catchment characteristics (size, subcatchment delineation, land use, slope)
- routine and event-based water quality measurements as outlined in the water quality monitoring section above and illustrated in Figure 35
- estimations of groundwater influence
- telemetered water-level logging
- berm dimensions (height, width, slope).

Mechanistic models

These include catchment runoff, flood, hydrodynamic and ecosystem response models, all of which can be useful in estimating responses in ICOLLs to freshwater and oceanic inputs if correctly configured. In certain circumstances, an ICOLL model suite coupled with real-time water quality data could be valuable in determining risks associated with entrance management scenarios. However, model development is expensive, requiring careful design and robust data to provide reliable outcomes, therefore a rigorous cost–benefit analysis of modelling justification should be undertaken.

Catchment runoff models (e.g. Source or MUSIC) can be used to estimate freshwater inputs based on rainfall data, however their accuracy is limited by a number of factors including, but not limited to:

- the density of rainfall stations within the catchment
- the availability of flow data for model calibration
- the dynamics of base-flows and groundwater flows in affecting rainfall-flow responses throughout the catchment
- the impacts of antecedent rainfall conditions.

In some cases, simpler empirical approaches relating rainfall to ICOLL water level may be sufficient to estimate risks.

Hydrodynamic models provide a detailed understanding of the movements of water and associated constituents throughout the ICOLL in response to freshwater inflows, tides, wind and density effects (e.g. Figure 18). Due to the spatial complexities introduced by variable depths and basin geometries, it is often necessary to use three-dimensional hydrodynamic models if the aim is to understand the water quality implications of stratification and wind-driven mixing processes. In addition, the close coupling between ICOLL waterways and their fringing wetland habitats necessitates a variable model domain approach that considers this dynamic.

Ecosystem response models (ERMs) provide estimations of water quality dynamics (e.g. dissolved oxygen fluctuations) in response to the hydrodynamic mixing of freshwater and oceanic inputs. ERMs are available as off-the-shelf biogeochemical models that will interface with most hydrodynamic models, however the appropriate configuration and calibration of ERMs is a highly specialised process requiring detailed data. This process is made especially difficult by the lack of understanding about key ICOLL biogeochemical functions. In addition, the representation of seagrass processes and health in ERMs is generally poorly resolved and is the subject of ongoing research (Delacruz et al. 2014).

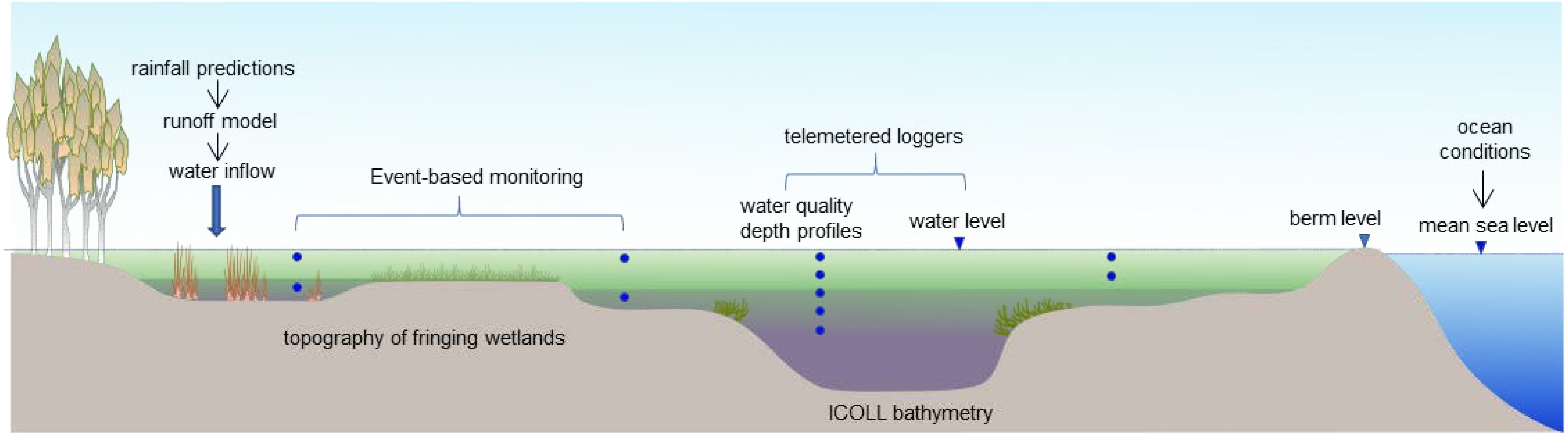


Figure 36 **Monitoring required for assessing ICOLL management options**

Recommended minimum monitoring required to support a risk-based assessment of entrance management options for an ICOLL.

