The Effect of Mouth State and Morphology on Stratification in Victorian Estuaries

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A thesis submitted to the School of Geography in partial fulfilment of the Bachelor of Science Degree (Honours).

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Abstract

Intermittently Open/Closed Estuaries (IOCE) are estuaries with entrances that close to the ocean. Closed periods cause problems for estuary managers because flooding of the estuarine basin often occurs. To mitigate flooding, estuary managers artificially open IOCE by digging a channel from the basin to the ocean to drain the estuary. Mass fish deaths have been directly caused by artificial openings. Artificially opening IOCE when highly stratified, and when the bottom layer of the water column is deoxygenated, is the primary cause of fish deaths. The draining period following the opening is when large drops in dissolved oxygen occur and this period is associated with large changes in mouth morphology.

Despite this, it is not well known what dominant processes affect stratification in IOCE and how these processes change during open/closed periods and in IOCE of different sizes and morphologies. There is also a lack of physicochemical measurements (e.g. dissolved oxygen and salinity) during the draining phase and this has limited prior work in linking changes in stratification to changes in mouth morphology. This project aims to fill these knowledge and data gaps by (1) determining what the dominant processes that affect stratification in IOCE are and how these change (a) during open/closed periods and (b) between IOCE of different sizes, and (2) providing a better understanding of how stratification of physicochemical variables is affected by hydrodynamic and morphological changes following artificial openings.

To meet the first aim, a Principal Components Analysis (PCA) was undertaken on decadal scale time series data. Physicochemical and physical-environmental data (e.g. upstream fluvial discharge, maximum air temperature) during open/closed phases from six different IOCE in Victoria (Australia) of varying sizes and morphologies were sampled. To meet the second aim, fieldwork was undertaken at two artificial openings: the Aire River and Painkalac Creek (Victoria). Physicochemical depth profiles, mouth morphology, upstream water velocity and estuary water level were measured at regular intervals for 24-48 hours after the opening to capture changes in stratification and mouth morphology.

From the PCA, it was found that indicators of river inflow and air temperature were the dominant variables affecting stratification. There was a marked difference in the response of stratification to river inflow and maximum air temperature between small and large catchment area IOCE that reflected seasonal variation in stratification. In smaller catchment IOCE, during winter and spring increases in freshwater river inflow overtop the saline water layer, increasing stratification. As river inflow decreases and air temperature increases over summer, the freshwater layer evaporates away, decreasing stratification. In larger catchment estuaries, over winter and spring, saline water is flushed out of the estuary by increased river inflow, decreasing stratification. Then over summer, as river inflow decreases, there is only enough river inflow to overtop the saline water layer, increasing stratification.

Analysis of fieldwork data shows two distinct responses to artificial openings. The opening at Painkalac Creek was a small, low energy opening with a small decrease in water level (0.3m) and low discharge at the mouth (maximum of 5-6m^3/s). This led to little changes to stratification during the measuring period. At Aire River, there was a much larger drop in water level (>1.0m) and discharge at the mouth was >30 times larger than Painkalac Creek. This higher energy opening caused the estuary water column to become mixed before saline water was flushed out from the estuary by freshwater from upstream. These changes to the water column were found to be related to changes in morphology at the mouth.

The results from the PCA analysis provide us with a better understanding of what conditions lead to high degrees of stratification and how stratification in IOCE may change into the future. This will enable estuary managers to identify high risk periods for artificial openings and reduce mass fish deaths in the future. The results from the fieldwork data analysis are important because the size and energy of the opening are affected by what time of day the estuary is artificially opened and the initial dimensions of the channel that is dug between the IOCE basin and the ocean. These variables are easily manipulated by estuary managers. By having more control over what rate of drainage occurs, mass fish deaths can be prevented in the future.

Key Words

Estuaries, IOCE, Physicochemistry, Stratification, Geomorphology

Declaration

This thesis is submitted to the School of Geography at The University of Melbourne in partial fulfillment of the requirements for completing the Bachelor of Science (Honours). This is to certify that this thesis comprises only my original work, except where due acknowledgement has been made in the text to referenced work.

