

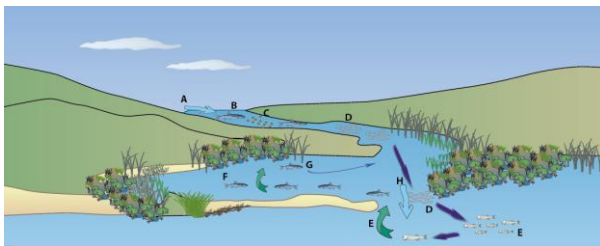


Literature review and factsheet on the known adverse environmental impacts of artificial estuary openings

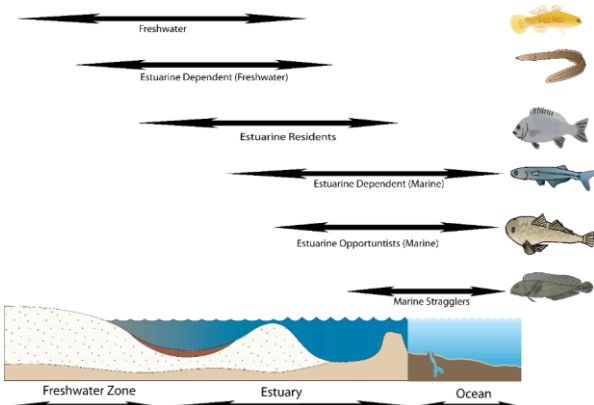
(CCMA Project No. COR-230)

Report prepared by:

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A Freshwater flows provide for longitudinal connections and breeding triggers for adult Australian Grayling. **B** These freshwater fish which use estuaries as juveniles and breed in freshwaters in May. **C** and larvae are washed out to sea **D** in May to July and juveniles begin to mature at sea **E** in May to October sub-adult fish spend time in the estuary before upstream migrations into freshwaters in October to December. **G** High freshwater flows allow mouth opening to allow larvae to move out to sea in May to July and upstream into the estuary and upstream between October to December.



Project Ref: LE2414

18th March 2025

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1 INTRODUCTION

The Corangamite Catchment Management Authority (CMA) commissioned **LLOYD ENVIRONMENTAL PTY LTD** to undertake this review (and factsheet development).

Intermittently Open and Closed Estuaries (IOCEs) represent crucial ecosystems often marked by contention. The closure of estuarine lagoons' mouths leads to rising water levels, which can create challenges for adjacent landholders, caravan parks, urban developments, roads, and other infrastructure. However, these processes, including the closure of beach berms and rising water levels, play vital roles in ecosystem functioning. Estuary mouth openings occur when environmental conditions within the catchment, estuary, and sea align to facilitate opening. Without the simultaneous occurrence of these conditions, the mouth may not open effectively, potentially leading to adverse impacts on ecosystem health, water quality, and geomorphological aspects of the system.

The practice of artificial estuary mouth openings has evolved over time without a solid scientific foundation. Various Catchment Management Authorities (CMAs), particularly Corangamite CMA, have conducted investigations and published a series of projects (Alluvium 2017, 2017; Barton 2008; Barton & Sherwood 2004; CCMA 2012, 2015, 2017; GHD 2021a; Lloyd 2023) addressing the impacts of artificial estuary openings. However, a comprehensive review of this prior work, along with relevant papers and reports from Australia and internationally, is necessary to consolidate existing knowledge and provide authoritative, science-based guidance for better management of IOCEs. Lloyd Environmental has closely participated in many past projects examining the impacts of artificial estuary openings within the Corangamite CMA region and nearby areas. However, there has not been a dedicated review which would potentially identify knowledge gaps which are required to strengthen management advice. This advice will facilitate the implementation of management strategies that allow IOCEs to open naturally, gradually adapting to the impacts of climate change.

This review will offer substantial insights into knowledge gaps and recommend further research and investigations to bolster management advice in the future, establishing a continuous process of review and knowledge enhancement. A fact sheet summarising the review and the current state of knowledge will allow the Corangamite CMA to advocate for considering the adverse environmental impacts associated with artificial estuary openings. Moreover, it will serve as an educational and awareness-raising tool when engaging with other agencies and community members.

Barton & Sherwood (2004) and Lloyd et al. (2012) describes the natural processes associated with various estuary types, including opening and closing estuaries. The condition of estuary mouths greatly affects tidal mixing energy. These mouths follow an annual cycle where winter and spring floods can remove all salt water from the estuary for weeks. As floodwaters recede, oxygenated seawater re-enters, triggering breeding in estuarine species. During summer and autumn, reduced flows allow coastal longshore drift to bring sand into the estuary entrance, reducing tidal exchange and often leading to complete closure for months. Water levels rise due to freshwater inflow and wave overtopping, and in estuaries with fringing wetlands like those of the Aire, Curdies, and Gellibrand Rivers, flooded wetlands provide crucial drought refuges for water birds. Meanwhile, deeper saline water layers can become anoxic due to oxygen depletion.

Beyond artificial mouth opening, estuaries face impacts such as nutrient enrichment, water quality deterioration, introduced species, altered inflows, drainage of floodplains and wetlands, land use changes, vegetation clearance, and climate change. Wave-dominated estuaries are particularly vulnerable because these tend to have sand bars which close off the estuarine lagoon and are subject to development pressures, as seen in the high number of modified estuaries. To address water quality and navigation issues, estuary entrances are

sometimes artificially opened with training walls (these are permanent rock or wooden walls which hold the entrance open e.g. Wallis Lake in New South Wales, Lakes Entrance in Victoria) or by bulldozing the beach berm (e.g. smaller estuaries in New South Wales and Victoria). This can have ecological consequences, such as stranding immature black swans in wetlands, as seen at Smith's Lake and Lake Cathie – Lake Innes in New South Wales. Debates over artificial opening strategies highlight the need to balance various management objectives, including waterbird breeding, fisheries, navigation, water quality, flooding risk, and seasonal wave conditions (Gillanders 2011; National Land and Water Resources Audit 2002).

The MAC Act (2018) in Victoria focuses on ecosystem-based management for marine and coastal environments. It highlights the importance of maintaining, and where necessary, restoring the structure and function of these ecosystems. This ensures the continued use and enjoyment of Victoria's marine resources. The Act also seeks to avoid cumulative or incremental damage to these ecosystems. Other legislation now in place such as the EPBC Act (1999), the FFG Act (1998) and the policy Biodiversity 2027 and the EPA Act 2017 obligate estuary managers to consider the role of artificial estuary openings in managing biodiversity in estuaries and to reduce the demonstrated impacts by assessing these impacts and limiting the numbers of artificial estuary openings to achieve better outcomes for the estuary ecosystems.

The best management approach for IOCEs is to allow natural processes to occur without interference. This principle is widely accepted as the most effective strategy. (Webb McKeown & Assoc., 1994 and NSW National Parks and Wildlife Service, 1999; Victorian Marine and Coastal Act 2018).

2 PROJECT METHODOLOGY

2.1 Information Review

The literature review of Australian and international research papers, strategies, reports, and data was the core and critical task of this project, as everything will build off the review. Our literature search used a variety of keywords and phrases, as efficient searches require targeted search words. Additionally, searching the reference lists of key documents can identify original documents that may not have been identified by other search techniques. Our literature review techniques included searches of a variety of resources, such as:

- CCMA Knowledge Base
- Coastal CMA and Government websites
- Library searches of journals and reports
- Searches of Literature databases via the University of Adelaide Library
- Journals such as Marine and Freshwater Research, NZ Marine and Freshwater Research, US Marine Journals, Royal Society of South Africa
- Internet searches for documents and reports
- Google Scholar search resulting in 25 pages of "estuary opening" search
- A search of the ASM papers database on RBMS website (www.rbms.org.au)
- Key documents provided by CCMA and others
- Lloyd Environmental Publications Database

About 185 documents were retrieved and these are either reviewed or added to the bibliography if they didn't directly contribute to the review.

The information was reviewed and organized into sections on the history of estuary openings, estuary ecological processes, and the impacts of artificial estuary openings. Following this, recommendations were made for the research and management of estuary mouths in Victoria.

3 ARTIFICIAL ESTUARY OPENING HISTORY

Closure of the estuary mouth results from natural processes related to river flows and tidal movements (CCMA, 2020a). However, this closure can be exacerbated by reduced flows due to water extraction. Estuary openings also occur naturally, typically depending on wave processes from January to March when stream flow is low, and on high flows over winter (McSweeney et al., 2020). More often, estuaries are opened artificially, which, due to the system's complexity (including adjoining wetlands and salt wedges), can threaten water quality, ecology, recreation, and agriculture (Dwyer and Lester, 2021).

Over time, the management of artificial estuary openings in Victoria and the Corangamite region has evolved (Figure 1), influenced by available science and policies (or the lack thereof). Inadequate records of natural and artificial openings, along with a lack of relevant research, make it challenging to assess the impacts of artificial openings or to determine the natural regime. Artificial openings have occurred for at least 50 years in most estuaries, but changes in the frequency of mouth openings over this period remain unknown (Barton and Sherwood, 2004).

History Of Artificial Estuary Openings

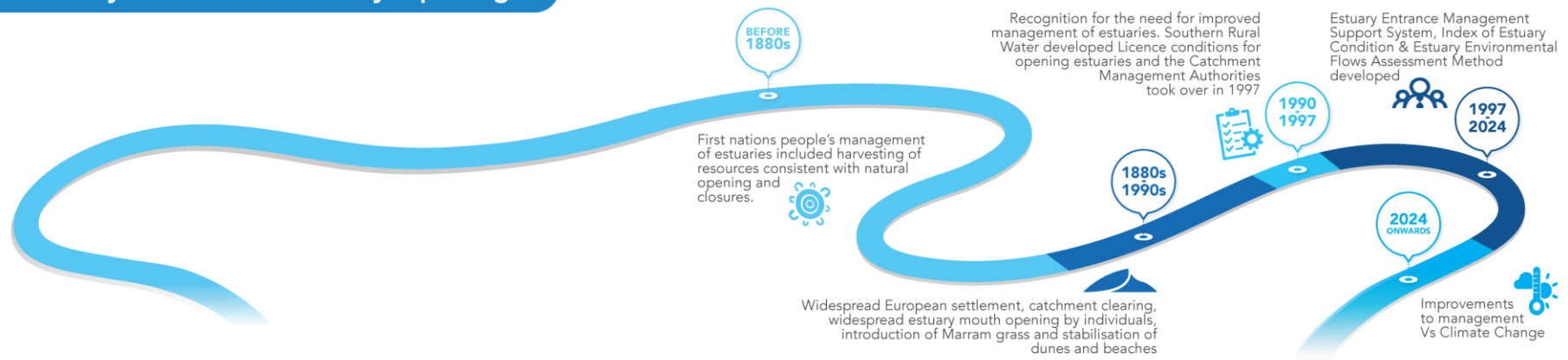


Figure 1: History of estuary mouth openings

Table 1 provides a concise overview of the historical and current management practices of estuary openings, highlighting key developments and considerations.