Case study – flood modelling

While flood mitigation might be cited as a reason to manage ICOLL entrances, it is more commonly used to limit nuisance inundation of low-level areas built on flat areas adjacent to the entrance shoals and channels. Most of this land is at elevations between 1 and 2.5 metres AHD so that it is below the beach berm crest height, which is why it can stay inundated for extended periods when lake levels rise. Detailed hydrodynamic modelling of ICOLLs across the NSW South Coast as part of flood studies suggests that if the berm crest is lower than the peak catchment-generated flood level, then the system will break out on the rising limb of the flood. The entrance will then scour sufficiently to pass the arriving catchment-generated instantaneous discharge, so the peak flood level will be within 0.1 metre of what it would be if the entrance was open at the start of the event. The analyses carried out for these studies suggest that entrance management is entirely ineffective in mitigating flooding of development built above a flood planning level of 1% annual exceedance probability (AEP) + 0.5 metre freeboard.

Public education

General community knowledge of the unique functions and ecology of ICOLLs and their linkages to interannual to decadal climatic cycles is generally poor, resulting in common misconceptions and expectations about 'normal' conditions. While local communities can have a wealth of observations about natural cycles in ICOLLs, perceptions are based on the relatively limited time periods of personal experience which may span only part of a multidecadal climatic cycle (e.g. a flood-dominated period). This can lead to beliefs that an ICOLL should always be open, when in fact it may be part of its natural cycle to close during periods of extended drought. There are also misconceptions around the role that entrance opening and tidal flushing can play in improving water quality in ICOLLs, either for perceived or real water quality problems. These misconceptions (and others) can result in widespread and recurring political pressure from local communities to open ICOLL entrances as a panacea for all problems.

There is a clear need for improved communication of the general principles of ICOLL form and function, how these apply to particular systems, and how artificial entrance management affects these functions. While the application of the risk-based framework requires community values and expectations to be taken into account when assessing management options, this is based on the assumption that the community is well-informed about the issues and processes underpinning them. Significant work has been done to provide accessible and plain English summaries of current scientific understanding about ICOLL processes and values in some systems (e.g. Lake Conjola and Tuggerah Lakes[4]), however there is an ongoing need for this work to be updated and expanded as the population pressures increase and new people move into ICOLL catchments.

System-specific guidelines and thresholds

The setting of entrance management thresholds (e.g. water-level triggers for artificial entrance opening) requires making trade-offs between various issues including:

- reduction of nuisance inundation risks, including public parkland, private backyards, floor levels of housing, roads, sewage systems, and aquaculture (e.g. oyster farming) infrastructure
- extreme water quality events and fish kills

[4] Educational video: Don't open that entrance – it's an ICOLL, OEH 2015.

- disturbance of the natural inundation and drainage regimes across the ICOLL habitats
- disturbance of invertebrate and fish ecological cycles
- disturbance of shorebirds
- cumulative impacts of marine sand ingress and associated shoaling of the entrance shoals
- community concerns about ‘poor’ water quality and amenity such as ‘murky water’ and odours
- costs of mechanical interventions to artificially open the entrance and dredge entrance shoals
- poor individual risk management complacency due to misunderstanding, relying on entrance management (that may or may not occur) to reduce risk to life and property during times of flood.

In the short term, a rational assessment of the existing risks associated with each of these issues, and interactions among them, can best be achieved using an appropriate system-specific management model (as outlined above). This approach is consistent with the application of the risk-based framework as required in the preparation of a CMP, and will allow the setting of trigger levels and conditions that minimise risk while maximising beneficial outcomes.

It is crucial to also consider longer term factors such as climate change impacts (e.g. sea level rise, changes in rainfall and storm activity, temperature increases, etc.) and the adaptations required for existing assets and infrastructure, future developments, and the planning that is needed to meet these impacts. Climate change also presents significant challenges for the sustainability and health of ICOLL habitats, in particular fringing wetlands, creating a need to accommodate the landward migration of habitats over time. These challenges present an opportunity for improved management of ICOLLs if adaptations are designed to minimise the need for entrance management and maximise environmental outcomes.