Callum Edwards
13/11/2020

1 Introduction

Intermittently Open/Closed Estuaries (IOCE) are estuaries that temporarily close to the ocean by the formation of a wave-built beach berm. 93% of estuaries in Victoria are classified as IOCE and they are common on wave-dominated coasts worldwide (McSweeney, Kennedy & Rutherfurd 2017). IOCE are important because they provide environmental, ecological, economic, and social benefits. They provide spaces for recreation and tourism and habitats for many important plant and animal species (Haines 2006). Closed periods cause problems for estuary managers because raised water levels cause flooding. To mitigate these risks estuary managers artificially open IOCE by manually digging a channel through the berm to the ocean. Further encroachment of property and infrastructure onto IOCE floodplains has caused public pressure for artificial openings to increase in some IOCE (Haines, Tomlinson & Thom 2006). For example, landholders with farms surrounding Aire River, Victoria, lost large amounts of income when high water levels cut off access from roads and destroyed pastures in May 2020 (Bell 2020).

In some cases, artificial openings can lead to severe ecological consequences. There are many cases of mass fish deaths occurring following artificial estuary openings in Victoria (Becker, Laurenson & Bishop 2009) and overseas (Whitfield 1995). The issue of mass fish deaths is an ongoing problem in Victoria with one occurring at the Surrey River just recently (July, 2020) (Neal 2020). The main cause of mass fish deaths is undertaking artificial openings when the water column is highly stratified (Becker, Laurenson & Bishop 2009).

Stratification is where there are two distinct layers of water in the IOCE water column (Fig. 1.1). Stratification occurs when more dense marine water sinks to the bottom of the water column, leaving a freshwater layer on top and a saline water layer at the bottom. Over time, the dissolved oxygen in the bottom layer decreases as benthic organisms use up the available oxygen (Gale, Pattiaratchi & Ranasinghe 2006). When an estuary is artificially opened, the top oxygenated layer flows out to sea and leaves the deoxygenated water behind, lowering dissolved oxygen levels to a point where both freshwater and saltwater fish species can no longer survive (Becker, Laurenson & Bishop 2009).

There are many factors that affect vertical mixing and stratification in IOCE such as wind, tides and upstream discharge and the relative influence of these processes differs between open and closed phases (Gale, Pattiaratchi & Ranasinghe 2007; Sherwood, Mondon & Fenton 2008). However, the dominance of these processes in determining stratification during open and closed phases has not been well studied. Another major knowledge gap is how the processes affecting stratification differ between IOCE of different catchment areas and morphologies.

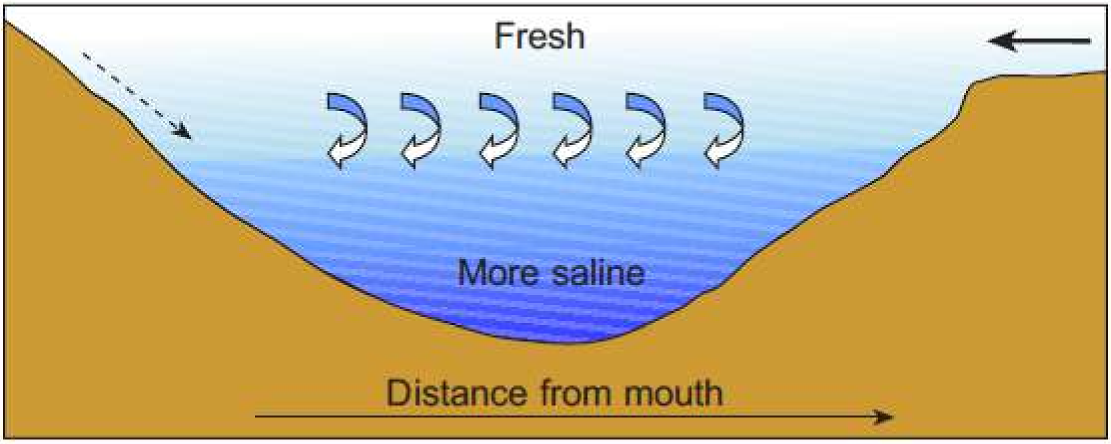

Figure 1.1: Conceptual diagram of a stratified estuary with a freshwater top layer and a saline water bottom layer (Snow & Taljaard 2007).