Table 1: History of Artificial Estuary Mouth Openings

Time Period	Key Events and Management Practices
Many thousands of years ago – 1880s	First Nations people's management of estuaries included harvesting of resources, consistent with natural opening and closures (we are unaware if First Nations people's intervened in estuary openings or not).
1880s to 1990s	Widespread European settlement, catchment clearing, introduction of Marram grass, and stabilization of dunes and beaches. Rivers were opened by various groups with conflicting interests and without authority or supervision.
Early 1990s	Public and management agency concerns about fish deaths led to identifying issues linked to artificial estuary openings: - Extent and duration of wetland inundation - Ecology of aquatic animals and vegetation - Times of wildlife breeding - Fish health - Effect of rapid salinity changes - Recreational activities (fishing, boating) - Sand dune and beach erosion - Access points for equipment - Presence of algal blooms - Effect on mosquito problems - Weather conditions for effective openings
Late 1990s	Southern Rural Water Commission (SRW) formalized concerns into licensing conditions for openings. Catchment Management Authorities took over licensing in 1997. Factors to consider include: - Significant rainfall in the upper catchment - Substantial instream flows towards the river mouth - Offshore winds and tidal conditions - Time of year - Social activities on the water - Effects on wildlife and fisheries - Water quality - Long-term impacts However, licenses often lack detailed guidance on balancing these factors. A specific trigger height for each estuary is specified in the license agreement, and the land manager adjacent to the mouth is generally responsible for opening it. Some estuaries, like the Surrey River, have a Committee of Management (SKM 2000). The Flora and Fauna Guarantee Act (FFG Act 1988) identifies threatened species that may be affected by artificial estuary openings and action statements and estuary managers need to consider the FFG Act in their decisions around artificial estuary mouth openings. www.environment.vic.gov.au/conserving-threatened-species/threatened-list

Time Period	Key Events and Management Practices
Post-2008 (Arundel et al.)	The Index of Estuary Condition (IEC) aims to monitor and assess the health of the estuarine reach of waterways, focusing on five components: physical form, hydrology, water quality, flora, and fish. ARI contributed to the fish, flora, and water quality themes: www.ari.vic.gov.au/research/rivers-and-estuaries/index-of-estuary-condition).
Late 2000s - 2024	Due to concerns over unpermitted estuary openings and the lack of clear guidelines, the Victorian Government developed the Estuary Entrance Management Support System (Keneley et al 2013). This tool aimed to help managers assess the environmental, social, and economic impacts of opening estuary entrances and manage the associated risks (DELWP, 2021a & b). Key policy considerations and guiding principles are outlined in the • Victorian Waterway Management Strategy 2013 (www.water.vic.gov.au/waterways/victorian-waterway-management-program/victorian-waterway-management-strategy - soon to be updated) • Marine and Coastal Act 2018 The nomination of the endangered Open-Coast Salt-wedge Estuaries Ecological Community in Victoria identified that estuary openings were not adequately managing the risks with further investigation and revised estuary management guidelines required. Biodiversity 2037 is Victoria's plan to stop the decline of our native plants and animals and improve our natural environment. Biodiversity 2037 is the Victorian Government's ambitious, whole of government plan to stop the decline of our biodiversity and achieve overall biodiversity improvement over the next 20 years. www.environment.vic.gov.au/biodiversity/biodiversity-plan
2024 Onward: Improved Management vs. Climate Change	Updated Victorian Waterway Management Strategy soon to be released. Regulations under the Marine and Coastal Act 2018 will soon be established for use and development of marine and coastal Crown Land. These regulations will streamline the process for obtaining consent and once made, will replace the general consent. Estuary managers need to comply with the Environmental Protection and Biodiversity Conservation Act 1999 (EPBC Act), which protects Matters of National Environment Significance and the endangered Open-Coast Salt-wedge Estuaries Ecological Community in Victoria. The Victorian Environment Protection Act (2017) reformed environmental protection in the state, introducing Environmental Reference Standards (ERS), which replaced the previous State Environment Protection Policies (SEPP). This legislation also states that if your activity is responsible for a pollution incident, you must restore affected areas back to their original state. Further, in some climate scenarios, artificial estuary openings may no longer be an effective flood mitigation tool. Managers need to assess and limit the number of artificial estuary openings to reduce impacts and achieve better outcomes for estuary ecosystems.

4 EXISTING KNOWLEDGE AND EVIDENCE BASE ON THE ADVERSE IMPACTS OF ARTIFICIAL ESTUARY OPENINGS

Artificial estuary openings have both short-term and long-term adverse impacts on environmental values. In the short term, a single opening or repeated openings within a year can disrupt fish populations, bird habitats, vegetation, and water quality. Long-term repeated interventions over many years can alter the ecological character of estuaries. Conversely, maintaining a closed estuary and allowing floodplain inundation can provide significant ecological benefits.

To comprehend the impacts of artificial estuary openings, it is crucial to understand what defines estuary conditions, the ecological processes involved, and how these factors interact within the overall system (as conceptual models).

4.1 Estuary Condition

According to Bucher and Saenger (1991), an inventory of Australian estuaries and enclosed marine waters highlights the importance of estuarine ecosystems. The Australian Estuaries Database, accessible via CAMRIS, provides comprehensive data on estuary conditions (CSIRO). The National Land and Water Resources Audit (2002) identified mouth opening as a modified condition in estuary assessments.

The Victorian Waterway Management Program, as reported by DELWP (2021a & b), uses the Index of Estuary Condition (IEC) to systematically measure and monitor the environmental condition of estuaries. The IEC framework aligns estuarine assessments with established methods for rivers and wetlands. This framework serves multiple purposes, including reporting on estuarine conditions to communities, guiding state policy and regional planning, and providing benchmarks for environmental conditions. The first statewide IEC benchmark assessed 101 Victorian estuaries (DELWP, 2021).

The Environmental Protection Authority (EPA) Victoria (2011) developed water quality guidelines for healthy estuaries, defining and identifying key environmental parameters (EPA Victoria, 2011).

Climate change poses significant challenges to all estuarine systems (Gillanders 2011; Hallett 2018). Rising sea levels, increasing air temperatures, and altered river hydrology will impact the environmental values of estuaries. Although the precise future conditions are uncertain, it is essential to enhance the resilience of the estuarine community by reducing other pressures. Adaptation strategies must focus on maintaining ecological balance, where some species may flourish while others may decline (Alluvium, 2020).

4.2 Estuarine Processes

Understanding estuarine processes is vital for effective estuary management because these processes define the health and functioning of the estuary. Estuaries are dynamic environments where river flows, tidal movements, and sediment transport interact. By understanding these processes, managers can predict how the estuary will respond to natural events and human interventions, such as artificial openings. This knowledge helps in making informed decisions that balance ecological health with human needs, ensuring the sustainability of the estuary's diverse ecosystems, which support fish, birds, vegetation, and water quality. Moreover, it aids in mitigating adverse impacts, preserving biodiversity, and maintaining the ecological character of the estuary over the long term.

Significant ecological processes that can impact on estuarine ecosystems under reduced estuary flows were defined by Peirson et al, 2002 (Table 2).

Table 2: Major ecological processes by which reduced estuary flows can impact on estuarine ecosystems (Peirson et al, 2002; processes low 9–11 were added by Peirson pers. comm. in Hardie et al. (2006) from Lloyd et al 2012).

Flow component	Process	
	No.	Nature
Low	1	Increased incidence of hostile water quality conditions at depth
	2	Extended durations of elevated salinity in the upper-middle estuary adversely affecting sensitive fauna
	3	Extended durations of elevated salinity in the upper-middle estuary adversely affecting sensitive flora
	4	Extended durations of elevated salinity in the lower estuary allowing the invasion of marine biota
	5	Extended periods when flow-induced currents cannot suspend eggs or larvae
	6	Extended periods when flow-induced currents cannot transport eggs or larvae
	7	Aggravation of pollution problems
	8	Reduced longitudinal connectivity with upstream river systems
	9	Increased retention times in estuary reaches
	10	Nutrient influxes from density dependent saline surface water -shallow groundwater interactions
	11	Reduced longitudinal connectivity with the downstream marine environment (mouth opening connectivity with marine environment) (low flow and high flow)
Middle-high	9	Diminished frequency of flushing of the estuary bed of fine sediments and organic matter – reducing the quality of physical habitat
	10	Diminished frequency of flushing of organic matter from deep sections of the estuary – reducing water quality
	11	Reduced channel maintenance processes
	12	Reduced inputs of nutrients and organic material
	13	Reduced lateral connectivity and reduced maintenance of ecological processes in water bodies adjacent to the estuary
All	14	Altered variability in salinity structure
	15	Dissipated salinity/chemical gradients used for animal navigation and transport
	16	Decreases in the availability of critical physical habitat features, particularly those components associated with higher velocities

When the estuary is artificially opened during periods of low flow and it was previously stratified, there is a risk of releasing the oxygenated surface water layer from the estuary. This can result in a stagnant layer of water with low dissolved oxygen (DO) levels, posing a risk to aquatic fauna (Alluvium, 2017; Figure 2).

Process	Antecedent conditions	Risk factor	Likely drop in DO if risk factor occurs (mg/L) and duration
<i>Process A – Estuarine flora respiration and photosynthesis</i>	- Diurnal pattern in DO observed (presence of significant estuarine flora) - Likely to occur after a long period of estuary closure	Multiple cloudy days in a row (weather changes sharply from sunny to cloudy)	4 mg / L, < 1 day
<i>Process B – Catchment inflow resulting in mixing of water column</i>	- Stratification of the estuary - Low DO levels from bottom of water column (and relatively high DO levels in top of water column)	Spike in catchment inflows (increase of > 20 ML/d in a few hours)	3 mg / L, < 1 day
<i>Process C – Catchment inflows delivering high organic load</i>	- Prolonged dry period where organic load has built up in the waterway upstream of the estuary - High water temperatures accelerate these processes	Large catchment inflows (> 130 ML/d)	7 mg / L, 4 days

Figure 2. Closed estuary water quality processes (Alluvium 2017)

Further, estuarine processes and environmental needs vary significantly over the year, affecting the risk and impact of artificial openings. This is an example for the Aire River estuary in western Victoria (Figure 3), however, a similar analysis needs to be completed for each estuary to ensure the seasonality of processes and environmental needs are understood.

In summer (December to March), the estuary entrance often becomes restricted or closed, creating critical foraging areas for waterbirds, especially during droughts. Deep saline water can lose dissolved oxygen, threatening aquatic life. Artificial openings during this time can also disrupt fish migration and breeding. Artificially opening the estuary during this period poses significant risks.

Autumn often sees high flows and floodplain inundation, crucial for fish life stages and migratory birds. The risks associated with artificial openings remain high during these months due to the potential disruption of these natural processes (Gillanders 2011).

During winter, the estuary entrance tends to be open, aiding in bird migration preparations. Increased inflows at this time help reduce salinity and support some fish recruitment and breeding. The risks of artificial openings are moderate, mainly affecting large shallow water areas needed by birds.

During early spring (August and September) winter storm surges increase and facilitate oxygenated seawater inflow, triggering breeding in estuarine organisms. The risk from artificial openings is high due to the essential processes supporting migratory and nesting birds.

Late spring (October-November) is critical for the breeding of species like Black Bream and Hooded Plovers, where stable water levels are crucial. Reduced river flows and tidal velocities further restrict the estuary entrance, impacting fish migration. This period carries the highest risk for artificial openings due to the potential disturbance to breeding and nesting activities and sensitive ecological transitions taking place (Alluvium 2017).

Month	Summary of estuary processes	Summary of environmental value requirements	Risk of artificial opening to meeting environmental requirements during this period
December		Facilitates waterbird foraging for many waterbird species from all guilds. This is particularly important when other areas in south-east Australia are in drought, and the Aire estuary can play an important role as a drought refuge for these species.	!!
January		Slow filling period advantages macrophytes and fresh/brackish-water herbs.	
February		Supports migration, breeding, and more importantly growth of juvenile fish bred in previous spring. Rapid dropping water level can impact Blue Spot Goby eggs, a species important for the estuary food chain.	
March	Deep saline water progressively loses DO and eventually may become anoxic, particularly in the upper estuary.		
April		The connectivity created by higher flows and floodplain inundation is important for life history stages of many fish species. Galaxiids breeding.	!!!
May		Inundation of Swamp scrub and higher levels of floodplain is important to avoid changes to EVCs.	
June		This is an important time for migratory birds to be fuelling up prior to migration north – this requires large shallow areas of water.	
July	Entrance predominantly open but can shift between open/closed in response to storms/variable river flows.	An open estuary during this time enables germination in late winter (before more inundation in Spring).	!
August	This period resets the estuary. Increased inflows can reduce salinity within the estuary and transport sediment through the estuary.	Galaxiids recruit and grow in estuary (or sea). Mudfish breed late winter in freshwater, larvae move into estuary. Estuary Perch breeding in estuary influenced by freshwater flows.	
September	Winter storm surge can occur when high waves push up the channel when entrance is open. This influx of well oxygenated seawater triggers breeding in many estuarine organisms.		
October	Reduction of river flow and ebb-tidal velocities results in restriction of the entrance channel. Seawater inflow is progressively reduced.	This is an important period for migratory birds returning to the estuary, requiring, freshwater inputs for drinking water, and high productivity resulting from floodplain inundation. This is also a period of waterbird nesting when water levels should not be rapidly altered.	!!!
		Spring is also a period for Black Bream breeding, and estuary openings can reduce spawning success if eggs are washed from the estuary or from the impacts of low DO conditions.	
November		It is also an important period for recruitment of Swamp Scrub and aquatic herbs. This period is also part of the Hooded Plover breeding season, where mechanical and human activity on the beach could impact breeding success. Migration back into the estuary for many fish species (Tupong, Mudfish, Galaxiids, Eels).	