Risk assessment of entrance management options

Entrance management strategies are most commonly focused on risks associated with inundation of assets which are easily quantified by relating ICOLL water level to the RL of various assets within the catchment (Stephens & Murtagh 2012). However, the commensurate risks to ecology are more difficult to assess, requiring a more detailed knowledge of the specific dynamics of the system at the time. In addition, where entrance intervention has been occurring for many years, a range of impacts including changes in vegetation distribution have likely already or partly occurred. For example, avoiding acute impacts (e.g. fish kills) requires knowledge of the risk factors (e.g. decanting) and the risk indicators (e.g. degree of stratification pre-opening and predicted rainfall totals, Table 2). This allows the likelihood of a fish kill to be assessed with much greater certainty. The risk assessment requires real-time data on the water quality status of the system, ocean conditions, and ICOLL water level. Reliable rainfall predictions coupled with a robust runoff model are necessary to assess the likelihood of decanting (low rainfall) or complete system flush (high rainfall).

A comprehensive risk assessment is best facilitated by a combination of telemetered monitoring, real-time modelling and predictive understanding of consequences. This needs to be developed for each ICOLL following consideration of the risk factors and risk indicators in Table 4. The level of detailed modelling should be commensurate with the level of understanding about system processes and the complexity of interacting factors.

Table 4 **Risk factors and risk indicators associated with different entrance management scenarios**

Management issue	Potential entrance management	Risk factors	Risk indicators
Flood mitigation	Artificial entrance opening at trigger threshold	Increased flooding as a result of ocean levels and wave runup ‘Decanting’ resulting in fish kills Insufficient rainfall to fully flush system Acid and hypoxic groundwater inputs post opening Biochemical interactions between ocean water and acid runoff Net sand infill of the entrance compartment resulting in reduced tidal prisms and habitat smothering Rapid entrance closure Longer term shifts in mean water level, water quality, habitats, and ecological communities Coincident ocean wave event which prevents access by excavator Sea level rise making the strategy increasingly unsuccessful over time Physical disturbance or disruption of migratory shorebird breeding and nesting	Trigger threshold level relative to mean sea level Ocean conditions (tide, storm surge, etc.) at the time of opening Degree of shoaling in entrance compartment Degree of stratification pre-opening Predicted and actual rainfall totals Presence and extent of low-lying swamps (hypoxic and acidic water inputs) Presence of migratory shorebirds and their breeding season
Hypersalinity	Low-level opening on incoming tide	Rapid net clogging of the entrance compartment resulting in reduced tidal prisms Highly restricted tidal flushing Rapid entrance closure Smothering of benthic habitats Inducing stratification from ocean water	Morphology of ICOLL (e.g. extent of entrance shoals and flood-tide delta) Degree of shoaling in entrance compartment Ocean conditions (tide, storm surge, etc.) at the time of opening Salinity levels pre-opening Degree of stratification pre-opening
‘Poor’ water quality	Artificial opening during either dry or wet weather	All of the factors above No measurable or perceivable effect on water quality Creation of false expectations in stakeholders and community Precedence	All of the factors above

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Appendix A – Baseline classification and morphometrics of NSW estuaries