Another common trend influencing mass fish deaths is that the most severe changes in water quality and stratification tend to happen whilst the estuary is draining (Becker, Laurenson & Bishop 2009; Stacey et al. 2017). Despite this, there is currently a major spatial and temporal data gap of depth profile water quality measurements whilst the estuary is draining and immediately after drainage. What is needed to bridge this knowledge gap are measurements taken at an hourly temporal resolution and across different locations within IOCE. These measurements would be able to capture the changes in stratification and estuarine mixing during the draining period. In general, few studies link physicochemical variables (e.g. dissolved oxygen) with mouth state. Filling these knowledge and data gaps will directly help estuary managers better understand the risks of artificial openings to help prevent mass fish deaths in the future.

1.1. Aims & Objectives

To address this knowledge gap, the aims of this study are as follows:

(1) To determine what the dominant processes that affect stratification in IOCE are, and how these change during open/closed periods and between IOCE of different sizes.

(2) To better understand how stratification of physicochemical variables are affected by hydrodynamic and morphological changes during and following artificial openings.

These aims will be achieved through the following research objectives:

(1) Determine the relationships between stratification of physicochemical variables and physical-environmental variables in different sized IOCE.

- Physicochemical variables are chemical parameters of water that are affected by both physical and chemical processes (e.g. dissolved oxygen)
- I have defined physical-environmental variables as a broad group of climatic, hydrological, morphological, and physical variables that are known to affect stratification in IOCE (refer to Chapter 2.4 and 4.1; Table 2.1)

The broad suite of processes that affect mixing and stratification of IOCE are well studied but these studies rarely sample at a sub monthly temporal scale (Gale, Pattiaratchi & Ranasinghe 2006; Snow & Taljaard 2007; Sherwood, Mondon & Fenton 2008). Additionally, the dominant processes affecting stratification during different mouth states and how this differs between differently sized IOCE has received much less attention. Through the analysis of historic physicochemical, climate and geomorphic data, the important relationships between physical-environmental variables (e.g. rainfall, maximum air temperature, upstream discharge, length of opening/closure) and stratification of physicochemical variables (e.g. dissolved oxygen, salinity and water temperature) will be extracted. By determining these relationships, estuary managers will better understand what conditions lead to stratification and can then undertake artificial openings under conditions which are less harmful to estuarine biota.

(2) **Develop a conceptual model of changes in stratification of physicochemical variables during the draining phase after an artificial opening and how this links to geomorphic changes at the mouth from field data.**

Currently there is no physicochemical data sampled at a high enough temporal resolution to capture the changes in water quality and stratification during the draining phase following an artificial opening. Field data measuring physicochemical depth profiles at hourly intervals will capture these changes and fill this data gap. The conceptual model developed from field data will demonstrate how stratification changes following artificial estuary openings due to variability in mouth morphology and estuary water level. The conceptual model will inform estuary managers of the risks of artificial openings during the draining phase and constrain the timings of high-magnitude change.

1.2 Thesis Plan

To achieve the aims and objectives, a review of existing literature on IOCE geomorphology, water quality, hydrodynamics and artificial estuary openings is undertaken in Chapter 2. Chapter 3 provides the necessary background information to understand the study sites chosen. Chapter 4 outlines the methods used to gather and analyse the data. Chapter 5 summarises the results of the study, broken down into (1) historic data analysis and (2) fieldwork results, categorised by field site. In Chapter 6, the results are interpreted and discussed in terms of knowledge advancements on prior research and the aims and objectives of the project, before the conclusions of this study are made in Chapter 7.