Figure 3: Seasonal risk factors in an estuary (example from the Aire River Valley Alluvium 2020) Summary by month of estuary processes, environmental requirements and risk of artificial openings (! = some risk, !! = moderate risk, !!! significant risk).

4.3 Conceptual models

Conceptual models are useful summaries of the ecological condition and processes within estuaries and can be used when communicating the understanding we have on individual or types of estuaries.

The main processes are represented in Figure 4 which encompass when the wave processes dominate and when fluvial and tidal processes dominate.

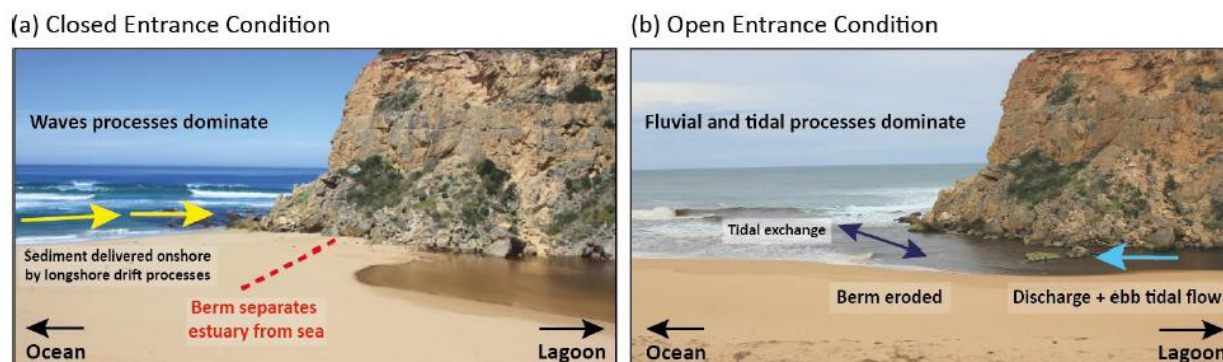


Figure 4. Conceptual diagram of (a) closed and (b) open entrance states. Photos from *EstuaryWatch Victoria* (2017), taken from Alluvium 2017, Gellibrand River mouth.

McSweeney et al. (2017) provides a geomorphic classification of Intermittently Open/Closed Estuaries in Victoria (IOCEs).

Rustomji (2007) detailed the three flow regimes of the wave-dominated Tuross Lake (in NSW) estuary under normal, drought, and flood conditions. During low river flow conditions, high evaporative losses, and seasonal reductions in ocean wave height, the estuary mouth can completely close. Twentieth-century streamflow estimates indicate that hydrologic variability likely caused significant variations in the estuary's opening regime. Since 2000, the estuary has experienced relatively few flood-driven scour events, explaining the current congested state of the estuary mouth (Figure 5).

As indicated by Peirson et al. (2002), water quality is critical. EPA Vic (2011) further details how these factors are interrelated (Figure 6). Water quality is critical to estuaries because it directly affects the health and functionality of these unique ecosystems. Good water quality supports a diverse range of aquatic life, including fish, birds, and vegetation. It ensures that the estuary can provide essential ecological services such as nutrient cycling, habitat provision, and water filtration. Poor water quality, on the other hand, can lead to problems such as hypoxia (low oxygen levels), harmful algal blooms, and the accumulation of toxins, which can harm wildlife and degrade the overall health of the estuary. Maintaining good water quality is essential for sustaining the biodiversity and ecological balance of estuarine environments.

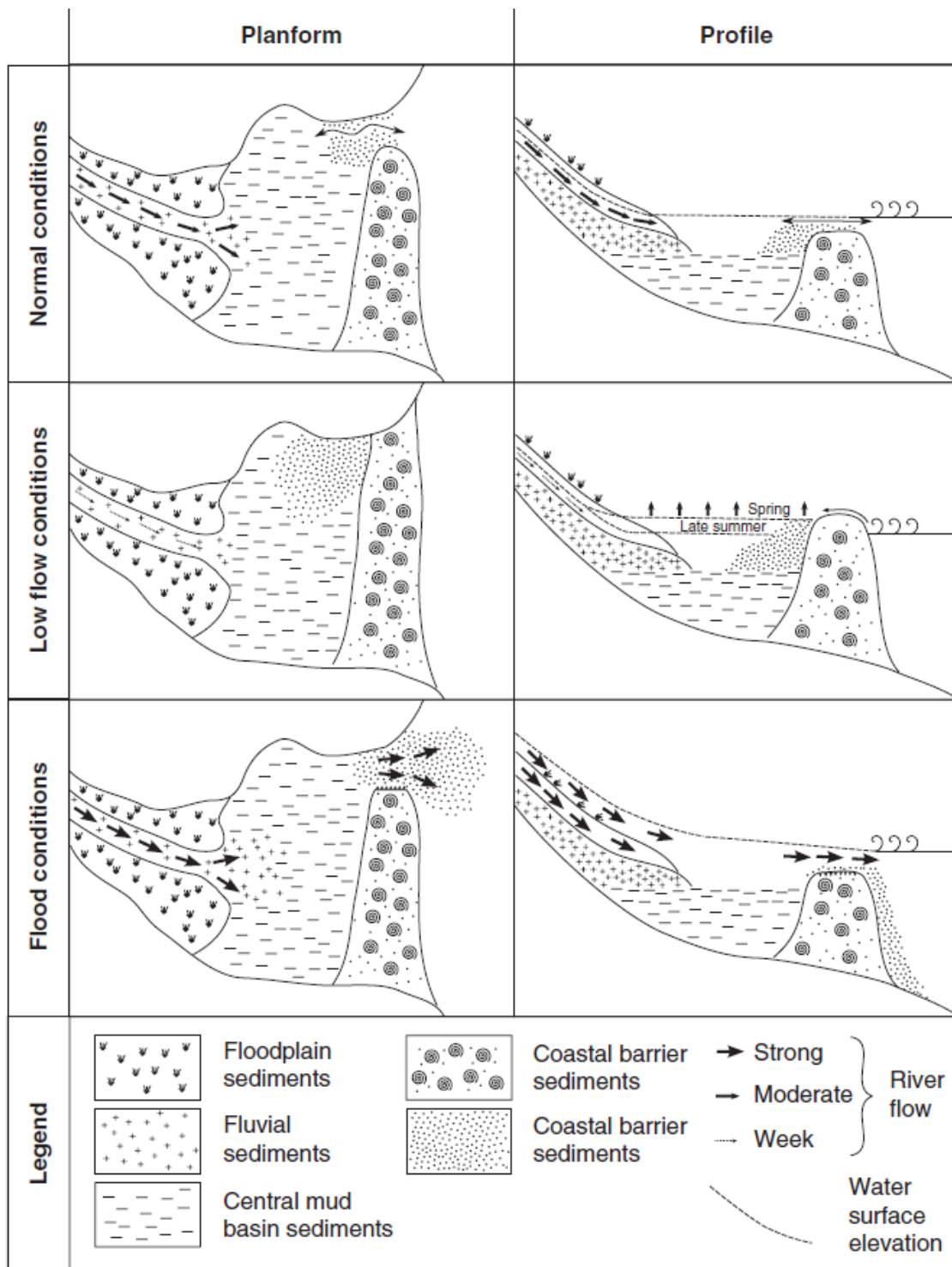


Figure 5: Schematic model of a wave-dominated estuary under normal flow, drought and flood conditions (Rustomji 2007).

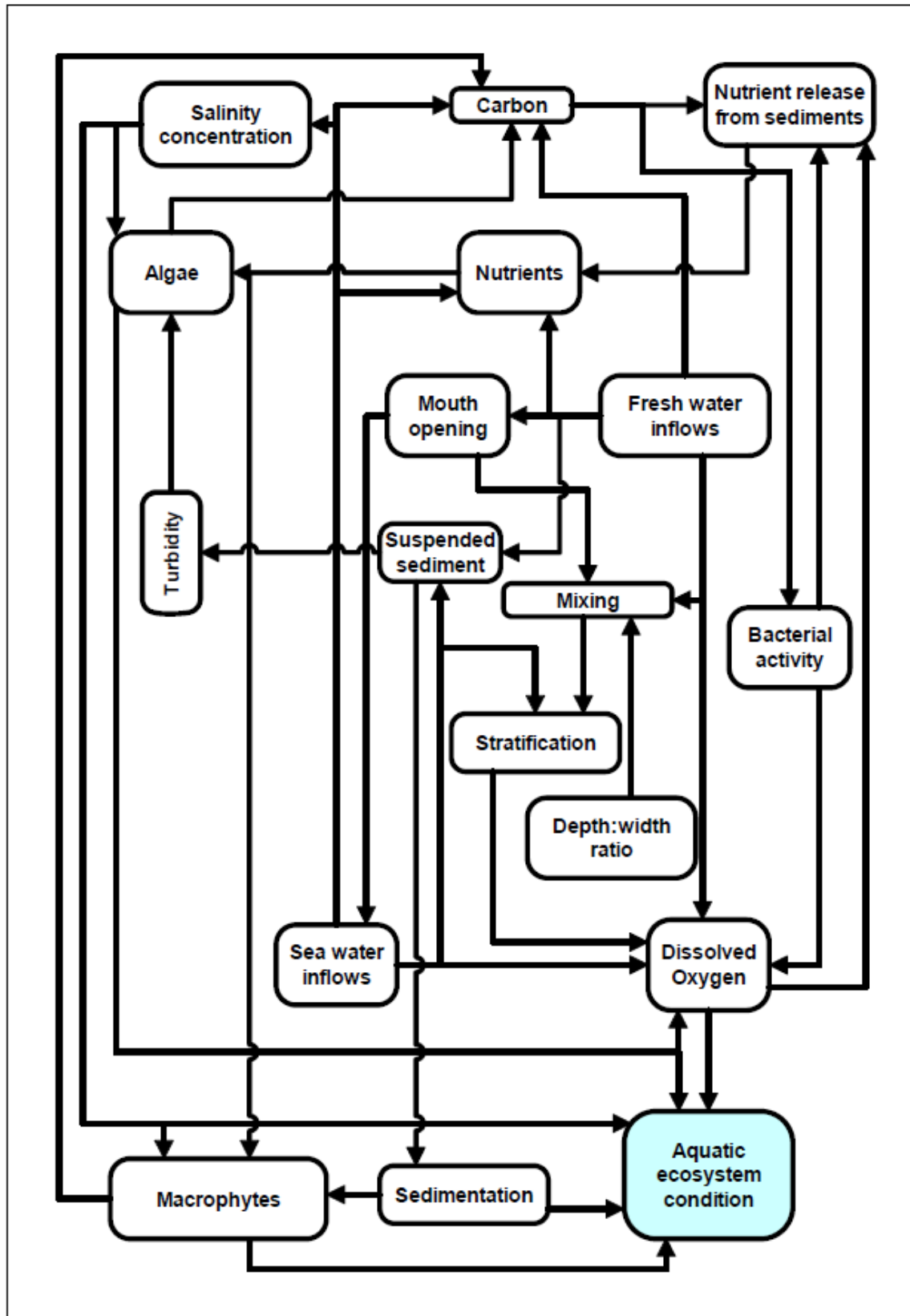


Figure 6: Conceptual model of water quality factors affecting the aquatic ecosystem condition of riverine estuaries (EPA Vic 2011)

Victoria's Estuary Environmental Flow Assessment Methodology (EEFAM; Lloyd et al 2012) uses conceptual models to help understand the relationships of water flow, mouth opening status and water quality in various ecological communities. Two examples of these conceptual models are found in figures 7 and 8. They are intended to cover all estuaries in Victoria and have been applied to multiple estuaries in Victoria. Conceptual models will help define the role of flow in providing habitat and other requirements of ecological assets and in driving ecological, geomorphological, and salinity processes (Lloyd et al. 2012). The example models here are for two "representative objectives" (estuarine reedbeds and common jollytail, a fish) which highlight the needs of key species which overlap with other species within the estuary but because all species are generally adapted to natural cycles within an estuary, provision of key flow components for representative objectives will provide for the ecosystem in general. This is especially so when you cater for multiple representative objective species (Figure 7 and 8).

Estuary ecology and ecosystems are vital as they support biodiversity and provide essential services. Estuaries serve as nurseries for marine species, aiding in the growth of young fish and invertebrates. Additionally, estuaries offer flood control, carbon sequestration, and recreational opportunities, making them invaluable for both natural ecosystems and human communities (Figure 7 and 8).