Estuary	Class	Catchment area (km^2)	Open water (km^2)	Total estuary area (km^2)	Average depth (m)	Estuary volume (ML)	Perimeter (km)	Total flushing time (days)	Dilution factor	Seagrass area (km^2)	Mangrove area (km^2)	Saltmarsh area (km^2)
Tweed River	Barrier river	1055	17.2	22.7	2.6	56955	246.4	27	1.16	0.81	3.98	0.76
Cudgen Creek	Barrier river	69	1.9	2.1	1.1	2371	22.7	14	0.69	0.01	0.14	0.05
Cudgera Creek	Barrier river	61	0.2	0.5	0.6	250	14.0	6	0.09	0.03	0.15	0.07
Mooball Creek	Barrier river	109	0.4	0.5	0.7	351	13.2	4	0.07	0.02	0.11	0.01
Brunswick River	Barrier river	226	2.0	3.6	1.3	4268	79.2	8	0.22	0.04	1.23	0.31
Belongil Creek	Creek	30	0.1	0.3	0.5	88	6.2	43	0.05	na	0.07	0.08
Tallow Creek	Lagoon	5	0.1	0.1	0.4	47	4.2	24	0.14	na	na	0.00
Broken Head Creek	Lagoon	1	0.1	0.1	0.3	15	1.7	71	0.30	na	na	0.00
Richmond River	Barrier river	6862	31.4	38.4	3.2	119314	678.2	29	0.57	0.32	6.03	0.60
Salty Lagoon	Lagoon	4	0.2	0.2	0.4	69	5.9	102	0.64			
Evans River	Barrier river	76	1.9	2.7	1.1	2637	46.8	6	1.32	0.01	0.41	0.36
Jerusalem Creek	Lagoon	48	0.3	0.3	0.6	179	11.2	25	0.20	na	na	0.00
Clarence River	Barrier river	22055	120.9	132.3	2.2	283001	841.4	31	0.85	0.83	7.65	2.90
Lake Arragan	Lake	9	1.0	1.0	0.8	814	11.8	552	6.37			
Cakora Lagoon	Lagoon	12	0.2	0.4	0.5	114	11.1	121	0.55	0.00	0.00	0.13
Sandon River	Barrier river	132	1.5	2.6	1.1	2393	50.1	4	1.24	0.09	0.57	0.48
Wooli Wooli River	Barrier river	180	2.1	3.7	0.8	2611	63.1	8	0.92	0.09	0.86	0.67
Station Creek	Lagoon	21	0.3	0.3	0.5	132	13.1	50	0.37	na	0.00	0.00
Corindi River	Barrier river	146	0.9	1.9	1.2	1557	34.2	10	0.48	0.02	0.37	0.57
Pipe Clay Creek	Creek	2	0.0	0.0	0.2	2	1.1	52	0.04	na		
Arrawarra Creek	Lagoon	18	0.1	0.1	0.4	44	6.3	24	0.12	0.00	0.01	0.01
Darkum Creek	Creek	6	0.0	0.1	0.3	16	2.9	55	0.08	0.01	0.01	0.00

Estuary	Class	Catchment area (km²)	Open water (km²)	Total estuary area (km²)	Average depth (m)	Estuary volume (ML)	Perimeter (km)	Total flushing time (days)	Dilution factor	Seagrass area (km²)	Mangrove area (km²)	Saltmarsh area (km²)
Woolgoolga Lake	Lagoon	21	0.1	0.2	0.4	67	4.5	53	0.10	na	0.01	0.00
Flat Top Point Creek	Creek	3	0.0	0.0	0.2	5	2.1	55	0.05			
Hearns Lake	Lagoon	7	0.1	0.1	0.4	38	4.6	57	0.21	na	0.00	0.05
Moonee Creek	Barrier river	41	0.2	0.4	1.5	414	10.1	13	0.33	0.03	0.09	0.13
Pine Brush Creek	Creek	7	0.0	0.0	0.2	3	0.8	25	0.01			
Coffs Creek	Barrier river	24	0.3	0.5	0.6	293	11.6	6	0.25	0.00	0.19	0.00
Boambee Creek	Barrier river	48	0.6	1.0	0.8	805	24.7	6	0.39	0.06	0.33	0.03
Bonville Creek	Barrier river	113	1.3	1.7	1.0	1466	37.2	8	0.20	0.09	0.14	0.16
Bundageree Creek	Creek	10	0.0	0.0	0.1	0	0.3	8	0.00			
Bellinger River	Barrier river	1100	6.7	8.2	1.8	14442	145.0	11	0.19	0.13	1.17	0.14
Dalhousie Creek	Lagoon	6	0.1	0.1	0.3	22	4.6	36	0.15	0.00	0.01	0.01
Oyster Creek	Lagoon	17	0.1	0.1	0.4	58	9.2	21	0.12	na	0.00	0.00
Deep Creek	Lagoon	90	1.0	1.7	1.3	1387	26.5	43	0.51	0.01	0.04	0.64
Nambucca River	Barrier river	1299	9.3	12.6	2.0	23227	214.8	16	0.53	0.61	1.45	1.28
Macleay River	Barrier river	11287	20.7	31.6	2.6	70235	363.4	24	0.41	0.96	5.71	4.25
South West Rocks Creek	Lake	4	0.2	0.9	0.8	654	7.2	9	7.54	0.00	0.65	0.11
Saltwater Creek	Lagoon	11	0.3	0.3	0.3	83	9.1	68	0.29	na	na	na
Korogoro Creek	Barrier river	10	0.2	0.3	0.5	124	12.5	4	0.81	0.00	0.06	0.04
Killick Creek	Lagoon	8	0.2	0.3	0.8	236	9.6	167	1.96	0.00	0.05	0.01
Goolawah Lagoon	BDL	4	0.1	0.1	0.4	51	4.7	101	0.59			
Hastings River	Barrier river	3659	23.2	30.0	1.9	52686	433.3	13	0.38	1.46	3.44	1.87
Cathie Creek	Lagoon	105	7.9	13.7	1.1	8379	32.3	319	2.91	0.00	0.00	5.89
Duchess Gully	Creek	11	0.0	0.0	0.2	5	3.4	31	0.02			
Camden Haven River	Lake	589	19.7	32.2	3.6	113802	164.7	81	5.75	10.25	1.41	0.77
Manning River	Barrier river	8124	26.7	34.7	3.0	96259	395.4	32	0.43	1.65	3.91	2.45