2 Literature Review

2.1 Introduction

Water quality issues and flooding associated with prolonged entrance closures are a persistent problem for IOCE globally, including in Victoria (Whitfield et al. 2012; Stacey et al. 2017). Poor water quality in IOCE has caused major ecological issues such as low oxygen conditions, eutrophication, and algal blooms (Adams & Niekerk 2020). Artificial openings undertaken during periods of poor water quality have caused severe problems such as mass fish deaths (Whitfield 1995; Becker, Laurenson & Bishop 2009; Stacey et al. 2017). These persistent environmental issues highlight the importance of determining what physical processes cause poor water quality in IOCE.

IOCE differ to other estuary types because they have varying mouth states. The entrance state directly controls the internal functioning of the estuary and the processes which affect water quality (Gale, Pattiaratchi & Ranasinghe 2006; Snow & Taljaard 2007; Whitfield et al. 2012). However, the link between water quality and IOCE mouth state has been rarely made, especially in Victorian IOCE. This literature review will seek to determine how IOCE geomorphology, hydrodynamics, management, and water quality interact with each other during varying mouth states. It will bring together existing data or case studies, identifying major knowledge gaps which my thesis will aim to fill.

2.2 IOCE Environmental Setting & Classification

Estuary type and morphology can be broadly determined by the relative dominance of tide, wave, and river processes (Fig. 2.1). IOCE are classified as a subcategory of wave-dominated estuaries (Roy et al. 2001).

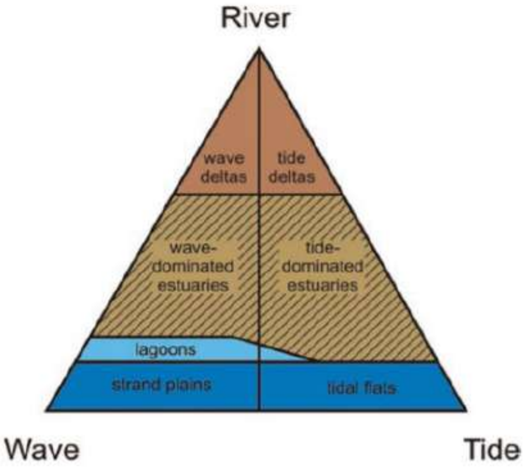

Figure 2.1: The classification of estuaries based on the dominance of river, wave and tidal processes (Skilbeck, Heap & Woodroffe 2017). Here IOCE correspond with 'lagoons' in the figure.

Globally, IOCE are found on wave-dominated, microtidal coastlines in the temperate mid-latitudes (McSweeney et al. 2017). In Australia, these estuaries have small tidal prisms and have rivers that have a low and variable annual discharge (Roy et al. 2001; Rustomji 2007). More specifically, in Australia they occur on coastlines with a significant wave height >1.25m and a tidal range <2 m (McSweeney et al. 2017). IOCE are found in these settings because the shifting dominance of wave and fluvial processes causes the entrance to open and close (Ranasinghe & Pattiaratchi 2003). The main processes that affect the morphology of the IOCE basin and mouth are water and sediment discharge, land use, climate, sea level, estuary geomorphology and coastal and barrier beach change (Rich & Keller 2013).

Estuaries are dynamic over geological timescales and represent alternate periods of infilling and incision. Under stable sea levels, estuaries are infilled from both marine and fluvial sediments. As the estuary basin matures and infills, the water area of the estuary decreases as the central mud basin is filled with sediment until the estuary becomes completely channelised (Roy et al. 2001; Sloss, Murray-Wallace & Jones 2007) (Fig. 2.2). The stage of estuarine maturity can influence many ecological and physical processes. For example, as an estuary approaches its mature stage and continues to infill, the intertidal area decreases within the estuary, reducing habitat diversity which reduces biological productivity (Saintilan et al. 2016). The stage of maturity also affects physical characteristics such as how estuarine waters are mixed, turbidity and depth (Roy et al. 2001). These processes are important for estuarine water quality (Roy et al. 2001). Therefore, the maturity and basin morphology of an estuary is an important characteristic when considering the water quality of an estuary and can drive diversity in form and in functioning (Saintilan et al. 2016).