Representative objective – estuarine reedbed (EVC 952)

Estuarine reedbed has a 'rare' conservation status in the Warrnambool Plains bioregion.

Estuarine reedbed occupies extensive areas of the floodplain approximately 1 to 3 km from the estuary entrance. It lies above the level of the daily high tide and is flooded only when estuary levels are particularly high (Arundel, 2006). This may result from closure of the entrance, unusually high tides, flood flows or a combination of these factors. Estuarine reedbed occurs in freely draining areas which do not retain water when estuary levels recede. Flooding events will usually last several days to weeks and will be separated by periods of several days to weeks.

Flood water will tend to be brackish or fresh. The lower salinities reported from backwater ponds range between 2,700 and 17,000 EC and indicate salinities during general floodplain inundation. The floodplain is underlain by shallow groundwater which will have a lower and less variable salinity. It is likely that groundwater sustains the growth of deep-rooted aquatic macrophytes in the estuarine reedbed.

Estuarine reedbed is dominated by *Phragmites australis* which forms dense and sometimes impenetrable beds. *Phragmites australis* tends to be most dense, tallest and particularly dominant on local rises on the floodplain such as the levees along the river bank. This species is favoured by inundation from late winter to late summer, reaching maximum canopy biomass in mid-late summer, although it responds to floods at other times (Hocking 1989a, 1989b).

Conditions become suboptimal within 1 km of the estuary entrance where surface water and groundwater salinities are likely to be higher. In this area *Juncus kraussii* is the dominant species and occurs with *Scheonoplectus pungens*, *Poa poiformis*, *Baumea juncea* and *Triglochin striata* (Breen 1982).

Conditions are also suboptimal for *Phragmites australis* in deeper floodplain areas within the estuarine reedbed. This may be because the depth of flooding is too great or because there is potential for water to pool and become too saline for *P. australis* through evaporation. These areas support a diverse community which includes the graminoids *Juncus kraussii*, *Isolepis nodosa* and *Poa poiformis* and a herb layer of *Cotula coronopifolia*, *C. reptans*, *Triglochin striata*, *Suaeda australis*, *Selliera radicans* and *Samolus reptans* (Breen 1982). *Sarcocornia quinqueflora* can also be present (pers. obs. M. Cooling). When subject to regular or sustained flooding, presumably in spring, estuarine reedbed can include *Chara* sp., *Nitella* sp. and *Ruppia maritima*. Areas flooded with fresher water can include *Rumex bidens*, *Calystegia sepium* and *Lotus hispidus* (Breen 1982). Ecological and hydrological requirements are shown below.

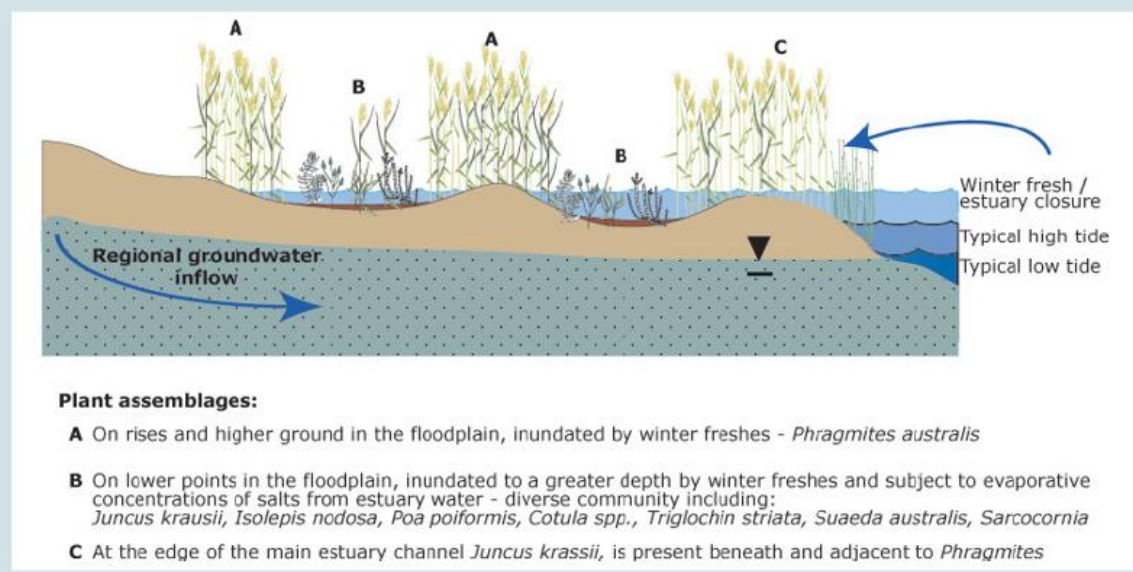


Figure 7: Conceptual model of Estuarine Reedbed EVC (Lloyd et al. 2012)

Representative objective – common jollytail (*Galaxias maculatus*) – estuarine dependent (freshwater derived)

Common jollytails are a widespread and often abundant species in Australia; they are found in coastal lakes and streams at low altitudes from Adelaide in the west to southern Queensland in the east (McDowall and Fulton 1996). They are also present in New Zealand and South America having a Gondwanian distribution. They are a significant species in the ecosystem as a food source for other fish and birds and are a significant invertebrate predator (Koehn and O'Connor 1990; McDowall 1996; Merrick and Schmida 1984). Ecological and hydrological requirements are shown below.

Habitat

Common jollytails are able to utilise a wide range of habitats and have a preference for still or slow-moving waters. They are capable of withstanding freshwater conditions through to very high salinities (well above that of sea water). They are also known to occur in landlocked populations (Koehn and O'Connor 1990; McDowall 1996; Merrick and Schmida 1984).

Movement

In autumn, adults move downstream to the estuary to spawn on a full or new moon and a high spring tide. The eggs hatch and the small, slender larvae are washed out to sea. The juveniles spend winter at sea and return to freshwater about 5–6 months later (Treadwell and Hardwick 2003; McDowall and Fulton 1996; O'Connor & Mahoney. 2000; Crook et al 2006).

Reproduction

Common jollytails spawn amongst vegetation (grasses, samphire and other low vegetation) around estuary entrances when under water at high tide. Most adults die after spawning. The eggs remain out of water for two weeks or more until the next spring tides; the eggs hatch on being re-inundated and the larvae migrate (or are washed out) to sea (McDowall and Fulton 1996). Eggs can tolerate and hatch in salinities ranging from fresh to seawater (Cadwallader and Backhouse 1983).

Information for conceptual model for common jollytail

- Provide flows (low flow freshes) to allow longitudinal connection in the channel for adult jollytail movement down to the estuary in January to March.
- Provide flows to open mouth to allow downstream migration of larvae in autumn.
- Provide flows (winter high flows) to open mouth to allow juveniles to migrate upstream from sea between July and December.
- Provide flow freshes to inundate vegetation beds and instream benches to stimulate invertebrate production for fish condition.

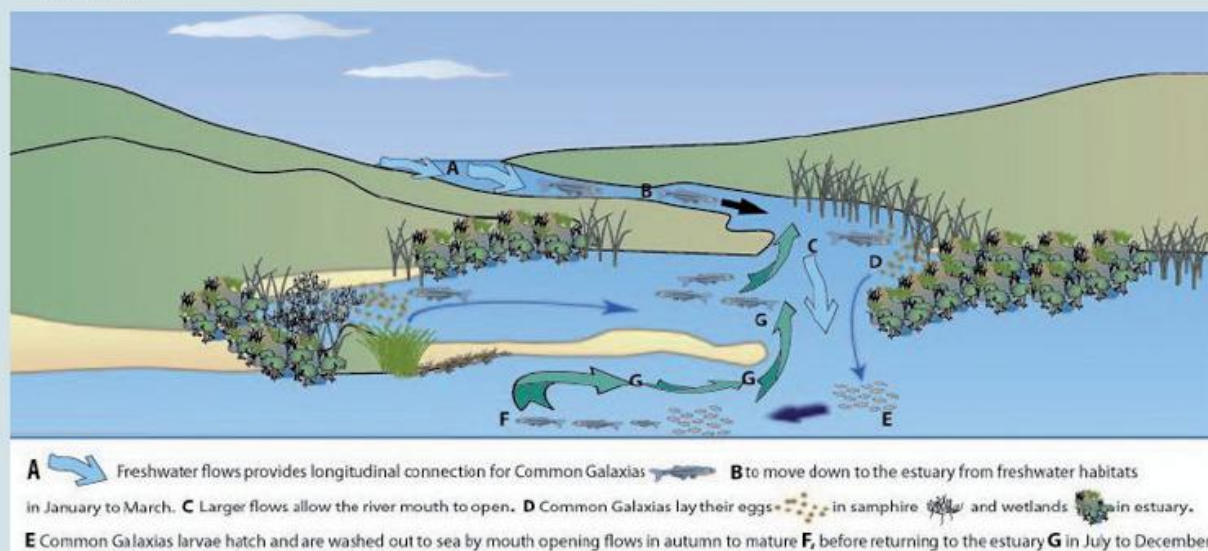


Figure 8: Conceptual model of the fish Common Jollytail (*Galaxias maculatus*; Lloyd et al. 2012)

4.4 Impacts on Estuaries of Artificial Mouth Opening

In Victoria, estuary mouths are often artificially opened to prevent inundation of low-lying land and structures, causing significant ecological changes both short and long term (EEMSS, 2006). Key aspects of this process include the proportion of artificial openings and the height of the water before an estuary is artificially opened.

Artificial mouth openings generally negatively impact estuary health with each one compounding upon the last (Arundel et al., 2009). Estuary closure is controlled by river flow rates, wave height, and wave direction, with only river flow rates being manageable at some times (Alluvium, 2017). Since most artificial openings occur at lower water levels than natural ones (McSweeney et al., 2020), they present a greater threat to resident biota (Dwyer & Lester, 2021).

Impacts can be grouped into 4 categories

- Fauna – fish, invertebrates, waterbirds, etc
- Vegetation – riparian, seagrass
- Water Quality – DO, Nutrients, pH, BGA
- Physical – erosion, sedimentation, physical changes

Fauna Impacts

Fish (and other fauna) deaths in estuarine environments are generally associated with periods of low dissolved oxygen (DO) levels. These events can be triggered by natural processes or human activities, such as the artificial opening of estuary mouths. These interventions not only alter the natural dynamics of the estuary but also compromise its ability to sustain a diverse and healthy ecosystem, ultimately affecting the waterbird communities that rely on these habitats.

4.4.1 Fish deaths

Fish deaths in estuarine environments are generally associated with periods of low dissolved oxygen (DO) levels (Arundel et al., 2009). These events can be triggered by natural processes or human activities, such as the artificial opening of estuary mouths.

Whitfield and Cowley (2018) documented a mass fish mortality event in a South African estuary, where receding water levels trapped fish in the vegetated littoral zone. This natural event, affecting over 20 species, is rare but provided a food source for piscivorous birds and otters. Similar fish entrapment and strandings have been observed in the Aire Valley system in Australia (Alluvium Consulting Australia, 2020) following an artificial estuary opening.

The Gellibrand River estuary has also experienced fish deaths, often linked to low DO levels. Investigations using literature on fish tolerance to DO have shown that such conditions are likely to cause fish deaths, either after the estuary's closure or during its subsequent artificial opening (Alluvium, 2017; Alluvium, 2020).

In the Gellibrand estuary, an additional factor was noted in a 2000 fish death event. Water draining from wetlands with low DO levels filled the estuary channel once the mouth was opened, exacerbating hypoxic conditions (Kelly, 2000). Similar issues have been observed in the Goukamma Estuary, South Africa, where natural salinity stratification, high nutrient concentrations, and microalgal blooms contributed to poor water quality and hypoxia (Kaselowski & Adams, 2013).

In July 2017, the Corangamite CMA reported a mass fish stranding due to an artificial estuary opening in a floodplain wetland (Curdies estuary). Approximately 4,000-5,000 fish

were relocated to the main estuary by Corangamite CMA, Fisheries, and volunteers, preventing their desiccation and exposure to poor water quality (CCMA, 2017).

These findings underscore the complexity of managing estuarine environments, particularly in balancing the needs for artificial openings with the ecological health of the system. Proper assessment and management strategies are crucial to minimize the adverse impacts on estuarine fish populations and overall ecosystem health.