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Khappinghat Creek	Lagoon	91	1.0	1.2	0.9	885	33.2	32	0.35	0.00	0.00	0.16
Black Head Lagoon	Creek	2	0.0	0.0	0.2	1	0.8	35	0.02	na	0.00	0.00
Wallis Lake	Lake	1197	59.4	98.7	2.3	217951	403.5	76	7.00	31.90	1.47	5.90
Smiths Lake	Lake	28	7.1	10.0	2.4	23552	29.0	916	36.45	2.96	na	0.00
Myall River	Lake	819	107.3	115.2	4.0	448258	297.4	31	30.98	2.17	3.03	2.67
Karuah River	Barrier river	1448	9.0	17.9	2.2	31221	153.0	9	0.87	0.07	5.07	3.76
Tilligerry Creek	Lake	115	8.3	20.5	2.5	51714	71.8	9	44.66	1.80	6.26	4.14
Port Stephens	Drowned valley	297	102.5	134.4	14.1	1741516	251.4	52	31.44	12.59	12.79	6.49
Hunter River	Barrier river	21367	22.6	47.0	3.3	137089	389.6	20	0.60	0.00	19.22	5.20
Glenrock Lagoon	Creek	7	0.1	0.1	0.3	15	2.2	21	0.09			
Lake Macquarie	Lake	604	97.3	114.1	5.7	646274	320.9	250	57.10	14.63	1.25	0.89
Middle Camp Creek	BDL	5	0.0	0.0	0.2	2	2.2	37	0.03			
Moonee Beach Creek	Creek	3	0.0	0.0	0.1	0	0.4	15	0.00			
Tuggerah Lake	Lake	714	63.3	80.8	2.4	193231	138.1	480	15.52	17.32	0.00	0.13
Wamberal Lagoon	BDL	6	0.1	0.5	1.7	880	6.3	190	4.68	0.44	na	na
Terrigal Lagoon	Lagoon	9	0.3	0.3	0.5	151	5.4	61	0.47	0.00	0.00	na
Avoca Lake	BDL	11	0.7	0.7	0.4	293	10.8	147	0.92			
Cockrone Lake	BDL	7	0.0	0.3	0.6	187	4.2	130	1.06	0.29	na	na
Brisbane Water	Lake	153	19.6	28.3	3.1	84199	126.5	25	20.59	5.58	2.08	1.12
Hawkesbury River	Drowned valley	21624	100.9	114.5	13.8	1541412	808.7	49	6.37	0.91	9.83	2.88
Pittwater	Drowned valley	51	16.3	18.4	9.9	181836	56.2	34	285.56	1.86	0.17	0.03
Broken Bay	Barrier river	13	17.1	17.1	9.8	167615	21.9	33	0.68	0.04	0.00	0.00
Narrabeen Lagoon	Lake	52	1.7	2.3	2.3	5252	21.7	119	3.89	0.62	0.00	0.01
Dee Why Lagoon	BDL	4	0.2	0.3	0.1	13	3.7	55	0.03	0.00	na	0.06
Curl Curl Lagoon	Lagoon	5	0.1	0.1	0.3	21	1.7	47	0.21			