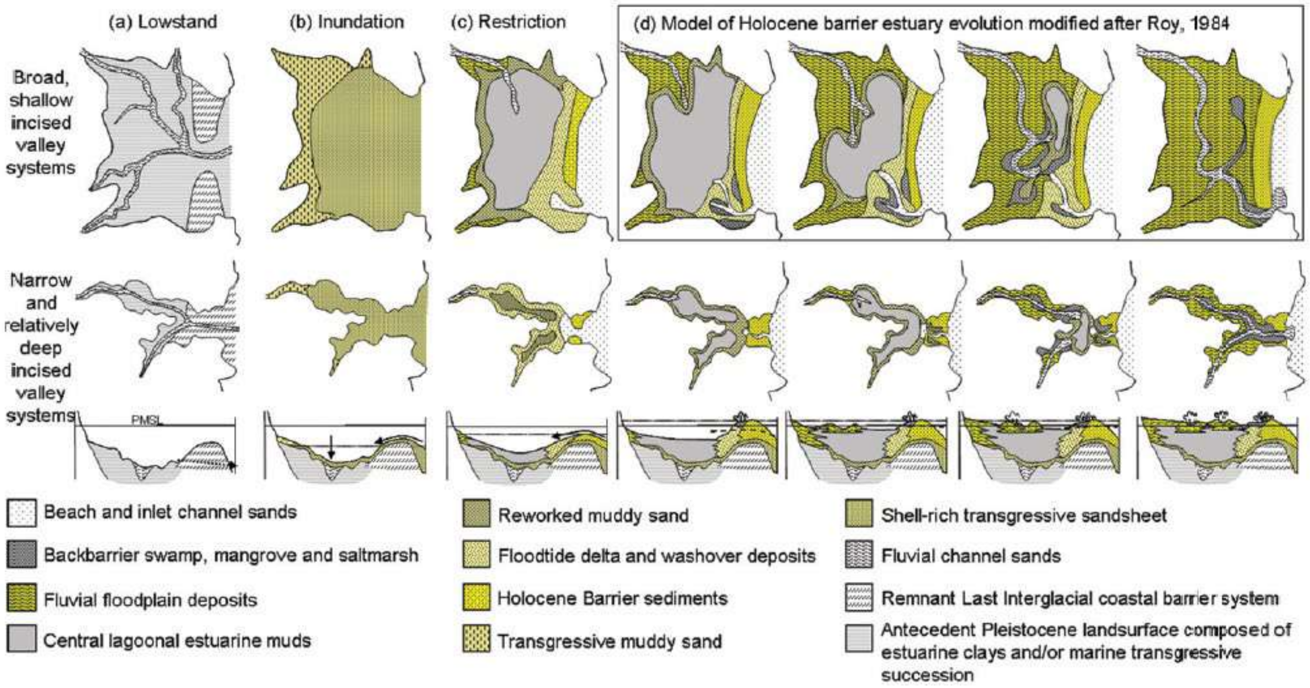

Figure 2.2: The progression of estuarine infill of barrier estuaries as they mature. Starting from (a) the remnant interglacial estuary, (b) as the valley drowned from rising sea levels and a transgressive sand sheet was formed, (c) when sea levels began to stabilise and a barrier starts to form and (d) as the estuary continually infills with stabilised sea levels until it is completely channelised (Roy 1984; Sloss, Murray-Wallace & Jones 2007). IOCE follow the same trajectory except they start closing from stage c-d onwards.