4.4.2 Impacts on Fish Breeding

Black bream are an estuary resident fish which move around an estuary seeking ideal salinities. Black bream are highly mobile, travelling the entire length of estuary and into neighbouring estuaries at times (Williams et al 2017). Black bream breeding in an estuary occurs at specific salinities, below 10g/l (10PPT) and viable eggs float on the halocline. Suitable conditions for spawning and survival of eggs may be disrupted if the water column is disturbed by sudden artificial mouth openings (Nicholson et al 2008). Estuary openings can reduce spawning success by floating eggs being swept out to sea (e.g. Black Bream, during spring and early summer months). Further to this, Black bream eggs fail to develop in waters below 5 g/L (5ppt), so if water is drained from the estuary and the salinity changes (freshwater replaces the brackish water) as the fish spawn, the eggs may not survive. Another requirement of Black bream eggs is that they need at least 50% saturation of dissolved oxygen to grow and hatch successfully (Hassell et al. 2008; Woodland et al 2019).

4.4.3 Impact on Fish Migration and Estuarine Fauna

The migration of fish in and out of estuaries is a crucial ecological process (Koster et al., 2021; Lloyd et al., 2012). The natural opening of estuary mouths plays a significant role in the survival and recruitment of various aquatic species. However, the outcomes of artificial openings are highly unpredictable and can have both beneficial and detrimental effects (Oz Coasts, 2017; Stephens & Murtagh, 2012). Freshwater outflows from estuaries are especially important for diadromous species, such as eels and galaxiids, as they transport eggs and larvae to the marine environment, attract juvenile stages, and trigger adult migrations (Dwyer & Lester, 2021).

The estuary mouth serves as a critical transitional zone for marine fauna (Gillanders 2011, Jones et al., 2021). Significant biomass flux has been observed with fish exiting the estuary during the day and returning at night, underscoring the importance of understanding diel residency patterns of estuarine fish. This connectivity supports a greater diversity of species, facilitating movement between estuarine and marine ecosystems (Jones et al., 2021; Meynecke et al., 2008). The lower reaches of estuaries, such as the Hunter River estuary in NSW, show elevated activity levels as nutrients travel downstream, attracting predators to these transition zones (Jones et al., 2021). This trophic relay effect can influence predator behaviour, with larger predatory fish often preferring these stable environments over upstream areas.

Studies on fish movement through artificial openings in modified estuaries have shown that fish migrate between habitats regardless of the width of the opening, with peak activity occurring at night (Kimball et al., 2010). Nocturnal periods typically see increased fish activity, species richness, and diversity across seasons (Ley & Halliday, 2007; Livingston, 1976; Yeoh et al., 2017). This daily variability may be due to enhanced foraging efficiency and reduced predation risk for smaller fish, driven by the specific feeding and sheltering needs of various species (Gannon et al., 2015; Meynecke et al., 2008; Rountree & Able, 1993, 1997; Taylor et al., 2006). For example, yellowfin bream (*Acanthopagrus australis*) tracked in the Georges River, NSW, displayed elevated activity at dawn and during the day, often near mangrove habitats (McSpadden et al., 2023).

Repeated artificial estuary mouth openings in the Bot River Estuary in South Africa resulted in lower macroinvertebrate diversities than previously existed (De Decker 1987) and similar results in southern Brazil (Netto 2012).

These findings highlight the complex and dynamic nature of estuarine ecosystems and the critical need for careful management of artificial estuary openings to support the ecological integrity of these habitats (Gillanders 2011).

4.4.4 Impact on Waterbird Communities and Diversity

Artificial estuary mouth openings can significantly impact estuarine environmental values, placing these ecosystems at risk. The diverse assemblages of vegetation, fish, and bird species in estuaries indicate that current management practices and climatic conditions are supporting some of the environmental objectives (e.g. CCMA 2015). However, the absence of certain species, in the Aire estuary, such as migratory birds, and the altered inundation regime that affects plant species like Swamp Scrub, suggest that the ecological potential of the estuary is being restricted (Alluvium, 2020). These interventions not only alter the natural dynamics of the estuary but also compromise its ability to sustain a diverse and healthy ecosystem, ultimately affecting the waterbird communities that rely on these habitats.

Artificial openings increase the frequency of estuary mouth openings compared to natural conditions under similar hydrological circumstances. This increased frequency leads to greater ecosystem disturbance and elevates the risk of adverse ecological effects. Each artificial opening disrupts the natural salinity and water level regimes, impacting the habitats and resources available to waterbird communities. The manipulated inundation regime, which fails to sufficiently flood certain Ecological Vegetation Classes (EVCs), further affects the habitat quality and availability for various bird species.

Artificial estuary openings can pose significant risks to bird breeding. Beach-nesting birds, such as plovers, may lose nests if the beach berm collapses after an artificial mouth opening and waterbirds that nest during stable high-water levels are vulnerable to habitat disruption and predation when water levels drop suddenly during from artificial estuary openings (Alluvium 2017, 2020). Artificial estuary openings can strand immature black swans in wetlands, as seen at Smith's Lake and Lake Cathie – Lake Innes in New South Wales. Additionally, changes to estuary plants can affect herbivorous birds by reducing their food sources, while disruptions to fish populations can have negative consequences for piscivorous birds. Effective management of water levels is essential to safeguard these bird species, maintain healthy food sources, and ensure successful breeding conditions (Terörde, AI. & Turpie, JK. 2012; (Alluvium 2017, 2020).

Effective management strategies must consider the ecological impacts of artificial estuary openings to preserve and enhance the environmental values of estuarine ecosystems. This includes maintaining natural hydrological regimes and ensuring adequate inundation of critical habitats to support the diverse assemblages of vegetation, fish, and bird species that contribute to the ecological integrity of estuaries (Alluvium, 2020).

Vegetation Impacts

These artificial openings can lead to subtle, complex, or longer-term ecological changes, such as differing species responses within ecological vegetation classes (EVCs), germination events induced by inundation or drying, successional changes following re-growth, the encouragement or prevention of exotic species invasion, and the eventual long-term recovery of vegetation after impact. Each additional opening causes greater ecosystem disturbance and heightens the risk of adverse ecological effects. When estuary mouths are artificially opened, it can lead to a decrease in water levels, exposing seagrass beds that are

typically submerged. This exposure can have detrimental effects on seagrass health and their ecosystems (Ribeiro et al. 2013. Sinclair et al. 2022). Repeated estuary openings and rapid draw downs is likely to mean that the plant community (structure and species) can rapidly change the types of aquatic plants found (Ribeiro et al. 2013; Sinclair et al. 2022).

4.4.5 Exposure of seagrass beds

The exposure of seagrass beds due to artificial estuary mouth openings can indeed be a significant impact, depending on various factors such as the duration and frequency of the openings, as well as the depth and location of the seagrass beds. When estuary mouths are artificially opened, it can lead to a decrease in water levels, exposing seagrass beds that are typically submerged. This exposure can have detrimental effects on seagrass health and the associated ecosystems (Water Technology, 2010; Edwards et al., 2023).

Deepening the entrance of the Anglesea Estuary is aimed at flushing out water (which is, at times, acidic) but is anticipated to cause a substantial decrease in water levels. Furthermore, deep openings result in extended exposure of seagrass beds in the lower estuary. An expert panel assessment concluded that the drawbacks of this option outweigh its potential benefits (GHD, 2016, 2021a & b).

4.4.6 Vegetation Damage

Sinclair et al. (2022) highlights the detrimental effects of artificial estuary mouth openings on vegetation compared to natural inundation. They show that the impacts from inundation need to be deeper and last longer than previously thought to justify opening estuaries. These artificial openings can lead to subtle, complex, or longer-term ecological changes, such as differing species responses within ecological vegetation classes (EVCs), germination events induced by inundation or drying (Baldwin et al., 2010), successional changes following re-growth, the encouragement or prevention of exotic species invasion (Xue et al., 2018), and the eventual long-term recovery of vegetation after impact (Sparks and Spink, 1998). These changes vary across different EVCs, complicating estuary management.

Artificial estuary mouth openings pose significant risks to estuary environmental values. While the diverse assemblages of vegetation, fish, and bird species indicate that current management and climatic conditions of the Aire River estuary can somewhat support its environmental values and objectives, the absence of some species, such as migratory birds, and the manipulated inundation regime may be restricting certain plant species (e.g., insufficient flooding of Swamp Scrub). This suggests that current management practices limit the ecological potential of the estuary (Alluvium, 2020).

Artificial openings increase the frequency of estuary mouth openings compared to natural occurrences under comparable hydrology. Each additional opening causes greater ecosystem disturbance and heightens the risk of adverse ecological effects (Alluvium, 2020).

Water Quality Impacts

Artificial estuary mouth openings, performed when natural flows are insufficient, introduce nutrient-rich, oxygen-poor water into lagoons, leading to blue-green algae proliferation and poor water quality. In the Curdies Estuary, this process lowers water levels, causing erosion, sedimentation, and harm to aquatic life and vegetation. High stream flows naturally flush the lagoon and improve water quality, highlighting the ineffectiveness of artificial openings. Southwest Victorian estuaries, like Surrey, Gellibrand, Aire River, and Yambuk Lake, face similar issues, with low oxygen levels and habitat loss leading to fish deaths. Understanding oxygen dynamics and stratification during openings is crucial for predicting and mitigating these impacts, especially in the context of climate change (Gillanders 2011; Hallett 2018).

4.4.7 Dissolved Oxygen Conditions

Southwest Victorian estuaries are particularly vulnerable during mouth openings. Many tend to develop a stratified water column nature, often leading to the outflow of oxygen-rich surface water and the potential loss of habitat for estuarine organisms when the mouths are artificially opened. Fish deaths have been observed in Surrey and Gellibrand estuaries, with reports suggesting similar incidents in Aire River and Yambuk Lake (Becker et al., 2009; Alluvium, 2017) indicating its likely to be a widespread problem.

In southwest Victorian estuaries, which are highly stratified, frequent mouth openings can lead to risks such as anoxia in deeper saline waters. Surface water, critical for estuarine organisms requiring dissolved oxygen levels above 5 mg/L, typically exits to sea once the mouth opens. Loss of oxygen-rich surface water can result in significant mortality among estuarine organisms (Water Technology, 2010).

In the Gellibrand estuary, a fish death in 2000 was exacerbated by low oxygen conditions in wetlands associated with the lower estuary, worsened during calm weather that depleted oxygen through organic matter decay. Opening the estuary mouth allowed anoxic water from these wetlands to fill the channel, further endangering aquatic fauna (Kelly, 2000; Dwyer and Lester, 2021).

During closures, estuarine oxygen levels are influenced by processes such as flora respiration, water mixing, and organic load inputs from the catchment. Artificial and natural openings decrease dissolved oxygen levels, with floodplain inundation potentially causing 'blackwater' events, threatening aquatic life (Alluvium, 2017).

Observations as the estuary drained show distinct responses in water column stratification, influenced by varying discharge rates at estuary mouths and fluvial inflows. High-energy openings tend to mix the water column uniformly, while low-energy openings maintain stratification, impacting estuary dynamics differently over different timescales (Edwards et al., 2023).

These insights into oxygen dynamics and stratification changes during estuary openings provide valuable tools for managers to predict and mitigate impacts, crucial in the face of climate change (Gillanders 2011, Hallett 2018, Edwards et al., 2023).

4.4.8 Increased Nutrient Conditions

Nutrient enrichment is a common condition observed in estuaries (largely due to cleared catchment and an increased nutrient run-off from catchments and agricultural practices in the catchment). However, an artificial estuary mouth opening can entrain nutrients from floodplains into the estuarine lagoon and then lower oxygen levels. In the Gellibrand estuary, the opening of the mouth allowed water from the wetland, rich in nutrients, to fill the channel and then depleted oxygen levels (Kelly, 2000). In the Goukamma Estuary, South Africa, natural salinity stratification, high nutrient concentrations, and microalgal blooms led to poor water quality (Kaselowski & Adams, 2013). The study highlighted that vertical stratification limited oxygenation below the halocline, contributing to hypoxia and anoxia in the estuary's middle and upper reaches.

In general, elevated nutrient levels in water bodies led to significant microalgal growth and biomass, particularly in the upper reaches due to agricultural runoff and reduced riparian buffer zones. The presence of cyanobacteria and high phytoplankton biomass confirmed excessive nutrient input (as per the Curdies Estuary, see Lloyd 2023). These findings underscore the necessity for detailed water quality studies (including nutrient levels) to understand and assess the potential for impacts from artificial estuary mouth openings (Dwyer and Lester, 2021).