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Manly Lagoon	Creek	17	0.1	0.1	0.4	36	5.6	43	0.07	0.00	0.00	na
Middle Harbour Creek	Drowned valley	77	5.9	6.1	13.4	81900	49.1	46	30.65	0.06	0.14	0.00
Lane Cove River	Drowned valley	95	2.6	3.0	4.2	12600	33.6	14	4.33	0.02	0.36	0.00
Parramatta River	Drowned valley	252	12.2	13.7	5.1	69700	111.8	17	14.14	0.11	1.35	0.09
Port Jackson	Drowned valley	56	28.7	29.1	13.0	376400	100.5	46	32.49	0.34	0.00	0.00
Cooks River	Barrier river	111	1.1	1.2	0.9	1084	37.6	3	0.39	0.00	0.11	0.00
Georges River	Drowned valley	931	20.0	26.6	10.5	271394	221.3	63	17.21	1.93	3.82	0.84
Botany Bay	Bay	55	31.1	39.6	11.4	440816	59.0	40	22.65	5.36	2.30	0.76
Port Hacking	Drowned valley	165	10.3	11.7	9.1	105262	74.3	31	35.92	1.00	0.30	0.13
Wattamolla Creek	Creek	8	0.0	0.0	0.2	8	1.6	46	0.06			
Hargraves Creek	Creek	2	0.0	0.0	0.1	0	0.4	18	0.01			
Stanwell Creek	Creek	8	0.0	0.0	0.2	1	0.6	17	0.01			
Flanagans Creek	Creek	2	0.0	0.0	0.1	0	0.3	9	0.00			
Woodlands Creek	Creek	2	0.0	0.0	0.1	0	0.4	13	0.00			
Slacky Creek	Creek	3	0.0	0.0	0.1	1	0.7	12	0.00			
Bellambi Gully	Creek	6	0.0	0.0	0.2	3	1.5	15	0.01			
Bellambi Lake	Creek	1	0.0	0.0	0.2	7	1.5	22	0.08			
Towradgi Creek	Creek	9	0.0	0.0	0.3	11	3.2	23	0.02		0.00	
Fairy Creek	Creek	21	0.1	0.1	0.4	42	7.5	25	0.04			
Allans Creek	Barrier river	50	1.1	1.2	0.9	1042	16.0	7	0.38		0.02	0.01
Port Kembla	Bay	6	1.4	1.4	6.1	8439	7.8	21	38.54			
Lake Illawarra	Lake	238	27.6	35.8	2.1	74275	88.5	261	7.53	7.97	0.00	0.30
Elliott Lake	Creek	10	0.1	0.1	0.3	27	4.1	41	0.07	0.01	0.01	0.00
Minnamurra River	Barrier river	117	0.5	1.9	1.0	1517	16.8	5	0.27	0.12	0.88	0.33
Spring Creek	Creek	6	0.1	0.1	0.3	15	2.6	49	0.07	0.00	na	na

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Munna Munnora Creek	Creek	4	0.0	0.0	0.1	0	0.5	14	0.00			
Werri Lagoon	Creek	16	0.1	0.1	0.4	62	8.1	37	0.07	0.00	0.00	na
Crooked River	Barrier river	32	0.2	0.3	0.5	141	7.3	4	0.12	0.05	0.01	0.02
Shoalhaven River	Barrier river	7086	21.4	31.9	2.9	86509	271.9	78	0.63	4.24	4.18	2.06
Wollumboola Lake	BDL	34	5.0	6.3	0.8	4979	25.7	438	4.81	1.34	na	na
Currarong Creek	Creek	12	0.0	0.0	0.2	9	3.4	26	0.02			
Cararma Creek	Lake	7	0.0	2.4	1.2	2767	12.9	9	10.19	0.26	0.99	1.09
Wowly Gully	Lagoon	6	0.1	0.2	0.4	71	3.2	64	0.40			0.09
Callala Creek	Creek	20	0.0	0.0	0.1	1	0.4	9	0.00			
Currambene Creek	Barrier river	160	0.8	2.2	1.1	2511	38.2	9	0.44	0.25	0.94	0.27
Moona Moona Creek	Creek	29	0.1	0.1	0.4	58	4.7	36	0.06	0.03	0.05	
Flat Rock Creek	Creek	7	0.0	0.0	0.2	3	1.0	19	0.01			0.01
Captains Beach Lagoon	Creek	3	0.0	0.0	0.3	13	2.4	23	0.09		0.00	
Telegraph Creek	Creek	4	0.0	0.0	0.1	1	0.6	15	0.00			
Jervis Bay	Bay	32	118.3	123.9	16.2	1977656	62.4	56	217.03	5.53	0.06	0.03
St Georges Basin	Lake	316	37.3	40.9	5.3	215079	124.7	471	19.80	3.17	0.28	0.15
Swan Lake	BDL	26	4.4	4.7	2.4	10998	16.2	460	14.65	0.26	na	na
Berrara Creek	Lagoon	35	0.2	0.3	0.5	132	8.0	50	0.14	0.05	na	0.01
Nerrindillah Creek	Creek	17	0.0	0.1	0.3	24	2.9	29	0.04	0.03	na	na
Conjola Lake	Lake	139	6.5	6.7	4.0	26799	58.2	56	5.85	0.17	0.00	0.03
Narrawallee Inlet	Barrier river	81	0.4	1.0	0.7	636	17.1	4	0.24	0.09	0.42	0.18
Mollymook Creek	Creek	3	0.0	0.0	0.1	1	0.9	14	0.00	0.00	0.00	0.00
Millards Creek	Creek	5	0.0	0.0	0.1	1	0.3	8	0.00	0.00	0.00	0.00
Ulladulla	Bay	0	0.1	0.1	3.7	350	1.2	13	18.87	na		
Burrill Lake	Lake	61	3.4	4.4	4.3	17653	34.9	163	7.48	0.76	na	0.24