2.3 Entrance Processes/Dynamics

IOCE entrance condition is a function of the balance between onshore and offshore sediment transport at the mouth (McSweeney, Kennedy & Rutherfurd 2018). The processes that control sediment transport in IOCE are wave and tidal processes and fluvial flow variability (Ranasinghe & Pattiaratchi 2003; Rustomji 2007; Rich & Keller 2013). Wave processes transport sediment onshore and lead to the formation of a beach berm (Morris & Turner 2010). Larger and higher onshore waves results in greater berm deposition because higher waves have a greater ability to transport sediment onshore (Morris & Turner 2010). Fluvial flow variability is the main control of the erosive capability of IOCE flow and drives offshore sediment transport (Rustomji 2007). Tide processes are also important in sediment transport. The flood tide transports sediment onshore and the ebb tide transports sediment offshore. When the IOCE is open, and under higher river flows, the ebb tidal prism increases (McSweeney, Kennedy & Rutherfurd 2018). An increased ebb tidal prism means that there is a greater ability for the ebb tide to transport sediment offshore via an increase in ebb-tidal current velocities at the mouth. The episodic fluvial inflow and persistent high wave energy characteristics of these estuaries cause changes in process dominance at the mouth that causes IOCE to open and close (Rustomji 2007; Rich & Keller 2013).

Closures occur when wave processes dominate, and the net direction of sediment transport is onshore. Sediment tends to settle out in the surf zone due to decreased velocity and increased turbulence (Whitfield et al. 2012). This sediment can either be transported across the mouth by longshore transport processes or can be transported perpendicular to the mouth by cross-shore transport processes (Ranasinghe & Pattiaratchi 2003) (Fig. 2.3). When closures happen, ebb tides and fluvial discharge are unable to remove enough sediment that is transported onshore by waves and the flood tide to prevent a berm from forming across the mouth. As long as wave processes dominate, the IOCE will remain closed.

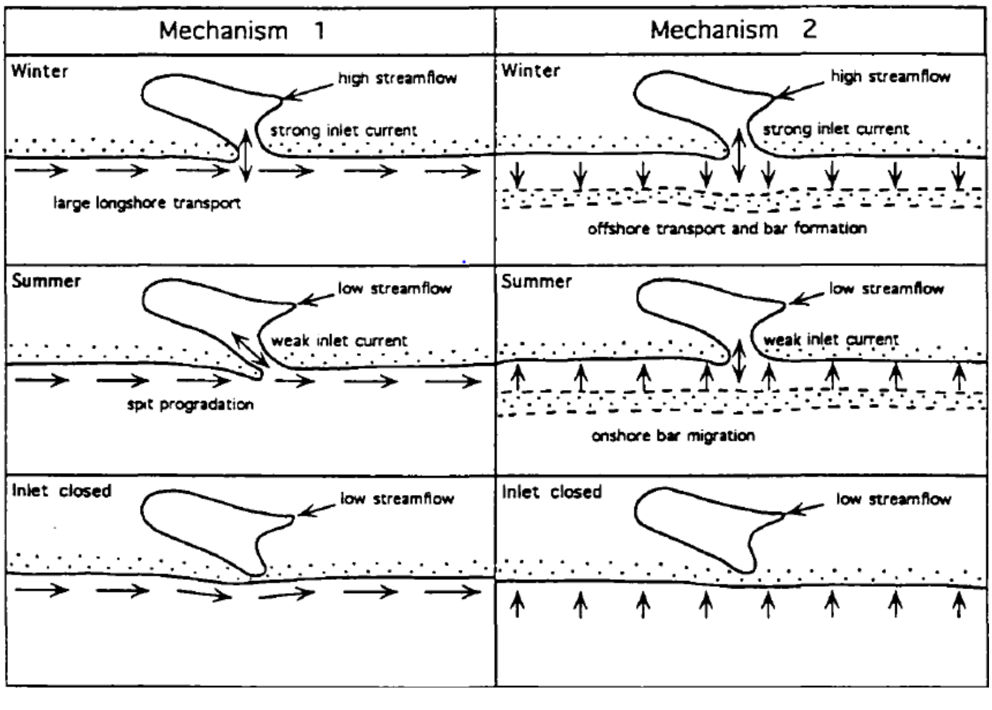

Figure 2.3: IOCE closed by longshore sediment transport processes (mechanism 1) and cross-shore sediment transport processes (mechanism 2) (Ranasinghe & Pattiaratchi 2003).