4.4.9 BGA Blooms and artificial mouth openings

Artificial estuary mouth openings are typically conducted when natural flows are insufficient to keep the mouth open, resulting in poor estuary flushing (CCMA, 2018; 2022). This process can introduce nutrient-rich and oxygen-poor water from adjacent estuarine swamps into the estuary lagoon. Blue-green algae (BGA) spores, present in estuary and river sediments, can rapidly proliferate even after blooms are temporarily removed.

In the Curdies Estuary, artificial openings trigger a series of events that ultimately impact water quality and ecosystem health. As water levels drop following the release of water, low stream flows cause the estuary mouth to close quickly. The lowering of water levels results in nutrient-rich and oxygen-poor water from the estuarine wetlands filling the estuarine lagoon. This poor water quality, particularly low dissolved oxygen levels, can lead to fish and aquatic fauna deaths, loss of aquatic vegetation, and geomorphic impacts such as erosion and sedimentation. Although some BGA may be lost from the lagoon, the spores remaining in the sediment quickly recolonize, thriving in the nutrient-rich and low-oxygen conditions (Lloyd, 2023).

Conversely, during periods of high stream flow, natural openings occur, allowing high flows to retain water in the wetlands and flush the lagoon, effectively removing nutrient-rich sediments. Thus, artificial mouth openings are unlikely to improve water quality or reduce algal blooms and are more likely to contribute to ecosystem decline and exacerbated BGA issues (Lloyd, 2023).

Physical Impacts

Physical impacts involve changes to the estuary's overall size, shape, and water levels. They also affect the natural mixing of fresh and saltwater, which influences the estuary's structure and ecological processes. Estuaries fill and empty with ocean tides, influenced by factors like atmospheric pressure, wind, and sedimentation. In southwest Victorian estuaries, frequent mouth openings can cause anoxia in deeper waters and harm estuarine organisms due to the loss of oxygen-rich surface water. Climate change and increased upstream water extraction may lead to more frequent estuary mouth closures, affecting salinity and oxygen levels (Hallett 2018). Erosion and sedimentation can result from artificial openings and sudden water level drops, with future floods potentially exacerbating these issues or reducing the ability to keep mouths open between floods.

4.4.10 Erosion, sedimentation and estuary mouth status

Erosion and sedimentation occur when river runoff responds to artificial openings and sudden drops in water levels. Artificially open estuaries can also exacerbate movement of berms inward and result in more frequent closures (McSweeney et al. 2020). Apart from factors like sea level variations and storm activity, which can influence how often estuary mouths open, these hydrological shifts suggest a more transient opening pattern.

Artificial estuary openings have already increased the frequency of openings beyond what would occur naturally, disrupting the natural patterns of estuarine dynamics. This alteration in timing and frequency significantly impacts the physical structure and ecological processes of the estuary. In the future, while floods may become more effective in clearing estuary mouths, diminished river base flows between floods could reduce the ability to keep estuary mouths open during those periods (Water Technology, 2010). This could lead to increased pressure for more frequent artificial estuary openings.

There is an increased likelihood of opening failure with time, due to sea level rise affecting berm height. Water Technology (2024) documented an increased risk of an opening failure as the water levels inside the river need to rise in equivalence with sea level rise to have the

same rate of success of openings as at present. That is, with climate change, artificially open estuaries will be less effective.

4.4.11 Salinity

Estuaries respond to oceanic tides by filling and emptying through their mouths. Water flows in during flood tides and out during ebb tides, with narrow mouths potentially throttling water currents and affecting tidal exchange volumes (Barton & Sherwood, 2004). In addition to tides, factors such as atmospheric pressure, wind, wave action, sedimentation, and seasonal river flows also influence saltwater levels within estuaries.

Artificial estuary openings often cause rapid and unnatural mixing of freshwater and saltwater layers, disrupting the natural stratification of the estuary. This sudden mixing can lead to shifts in water temperature, salinity, and oxygen levels, negatively affecting aquatic species sensitive to these changes. Natural estuary openings, by contrast, tend to occur more gradually, promoting a slower and more balanced mixing process. This helps preserve stratification patterns that support diverse habitats and species reliant on the stable layering of fresh and saltwater. Maintaining these natural cycles is crucial for estuarine ecosystem health and resilience.

Climate change and increased upstream water extraction may lead to more frequent and prolonged closures of estuary mouths, impacting water quality by altering salinity and oxygen levels (Hallett 2018). The effects of these changes depend on multiple factors, including the natural frequency of mouth openings and closures (Water Technology, 2010). The exchange of water with the marine environment is closely tied to the cross-sectional area of an estuary's mouth. Frequent increases in estuarine salinity during winter, detected through continuous monitoring, highlight the influx of marine waters via artificial openings, posing challenges to estuarine ecosystems. Elevated salinity disrupts ecosystems adapted to lower salinity levels, potentially harming species dependent on specific salinity ranges (GHD, 2016; 2021a & b). Beyond salinity, the introduction of marine water alters nutrient levels, dissolved oxygen, and sediment dynamics, which collectively impact primary productivity, biodiversity, and the resilience of estuarine habitats to both natural and human-induced stressors (GHD, 2016; 2021a & b).

4.4.12 Impacts on Estuary Condition

Estuary entrances often close naturally when freshwater inflows are insufficient to counter sediment deposition by ocean currents. This closure leads to rising estuarine water levels, inundating low-lying shores and flats, which is crucial for nutrient cycling, sediment deposition, and the life cycles of many species. Periodic inundation of adjacent wetlands and fringing vegetation is essential for their health.

However, reduced freshwater inflows due to extended dry periods, water interception by dams, and climate change can lead to fewer natural flushing events, resulting in longer estuary closures. High water levels and prolonged inundation can cause social and economic issues by flooding nearby agricultural or residential areas, roads, and infrastructure such as jetties and boat ramps.

To mitigate these social and economic costs, estuary entrances are sometimes artificially opened to release excess water. While this can prevent flooding, it can also disrupt the natural estuarine condition. Artificial openings can alter water quality patterns, harm plants and animals (e.g., causing fish deaths), and disrupt animal migration and reproductive cycles.

Due to concerns over unpermitted estuary openings and the lack of clear guidelines, the Victorian Government developed the Estuary Entrance Management Support System. This tool helps managers assess the environmental, social, and economic impacts of opening

estuary entrances and manage the associated risks effectively (DELWP, 2021a & b). In practice, the tool may provide information on likely impacts and perhaps delay artificial estuary openings, but usually doesn't prevent artificial estuary openings (Alluvium 2017, 2020; Barton et al 2008; Keneley 2013).

As of 2021, only 31% of Victoria's estuaries had unmodified or near-unmodified hydrology, while 45% were significantly or extremely modified (DELWP, 2021b). Artificial mouth openings generally negatively impact estuary health with each one compounding upon the last (Arundel et al., 2009). Since most artificial openings occur at lower water levels than natural ones (McSweeney et al., 2020), they present a greater threat to resident biota (Dwyer & Lester, 2021).

5 PLANNING AND ASSESSMENT IMPLICATIONS OF ARTIFICIAL MOUTH OPENINGS

In recent years, artificial estuary openings have been regulated by the Corangamite CMA under By-law No.4 Waterways Protection 2014, a By-law that the Corangamite CMA adopted under the Water Act 1989. At the time this literature review was being written, the By-law was renewed and the Corangamite CMA's approach to regulating artificial estuary openings was being reviewed (Jackson pers. comm.). In the past, the Coastal Management Act 1995, now replaced by the Marine and Coastal Act 2018 has also played a role in regulating artificial estuary openings in Victoria. At the time this literature review was being written, the Department of Energy, Environment and Climate Change (DEECA) were drafting Marine and Coastal Act 2018 regulations for use and development of marine and coastal Crown Land. As part of this process, DEECA were considering how the regulations would be applied to artificial estuary openings (Jackson pers. Comm).

There are two other environmental conservation/planning laws that are applicable to artificial estuary openings which are the EPBC Act (1999) and the Environment Protection Act (2017) and these need to be considered before any estuary opening works are undertaken.

5.1 EPBC ACT 1999

The Environmental Protection and Biodiversity Conservation Act 1999 (EPBC Act) provides the legal framework to protect and manage unique plants, animals, habitats and places, which includes heritage sites, marine areas and some wetlands. The Act also protects listed threatened and migratory species across Australia. The EPBC Act requires managers, developers, individuals to consider the action they are taking on natural systems which may affect listed species, listed ecological communities and matters of national significance. More details are found here www.dcceew.gov.au/environment/epbc/our-role.

The EPBC Act (1999) covers 9 protected matters:

- listed threatened species and ecological communities
- listed migratory species (protected under international agreements)
- wetlands of international importance (listed under the Ramsar Convention)
- world heritage areas
- national heritage places
- Commonwealth marine areas
- Great Barrier Reef Marine Park
- nuclear actions (including uranium mines)
- water resources (that relate to coal seam gas development and large coal mining development).

The first 3 protected matters (Ramsar wetlands, listed threatened species and ecological communities, and listed migratory species protected under international agreements) are the most likely protected matters that are found in estuaries in Victoria.

Given there are ongoing short-term and long-term impacts of artificial openings, and more importantly that these impacts are cumulative in the long-term (section 4.4 and Arundel et al., 2009 Alluvium, 2017, McSweeney et al., 2020), as well as the fact most estuaries have at least the 3 groups of protected matters, each estuary manager should consider the impact of an artificial estuary opening on the estuary concerned.

The Department of Climate Change, Energy, the Environment and Water (www.dcceew.gov.au/) have provided the Protected Matters Tool

(www.dcceew.gov.au/environment/epbc/protected-matters-search-tool) to enable a rapid assessment of the matters that need to be considered when contemplating an artificial estuary opening, as well as other assessment undertaken. The tool provides a report of all Matters of National Environmental Significance (MNES) which then becomes a checklist which can be assessed against the likely impacts on those matters.

In order to demonstrate the importance of the EPBC Act (1999) and the matters of national environmental significance (MNES), this review has applied the protected matters assessment tool to four estuaries in south west Victoria (the Aire, Painkalac, Gellibrand, & Curdies River Estuaries). This revealed that each had at least

- 3 Listed Threatened Ecological Communities,
- 71 Listed Threatened Species, and
- 45 Listed Migratory Species.

All of these need to be considered in any assessment of impacts from artificial estuary openings (Table 3).

Table 3: Matters of National Environment Significance (MNES) of 4 estuaries in the Corangamite CMA area (PMST assessment, August 2024).

Matters of National Environment Significance	Aire	Painkalac	Gellibrand	Curdies
World Heritage Properties	0	0	0	0
National Heritage Places	1	1	1	1
Wetlands of International Importance (Ramsar Wetlands)	0	0	0	0
Great Barrier Reef Marine Park	0	0	0	0
Commonwealth Marine Area	0	0	0	0
Listed Threatened Ecological Communities	3	4	3	3
Listed Threatened Species	71	77	73	77
Listed Migratory Species	46	45	45	49

Collectively, these 4 estuaries (in Table 3) support 88 nationally listed threatened species. Considering the other 5 major estuaries in the Corangamite CMA area (Spring Creek, Thompson Creek, Anglesea River, Erskine River and Barham River Estuary), together these 9 major estuaries support at least 100 nationally listed threatened species. It is possible further nationally listed threatened species may be supported in the 5 other estuaries in the Corangamite CMA region which open and close. While only a subset of the species listed are likely to be water dependent and therefore significantly affected by artificial estuary openings, it is a very significant subset.

Each of these “matters” (the threatened communities or species, or migratory species) need to be assessed to see if an artificial estuary opening is an ongoing and increasing threat to these matters. Without an MNES assessment an estuary manager cannot demonstrate they are proactively managing ongoing artificial estuary openings of that estuary.

Further, special consideration when assessing artificial estuary openings should be given to one of the listed ecological communities in Western Victoria is the "Assemblages of species associated with open-coast salt-wedge estuaries of western and central Victoria ecological community (<https://www.environment.gov.au/cgi-bin/sprat/public/publicshowcommunity.pl?id=132>)" which is regarded as endangered since 2018.

It was thought that the listing of this endangered ecological community should assist with future management planning and implementation. The priority research and conservation actions in the Conservation Advice (prepared for this EPBC listing) should have been reviewed within five years, after evaluating the effectiveness and completeness of the actions (review was due in Oct 2023). Given only parts of the research and monitoring, and other actions, as recommended has been undertaken, it is not possible to demonstrate that this endangered ecological community is being protected under the current management arrangements (EEMSS 2007) or existing estuary management plans. Therefore, a new approach to artificial estuary openings is required as there are ongoing short-term and long-term impacts from these activities.