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Tabourie Lake	BDL	46	1.2	1.5	0.8	1124	22.4	76	0.82	0.22	na	0.04
Termeil Lake	BDL	14	0.6	0.6	0.7	398	10.3	97	0.96	0.01	na	na
Meroo Lake	BDL	19	0.6	1.4	0.9	1297	15.9	170	2.29	0.75	na	na
Willinga Lake	BDL	14	0.1	0.3	0.3	95	7.4	57	0.25	0.17	na	na
Butlers Creek	Creek	3	0.0	0.0	0.2	6	1.8	38	0.04	0.01	na	0.00
Durras Lake	Lake	58	3.1	3.8	1.4	5051	37.9	187	3.51	0.50	na	0.17
Durras Creek	Creek	6	0.0	0.0	0.2	4	2.0	38	0.04			
Maloneys Creek	Creek	8	0.0	0.0	0.2	6	2.1	37	0.04	0.00	0.00	0.00
Cullendulla Creek	Barrier river	15	0.1	1.3	0.9	986	9.0	5	1.63	0.13	0.88	0.17
Clyde River	Barrier river	1723	12.9	17.5	3.0	50737	187.9	13	0.99	0.79	3.31	0.52
Batemans Bay	Bay	28	34.3	34.5	11.1	383484	44.1	38	7.27	0.19	0.00	na
Saltwater Creek	Creek	3	0.0	0.0	0.1	0	0.3	10	0.00			
Tomaga River	Barrier river	92	0.7	1.8	1.0	1411	29.0	6	0.57	0.29	0.35	0.46
Candlagan Creek	Barrier river	24	0.0	0.2	0.4	52	5.5	4	0.09	0.05	0.04	0.07
Bengello Creek	Creek	16	0.0	0.0	0.2	2	1.1	14	0.01	0.00	0.00	0.00
Moruya River	Barrier river	1424	3.7	6.1	1.9	10168	77.7	8	0.26	1.20	0.47	0.79
Congo Creek	Creek	43	0.1	0.1	0.4	45	9.1	23	0.03	0.00	na	0.01
Meringo Creek	BDL	5	0.1	0.1	0.3	24	4.4	37	0.15	na	na	0.01
Kellys Lake	BDL	2	0.1	0.1	0.3	20	2.4	55	0.24	0.00	0.00	0.00
Coila Lake	Lake	48	5.4	7.1	2.3	15442	24.1	405	11.28	1.37	na	0.34
Tuross River	Barrier river	1814	11.9	15.5	1.2	18208	161.8	13	0.41	2.18	0.66	0.80
Lake Brunderee	Lagoon	6	0.2	0.2	0.5	90	4.9	87	0.52	0.03	na	0.02
Lake Tarourga	BDL	6	0.3	0.3	0.6	185	3.9	159	1.24	na	na	na
Lake Brou	BDL	42	2.4	2.5	1.2	2736	15.1	165	2.53	0.00	na	0.09
Lake Mummuga	Lagoon	26	1.3	1.7	1.0	1649	17.0	174	2.39	0.33	0.01	0.02