Natural openings occur when the basin water level exceeds the berm height, causing water to spill over and incise a channel through the berm. Natural openings are mainly caused by increased fluvial discharge but can less commonly be caused by waves eroding or overtopping the berm and causing a similar rise in water level (Rustomji 2007). In the initial stages (1-2 hours) of the natural opening there is a gradual outflow when the water first overtops the berm but only scours the berm face (Gordon 1991; Stretch & Parkinson 2006). The top of the berm then starts to be eroded down and eventually the breach width grows rapidly and discharge from the mouth increases dramatically (Gordon 1991; Stretch & Parkinson 2006). The mouth is kept open by the hydraulic head that is formed because the estuary water level is at a higher elevation than sea level during the initial drainage period (Fig. 2.4). This outflow usually has sufficient velocity to counteract any sediment transported by waves and prevents any marine water from entering the IOCE (Haines 2006). This state is known as the draining or outflow phase.

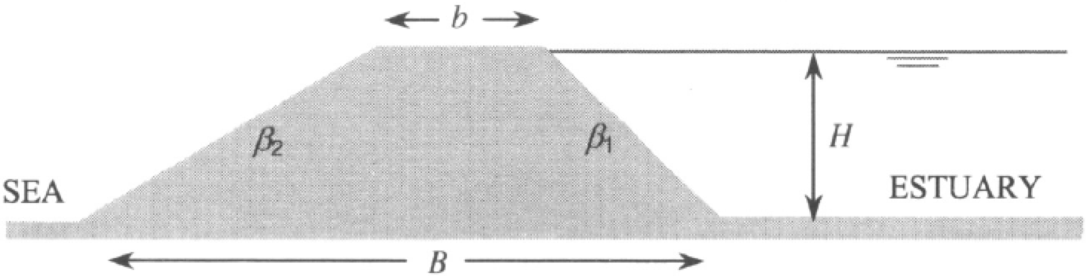

Figure 2.4: A diagram of an estuary where the estuary water level is higher than sea level, known as a perched estuary, where H is the difference in height between sea level and estuary water level, known as the hydraulic head (Parkinson & Stretch 2007).

Once the estuary drains and the water level of the basin approaches sea level, the hydraulic head is removed. When this occurs, the duration of the opening is then determined by geomorphic controls such as the transport of sediment by waves vs fluvial processes (as described earlier) (McSweeney, Kennedy & Rutherfurd 2018). Because the draining phase has finished, marine water and sediment can enter the IOCE more easily than during the draining phase as outflow velocity decreases. Water levels oscillate with the tides (Gale, Pattiaratchi & Ranasinghe 2007) and the IOCE will remain open whilst the ebb tidal prism can remove sediment transported onshore by waves, currents, and the flood tide. Once this sediment can no longer be removed, the estuary will eventually close. As the berm height increases, a point known as the semi-closed phase is reached where outflow from the IOCE can still occur (typically on the falling tide), but seawater intrusion into the IOCE mouth has been restricted (Fig. 2.5) (Snow & Taljaard 2007). As a result, there is no tidal influence on water levels. As more sediment is transported to the berm, the berm height becomes greater than the IOCE water level and the IOCE becomes closed.

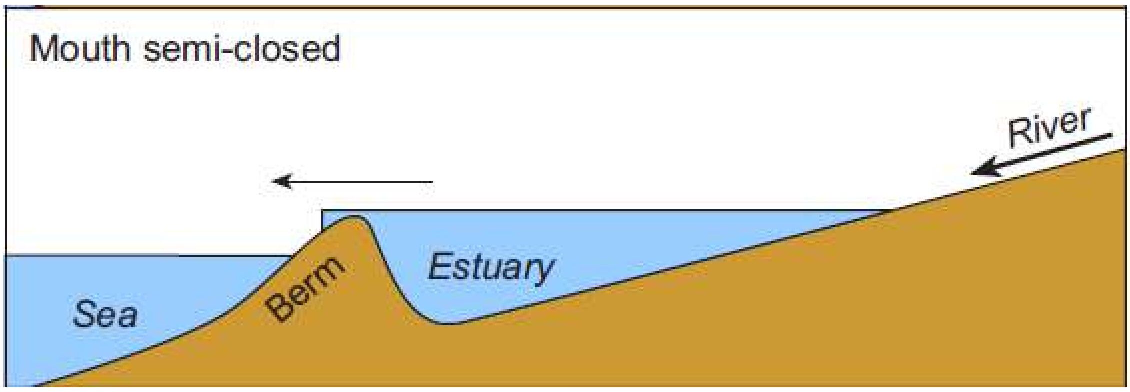

Figure 2.5: A schematic of a semi-closed estuary (Snow & Taljaard 2007).