5.2 Flora and Fauna Guarantee Act (FFG Act 1988)

The Flora and Fauna Guarantee Act (FFG Act 1988) identifies threatened species that may be affected by artificial estuary openings and action statements and the FFG Act also identifies potentially Threatening Processes which may be triggered by artificial estuary openings. Estuary managers need to consider the FFG Act in their decisions around artificial estuary mouth openings. See this website for details www.environment.vic.gov.au/conserving-threatened-species/threatened-list.

5.3 Biodiversity 2037

Biodiversity 2037 is Victoria's plan to stop the decline of our native plants and animals and improve our natural environment (see www.environment.vic.gov.au/biodiversity/biodiversity-plan). Biodiversity 2037 is the Victorian Government's ambitious, whole of government plan to stop the decline of our biodiversity and achieve overall biodiversity improvement over the next 20 years.

5.4 Environment Protection Act 2017

Victoria's new environmental regulatory regime came into effect on 1 July 2021. The Victorian Environment Protection Act (2017) reformed environmental protection in the state, introducing Environmental Reference Standards (ERS), which replaced the previous State Environment Protection Policies (SEPP). This legislation also states that if your activity is responsible for a pollution incident, you must restore affected areas back to their original state (see <https://www.epa.vic.gov.au/about-epa/laws>).

5.5 Marine and Coastal Act (MAC Act 2018)

The MAC Act (2018) in Victoria focuses on ecosystem-based management for marine and coastal environments. It highlights the importance of maintaining, and where necessary, restoring the structure and function of these ecosystems. This ensures the continued use and enjoyment of Victoria's marine resources. The MAC Act also seeks to avoid cumulative or incremental damage to these ecosystems (www.marineandcoasts.vic.gov.au/marine-and-coastal-act).

5.6 Summary

Estuary managers need to take proactive actions to meet requirements under the Environmental Protection and Biodiversity Conservation Act 1999 (EPBC Act) which has provisions to assess impacts on Matters of National Environment Significance and protection for the endangered *Open-Coast Salt-wedge Estuaries Ecological Community* present along the south coast of Victoria.

The FFG Act 1998 and the policy Biodiversity 2027 provide guidance for estuary managers through species listings, identification of threatening processes and action statements to address species decline.

Additional guidance can be drawn from the EPA Act 2017 and the MAC Act 2018.

These requirements obligate estuary managers to alter their approach to artificial estuary openings to reduce the demonstrated impacts by assessing these impacts and limiting the numbers of artificial estuary openings to achieve better outcomes for the estuary ecosystems.

Further detail on the Environment Protection Act 2017 is found here (<https://www.legislation.vic.gov.au/in-force/acts/environment-protection-act-2017/004>); the Environment Protection Amendment Act 2018 (www.environment.vic.gov.au/sustainability/environment-protection-act-2017) and the Environment Protection Amendment Act 2019 (<https://www.legislation.vic.gov.au/as-made/acts/environment-protection-amendment-act-2019>).

The FFG Act (1998) is the pre-imminent legislation protecting threatened species in Victoria (www.environment.vic.gov.au/conserving-threatened-species/threatened-list).

Biodiversity 2037 is Victoria's plan to stop the decline of our native plants and animals and improve our natural environment (see www.environment.vic.gov.au/biodiversity/biodiversity-plan).

The Victorian Environment Protection Act (2017) reformed environmental protection in the state, introducing Environmental Reference Standards (ERS) and these also inform estuary managers in their decision making (see www.epa.vic.gov.au/about-epa/laws).

The Marine and Coastal Act (MAC Act 2018) in Victoria focuses on ecosystem-based management for marine and coastal environments. The Act also seeks to avoid cumulative or incremental damage to these ecosystems (www.marineandcoasts.vic.gov.au/marine-and-coastal-act).

6 KNOWLEDGE GAPS AND RECOMMENDATIONS

6.1 Knowledge Gaps

It is clear that while many artificial estuary openings are practiced in multiple locations there are still many knowledge gaps present. Managing estuarine ecosystems faces several key knowledge gaps. There is a lack of comprehensive records on mouth openings, insufficient hydrological and water quality data, and uncertainties about blue-green algae blooms. The impacts of artificial openings on vegetation, waterbirds, and fish migration are not well understood. The knowledge of ecosystem resilience and recovery is limited. Addressing these gaps is crucial for effective estuarine management. These include:

1. **Past and Present Opening Regimes and Protocols:**

- There is a lack of comprehensive records documenting the conditions (berm and water heights, water quality [salinity, DO, etc]) and timings of natural and artificial mouth openings. Sparse and incomplete records hinder the ability to understand historical patterns and impacts.

2. **Hydrological and Water Quality Data Deficiencies:**

- Limited understanding of velocity-dependent physical habitat requirements within the estuary (Dwyer & Lester, 2021).
- Insufficient data on dissolved oxygen levels and tolerance thresholds for estuarine species during hypoxic events in estuaries. The extent of specific factors that control dissolved concentrations and the overall impact on estuarine biota and surrounding wetlands remains under-researched.
- Limited knowledge of how artificial openings influence nutrient dynamics, biogeochemical cycles, and the occurrence of algal blooms and hypoxic events in estuarine ecosystems (CCMA, 2018 & 2022; Alluvium, 2018, 2020).

3. **Blue-Green Algae (BGA) Blooms:**

- Uncertainty regarding the mechanisms driving BGA blooms following artificial openings and strategies to mitigate their proliferation in nutrient-rich estuarine environments (Lloyd, 2023).

4. **Vegetation and Plant Species Dynamics:**

- Insufficient understanding of how artificial estuary openings affect different Ecological Vegetation Classes (EVCs), such as Swamp Scrub, and their regeneration dynamics (Sinclair et al., 2022).

5. **Waterbird Communities and Biodiversity:**

- Lack of long-term data on the impacts of artificial estuary openings on waterbird communities and their diversity, particularly regarding changes in inundation regimes affecting migratory birds (Alluvium, 2020).

6. **Fish Migration and Survival:**

- Need for studies on the effects of artificial openings on fish migration patterns, survival rates, and recruitment of diadromous species, including their transition between estuarine and marine environments (Koster et al., 2021; Lloyd et al., 2012).

7. **Net Environmental Impact of Artificial Openings:**

- While it is likely that artificial openings may not provide net environmental benefits and do disrupt the natural hydrological function, increase

sedimentation, and restrict natural processes the details and further and specific evidence is lacking (GHD, 2021a & b).

8. **Ecosystem Resilience and Recovery:**

- Inadequate understanding of the resilience and recovery mechanisms of estuarine ecosystems following artificial disturbances, including factors influencing long-term ecosystem health (Sparks and Spink, 1998; Xue et al., 2018).

6.2 **Recommendations**

To effectively manage estuarine ecosystems, a comprehensive approach is necessary. This includes reviewing and updating protocols for artificial estuary openings, enhancing monitoring and data collection, improving research on key ecological gaps, and implementing vegetation and habitat management strategies. Long-term biodiversity monitoring, nutrient and water quality management, and algal bloom prevention are critical. Additionally, focusing on ecosystem resilience, developing adaptive environmental policies, and collaborating with stakeholders will support the dynamic nature and ecological integrity of estuaries.

a. **Review and Update Opening Protocols:**

- Reconsider the current and future drivers for artificial estuary openings, and actions should focus on the need for infrastructure and farmland adaptation rather than relying upon artificial estuary openings as a tool for management.
- Assess impacts from artificial estuary openings against impacts on Matters of National Environmental Significance (EPBC Act 1999), and application of the listed ecological communities in Western Victoria is the "Assemblages of species associated with open-coast salt-wedge estuaries of western and central Victoria ecological community.
- If artificial estuary openings are the only option, then consider allowing the estuary water levels to rise higher before considering artificial openings (GHD, 2021a & b).

b. **Enhanced Monitoring and Data Recording:**

- Improve and enhance monitoring and data collection of berm height and morphology through the EstuaryWatch citizen science program, as this data is crucial for understanding estuarine dynamics and informing management decisions (Estuary Watch database).
- Conduct detailed studies to investigate dissolved oxygen levels, species tolerance to hypoxia, and physical habitat requirements within estuaries.

c. **Improve Research:**

- Improve and enhance research on all knowledge gaps and recommendations in this review as well as the research outlined in the conservation advice for the endangered "Open-Coast Salt-wedge Estuaries Ecological Community".
- **Vegetation and Habitat Management:**
Conduct comprehensive studies to assess the impact of artificial openings on various EVCs and develop management strategies that support the health and regeneration of estuarine vegetation (Sinclair et al., 2022).

- **Biodiversity Monitoring and Protection:**

Implement long-term monitoring programs to evaluate the impacts on waterbird communities and fish populations, informing management decisions to promote biodiversity conservation (Alluvium, 2020).

- **Nutrient and Water Quality Management:**

Enhance research on nutrient dynamics and water quality to understand the causes of algal blooms and hypoxic events. Develop strategies to mitigate nutrient enrichment and improve water quality in estuarine ecosystems (EPA Victoria. 2011 CCMA, 2018 & 2022; Alluvium, 2018, 2020).

- **Algal Bloom Prevention and Control:**

Investigate specific conditions leading to BGA blooms after artificial openings and implement management practices to prevent their occurrence, focusing on maintaining balanced nutrient levels and oxygenation (Lloyd, 2023).

- **Ecosystem Resilience Strategies:**

Research factors enhancing the resilience and recovery of estuarine ecosystems post-artificial disturbances. Integrate findings into adaptive management plans to sustain estuarine health and functionality (Sparks and Spink, 1998; Xue et al., 2018).

d. Environmental Management and Policy Development:

- Review the requirements of the EPBC Act (1999), FFG Act (1998), Biodiversity 2037) and the Environment Protection Act (2017) and other legal instruments to detail how they may influence individual artificial estuary openings and ensure impacts on ecosystem health is avoided if estuary opening works are undertaken.
- Collaborate with stakeholders to develop coastal adaptation plans, including estuary management (or similar) that addresses the impacts of climate change and impacts of artificial estuary openings. This plan should align with Victoria's Marine and Coastal Policy and focus on adapting to local climate changes (Alluvium, 2020).
- Emphasize the importance of maintaining natural estuarine processes to support dynamic water levels, flows, and ecological conditions. Artificial interventions should be minimized to preserve the ecological integrity of estuaries (Becker et al., 2009).
- Integrate findings from existing studies (e.g., Glenelg, Fitzroy, Curdies, Gellibrand, and Aire estuaries) to develop comprehensive management plans that account for both current environmental values and anticipated climate change impacts (Barton and Sherwood, 2004; Alluvium Consulting Australia, 2020).
- Apply an adaptive management approach to estuary management with monitoring and research being used to optimize the ecological health and sustainability of estuarine environments.

By addressing these knowledge gaps and implementing the recommended strategies, the management of artificial estuary mouth openings can be optimized to support the ecological health and sustainability of estuarine environments. This should lead to less frequent artificial estuary openings to reduce impacts and achieve better outcomes for estuary ecosystems.

7 CONCLUSIONS

The role of Catchment Management Authorities (CMAs) in the planning and approval process for artificial estuary openings is shifting towards notifying planning needs and providing estuary managers with information to consider before making decisions.

Estuary managers need to take proactive actions to meet the requirements of the Environmental Protection and Biodiversity Conservation Act 1999 (EPBC Act), which assesses impacts on Matters of National Environmental Significance and protects the endangered *Open-Coast Salt-wedge Estuaries Ecological Community* along the south coast of Victoria. This legislation obligates estuary managers to assess and limit artificial estuary openings to reduce impacts and achieve better outcomes for estuary ecosystems.

By integrating these legislative principles into management practices, decision-makers can enhance the ecological integrity, resilience, and adaptive capacity of estuarine ecosystems. This approach supports environmental conservation and the sustainable use of estuarine resources for future generations.

It is widely accepted that the most effective estuary mouth management approach for IOCEs is to allow natural processes to occur without interference and to adapt infrastructure to prevent impacts. Furthermore, increasing ecosystem resilience to climate change by reducing artificial openings will improve the condition of IOCEs.