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Kianga Lake	BDL	7	0.1	0.2	0.4	63	3.3	58	0.31	0.11	na	0.00
Wagonga Inlet	Lake	93	5.9	6.9	5.7	39101	53.3	35	16.48	0.81	0.20	0.02
Little Lake (Narooma)	BDL	2	0.1	0.1	0.4	35	3.0	128	0.65	0.00	0.00	0.00
Bullengella Lake	Lake	1	0.1	0.1	0.4	63	2.3	1259	5.79	0.00	0.00	0.00
Nangudga Lake	Lagoon	9	0.4	0.7	0.7	389	9.9	182	1.31	0.20	na	0.15
Corunna Lake	Lagoon	30	1.9	2.1	1.1	2300	24.6	174	2.62	0.16	na	0.05
Tilba Tilba Lake	BDL	17	0.9	1.2	0.9	865	9.4	234	2.38	0.09	na	0.16
Little Lake (Wallaga)	Lagoon	2	0.1	0.1	0.4	45	2.5	229	1.06	0.00	0.00	0.02
Wallaga Lake	Lake	264	8.1	9.3	3.7	33512	78.3	117	5.91	1.09	na	0.16
Bermagui River	Barrier river	83	1.2	2.2	1.1	2160	33.4	4	1.31	0.27	0.47	0.17
Baragoot Lake	BDL	13	0.5	0.6	0.6	304	7.8	166	1.26	0.01	na	0.08
Cuttagee Lake	Lagoon	53	0.9	1.3	0.9	1130	22.3	102	1.19	0.38	na	0.11
Murrah River	Barrier river	196	0.6	0.8	0.7	500	17.1	6	0.12	0.10	0.02	0.16
Bunga Lagoon	Lagoon	12	0.1	0.1	0.4	41	3.4	44	0.19	0.00	na	0.03
Wapengo Lagoon	Lake	69	2.2	3.7	1.3	4070	19.2	11	3.35	0.42	0.56	0.51
Middle Lagoon	BDL	27	0.3	0.6	0.7	335	8.9	81	0.69	0.21	na	0.05
Nelson Lagoon	Barrier river	27	0.7	1.3	0.9	1078	11.8	9	2.85	0.01	0.49	0.16
Bega River	Barrier river	1935	3.0	3.8	1.9	6371	62.3	21	0.16	0.26	na	0.53
Wallagoot Lake	BDL	27	3.1	4.0	1.4	5342	15.6	1027	15.21	0.77	na	0.12
Bournda Lagoon	Creek	35	0.1	0.1	0.3	27	4.0	31	0.05	0.00	na	0.00
Back Lagoon	Lagoon	31	0.1	0.4	0.6	216	7.7	57	0.46	0.22	na	0.02
Merimbula Lake	Lake	38	3.0	5.6	2.6	12924	19.4	25	20.44	1.64	0.35	0.59
Pambula River	Barrier river	296	3.1	4.7	2.2	9774	34.6	14	1.93	0.71	0.58	0.37
Curalo Lagoon	Lagoon	28	0.5	0.8	0.9	638	8.1	132	1.45	0.18	na	0.09
Shadrachs Creek	Creek	13	0.0	0.0	0.2	1	0.7	16	0.01			

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Nullica River	Lagoon	55	0.3	0.3	0.6	176	7.7	33	0.25	0.01	0.01	0.02
Boydtown Creek	Creek	4	0.0	0.0	0.2	3	2.0	21	0.06			
Towamba River	Barrier river	1026	1.8	2.0	1.1	2050	37.4	8	0.12	0.10	0.02	0.13
Fisheries Creek	Lagoon	6	0.0	0.1	0.3	16	2.9	73	0.18	0.01	na	0.03
Twofold Bay	Bay	11	30.0	30.7	10.9	334559	39.0	37	17.44	0.74	na	0.00
Saltwater Creek	Creek	17	0.1	0.1	0.3	17	3.2	38	0.07			
Woodburn Creek	Creek	14	0.1	0.1	0.3	14	4.6	20	0.08			
Wonboyn River	Barrier river	335	2.9	4.2	2.7	9809	33.9	66	2.15	0.81	0.00	0.52
Merrica River	Creek	61	0.1	0.1	0.4	48	3.7	27	0.05	na	na	na
Table Creek	Creek	17	0.1	0.1	0.3	17	3.2	43	0.08	0.00	0.00	0.00
Nadgee River	Creek	59	0.2	0.3	0.5	90	7.2	39	0.08	0.00	na	0.08
Nadgee Lake	BDL	14	1.2	1.2	0.9	1090	5.8	714	8.34	0.03	na	0.00