8 REFERENCES AND BIBLIOGRAPHY

- Alluvium (2017). Gellibrand River estuary low flow investigation. Report by Alluvium Consulting Australia for Corangamite Catchment Management Authority, Colac.
- Alluvium Consulting Australia. 2020. Aire Valley estuary floodplain project: FINAL REPORT. Report authors: Technical Panel – Lance Lloyd, John Sherwood, David Carew, Sarah McSweeney, Elisa Zavadil, Dion Iervasi and Project team – Amanda Wealands, Amanda Shipp, Emma Hodson. Report Issued to Corangamite CMA, V03 –Final report, 10 September 2020.
- Arundel, H.P., Pope, A.J. and Quinn, G.P. (2009). Victorian Index of Estuary Condition: Recommended Themes and Measures. Technical Report by the School of Life & Environmental Sciences, Deakin University, Warrnambool for the Department of Sustainability and Environment, Melbourne, Victoria.
- Barton, J., Pope, A., Quinn, G. and Sherwood, J. (2008). Identifying Threats to the Ecological Condition of Victorian Estuaries. Technical Report by the School of Life & Environmental Sciences, Deakin University, Warrnambool for the Department of Sustainability and Environment, Melbourne, Victoria.
- Barton J. & Sherwood J. (2004) Estuary opening management in Western Victoria: An information analysis. Parks Victoria Technical Series No. 15. Parks Victoria, Melbourne.
- Becker, A. Laurenson, L.J.B., & Bishop, K. 2009. Artificial mouth opening fosters anoxic conditions that kill small estuarine fish. *Estuarine, Coastal and Shelf Science* 82 (2009) 566–572
- Bucher, D., & Saenger, P. (1991). An Inventory of Australian Estuaries and Enclosed Marine Waters: An Overview of Results. *Australian Geographical Studies*, 29: 370–381.
- CCMA. 2012. Anglesea River 2012-2020: Estuary Management Plan. Corangamite CMA, Colac.
- CCMA. 2015. Aire River Valley 2015-2023: Estuary Management Plan. Corangamite CMA, Colac.
- CCMA 2017. Curdies River estuary fish rescue. July 31, 2017 on <https://ccma.vic.gov.au/coasts-and-marine/curdies-river-estuary-fish-rescue/>
- Water Technology 2010 Hydrodynamic Study of the Snowy Estuary. Report to East Gippsland Catchment Management Authority July 2010.
- De Decker, H. P. (1987). Breaching the mouth of the Botriver Estuary, South Africa: Impact on Its Benthic Macrofaunal communities. *Transactions of the Royal Society of South Africa*, Volume 46, 1987, Pages 231-250. <https://doi.org/10.1080/00359198709520126>
- DELWP (2021a). Assessment of Victoria's estuaries using the Index of Estuary Condition: Background and Methods 2021. The State of Victoria, Department of Environment, Land, Water and Planning, East Melbourne, Victoria.
- DELWP (2021b). Assessment of Victoria's estuaries using the Index of Estuary Condition: Results 2021. The State of Victoria, Department of Environment, Land, Water and Planning, East Melbourne, Victoria.

Dwyer G.K., and R.E. Lester (2021) Gellibrand River Catchment: State of Knowledge Review. Report for the Corangamite Catchment Management Authority prepared by Deakin University. Waurin Ponds, Australia.

Edwards, C., McSweeney, S. & Downes, B.J. 2023. The influence of geomorphology and environmental conditions on stratification in Intermittently Open/Closed Estuaries. *Estuarine, Coastal and Shelf Science* 287 (2023) 108341. Available online 19 April 2023. 0272-7714.

EPA Victoria. 2011. Environmental Water Quality Guidelines for Victorian Riverine Estuaries. Publication 1347.1 January 2011.

GHD. (2016). Anglesea River Estuary Flow Assessment Final Approved Report. Report for Corangamite CMA - Anglesea River Estuary Flow Assessment 31/33459, January 2016.

GHD. 2021a. Anglesea River and Estuary Environmental Flow Study. Final. Report to the CCMA.

GHD 2021b Anglesea River and Estuary Environmental Flows Study 2020 -Summary Brochure Final. Report to the CCMA.

Gillanders, BM, TS Elsdon, IA Halliday, GP Jenkins, JB Robins, FJ Valesini. 2011. Potential effects of climate change on Australian estuaries and fish utilising estuaries: a review. *Marine and Freshwater Research*, 2011, 62, 1115–1131. CSIRO Publishing.

Hassell KL, Coutin PC, Nuggeoda D. 2008. Hypoxia impairs embryo development and survival in black bream (*Acanthopagrus butcheri*). *Mar Pollut Bull.* 2008;57 (6-12):302-6. doi: 10.1016/j.marpolbul.2008.02.045. Epub 2008 Apr 16.

Hallett, Chris S. & Alistair J. Hobday & James R. Tweedley & Peter A. Thompson & Kathryn McMahon & Fiona J. Valesini. 2018. Observed and predicted impacts of climate change on the estuaries of south-western Australia, a Mediterranean climate region. *Regional Environmental Change* (2018) 18:1357–1373. <https://doi.org/10.1007/s10113-017-1264-8>.

Kaselowski, T. and JB Adams. 2013. Not so pristine – characterising the physico-chemical conditions of an undescribed temporarily open/closed estuary. *Water SA* Vol. 39 No. 5 October 2013. <http://dx.doi.org/10.4314/wsa.v39i5.6>

M. Keneley, K. O'Toole, B. Coffey & A. MacGarvey (2013) Stakeholder participation in estuary management: the development of Victoria's Estuary Entrance Management Support System, *Australasian Journal of Environmental Management*, 20:1, 49-62, DOI: 10.1080/14486563.2012.756379

Lloyd, L.N., Anderson, B.G., Cooling, M., Gippel, C.J., Pope, A.J. and Sherwood, J.E. (2008). Environmental water requirements of the Gellibrand Estuary: final estuary FLOWS report. Lloyd Environmental Pty Ltd, [Syndal, Vic.]. Report for the Corangamite Catchment Management Authority.

Lloyd, L.N., Anderson, B.G., Cooling, M., Gippel, C.J., Pope, A.J. and Sherwood, J.E. 2012. Estuary Environmental Flows Assessment Methodology for Victoria. Lloyd Environmental Pty Ltd Report to the Department of Sustainability and Environment, Melbourne Water and Corangamite CMA, Colac, Victoria, Australia.

Lloyd, L. 2023. Curdies River/Estuary Blue-Green Algae Advice. Short report to Corangamite CMA. 23rd February 2023.

www.ccmaknowledgebase.vic.gov.au/kb_resource_details.php?resource_id=5505

Marine and Coastal Act 2018 | legislation.vic.gov.au Part 2- Objectives and guiding principles for the planning and management of the marine and coastal environment.

McSpadden, K.L., Raoult, V., Bennett, M.A. and Gaston, T.F. 2023. Imaging Sonar Reveals Diel Movement of Fish Throughout a Developed Australian Estuary. *Estuaries and Coasts*. <https://doi.org/10.1007/s12237-023-01315-6>.

McSweeney, S.L., Kennedy, D.M. and Rutherford, I.D. (2017). A geomorphic classification of intermittently open/closed estuaries (IOCE) derived from estuaries in Victoria, Australia. *Progress in Physical Geography* 41, 421-449.

McSweeney, S. L., J. C. Stout, I. D. Rutherford, and D. M. Kennedy (2020), Predicting the entrance opening duration of Intermittently Open/Closed Estuaries (IOCE) in Victoria, in *Proceedings of the 9th Australian Stream Management Conference*, edited, Hobart, Tasmania.

National Land and Water Resources Audit. 2002. Australian Catchment, River and Estuary Assessment 2002, volume 1. Commonwealth of Australia, Canberra.

Netto, Sérgio A. & André Menegotto Domingos & Márcia Neunschwander Kurtz. 2012. Effects of Artificial Breaching of a Temporarily Open/Closed Estuary on Benthic Macroinvertebrates (Camacho Lagoon, Southern Brazil). *Estuaries and Coasts* (2012) 35:1069–1081. DOI 10.1007/s12237-012-9488-9.

NSW National Parks and Wildlife Service November. (1999). LAKE INNES NATURE RESERVE PLAN OF MANAGEMENT. NSW NPWS.

Pierson W.T., Bishop K., Van Senden D., Horton P.R. and Adamantidis C.A. (2002) *Environmental Water Requirements to Maintain Estuarine Processes*, Environment Australia, Environmental Flows Initiative Technical report No. 3 (147pp).

Ribeiro, JPN., A Saggio. MIS. Lima and A. Saggio. (2013). The effects of artificial sandbar breaching on the macrophyte communities of an intermittently open estuary. *Estuarine, Coastal and Shelf Science* 121-122 (2013) 33e39

Rustomji, P. 2007. Flood and drought impacts on the opening regime of a wave-dominated estuary. *Marine and Freshwater Research*, 2007, 58, 1108–1119

Sherwood, J. 2006. Environmental Flow Needs of the Bunyip River Estuary. Associate Professor John Sherwood. Deakin University, 27 October 2006.

Steve J. Sinclair, Khorloo Batpurev, Michele Kohout, 2022. Considering vegetation flood tolerance in estuary opening decisions, *Ocean & Coastal Management*, Volume 220, 2022, 106071, ISSN 0964-5691, <https://doi.org/10.1016/j.ocecoaman.2022.106071>.

Terörde, AI. & Turpie, JK. (2012) Use of a small, intermittently-open estuary by waterbirds: a case study of the East Kleinemonde Estuary, Eastern Cape, South Africa, *African Journal of Aquatic Science*, 37:2, 183-190, DOI: 10.2989/16085914.2012.672397

Warry, F.Y., Reich, P., Cook, P.L.M. et al. The role of catchment land use and tidal exchange in structuring estuarine fish assemblages. *Hydrobiologia* 811, 173–191 (2018). <https://doi.org/10.1007/s10750-017-3487-6>

Water Technology. 2024. Exposure Analysis Report Aire Valley Estuary Floodplain Project Part 2 Report for RMCG and CCMA, 9 February 2024.

Webb McKeown & Assoc. 1994. Lake Cathie/Laake Innes Estuary Management Plan. Report to Hastings Council May 1994 with appendices.

AK Whitfield & PD Cowley (2018) A mass mortality of fishes caused by receding water levels in the vegetated littoral zone of the West Kleinemonde Estuary, South Africa, *African Journal of Aquatic Science*, 43:2, 179-186, DOI: 10.2989/16085914.2018.1466685

Williams, J., Hindell, J. S., Jenkins, G. P., Tracey, S., Hartmann, K., & Swearer, S. E. 2017. The influence of freshwater flows on two estuarine resident fish species show differential sensitivity to the impacts of drought, flood and climate change. *Environmental Biology of Fishes*, 100, 1121–1137.

Woodland, R.J., Thomson, J.R., Mac Nally, R., Reich, P., Evrard, V., Wary, F.Y., Walker, J.P., Cook, P.L.M. 2015, Nitrogen loads explain primary productivity in estuaries at the ecosystem scale, *Limnology and Oceanography*, Vol. 60, Issue. 5, pp1751-1762

Woodland, RJ, Warry, FY, Zhu, Y, Mac Nally, R, Reich, P, Jenkins, G, Brehm, D, Cook, PLM. 2019. Role of benthic habitat structure and riverine connectivity in controlling the spatial distribution and ecology of estuarine fish. *Marine Ecology Progress Series*, INTER-RESEARCH, DOI: 10.3354/meps13116

8.1 Bibliography

Aldo S. Steffe, Jeffrey J. Murphy, Douglas J. Chapman, Geoff P. Barrett and Charles A. Gray. 2005. An assessment of changes in the daytime, boat-based, recreational fishery of the Tuross Lake estuary following the establishment of a 'Recreational Fishing Haven'. NSW Department of Primary Industries - Fisheries Final Report Series. No. 81. ISSN 1449-9967. December 2005

CCMA. 2012. Anglesea River 2012-2020: Estuary Management Plan. Corangamite CMA, Colac.

Hassell KL, Coutin PC, Nuggeoda D. 2008. Hypoxia impairs embryo development and survival in black bream (*Acanthopagrus butcheri*). *Mar Pollut Bull.* 2008;57 (6-12):302-6. doi: 10.1016/j.marpolbul.2008.02.045. Epub 2008 Apr 16.

Lamontagne, S. et al., 2007. *Analysis of fish diet from the Murray Estuary using C, N, and S isotopes*. Water for a Healthy Country National Research Flagship, CSIRO.