Overtime, climate change and anthropogenic interventions, such as damming and water extraction, have reduced river inflow and have severely affected the natural opening and closure regimes for IOCE across the world (Whitfield et al. 2012; Scanes, Scanes & Ross 2020). Reduced river inflow tends to increase the length of closed periods because there is less chance that there is enough discharge to overtop the beach berm (Russell 2013). In some IOCE, river flow has been altered to such an extent that in some cases the only way to remedy this is to artificially open the estuary (Whitfield et al. 2012). This alteration of river flow has severe consequences for the water quality and ecology of IOCE because different physical and biological processes dominate in IOCE during open and closed periods (Ranasinghe & Pattiaratchi 2003; Gale, Pattiaratchi & Ranasinghe 2006; Taljaard, van Niekerk & Joubert 2009). The alteration of river flows into IOCE have resulted in losses of intertidal habitat and major changes in community and species composition (Adams & Niekerk 2020). Changes in river inflow and mouth state away from natural regimes affect water quality and the ecology of IOCE, and some estuarine species may not be able to adapt to this change.

2.4 IOCE Water Quality

Dissolved oxygen (DO), salinity, electrical conductivity, water temperature, turbidity and pH are important physicochemical variables in IOCE and are widely monitored (Pope & Wynn 2007). These physicochemical variables are important because they affect the ecology of IOCE and directly affect the functioning of the ecosystem (Pope & Wynn 2007). Organisms are adapted to a particular range of abiotic factors such as water physicochemical variables. When these abiotic factors go outside of their survivable range then these organisms are no longer able to survive. For example, mass fish deaths have occurred in IOCE due to extreme changes in DO, pH, water temperature and salinity (Whitfield 1995; Becker, Laurenson & Bishop 2009; Wong, Yau & Kennedy 2015). Organisms such as fish are also affected by turbidity levels in IOCE (Lowe, Morrison & Taylor 2015) and subaqueous plants in IOCE can be affected by turbidity because turbidity affects how much light can pass through the water which affects photosynthesis rates. Water temperature also directly affects physicochemical variables such as salinity and DO (Pope & Wynn 2007). The ecology of IOCE can be affected by dramatic changes in physicochemical variables in IOCE. As a result, these physicochemical variables are monitored regularly in IOCE through monitoring programs such as EstuaryWatch in Victoria (Iervasi et al. 2011).

There are a number of climatic, hydrological, and geomorphological factors and process interactions that influence water quality in IOCE. Roy et al. (2001) attempted to broadly describe characteristics that affect water quality in south east Australian estuaries. Roy et al. (2001) conclude that the main contributing factors to estuarine water quality are estuary type (i.e. via geomorphic classification), stage of infill (maturity), and inherited factors such as basin size. The degree of mixing that occurs within an estuary is an important factor in estuary water quality and is largely determined by the extent of tidal exchange of marine water (determined by estuary type) and basin morphology (determined by stage of infilling) (Roy et al. 2001). Boundary conditions such as climate, wave, tide and river characteristics have been found to be major drivers of estuarine water quality, especially at monthly-annual timescales (Gale, Pattiaratchi & Ranasinghe 2006; Russell 2013; Scanes, Scanes &

Ross 2020). For example, pH and salinity in IOCE are determined by the salinity and pH of freshwater from river inflow and marine water and how these waters mix (Snow & Taljaard 2007). Water temperature is largely determined by variations in air temperature but can be also determined by marine conditions (Snow & Taljaard 2007). The way that these factors interact with each other is often dynamic and can rapidly change, even over hourly scales. Changes in mouth state are a good example of how rapid, event driven changes in climatic, hydrological, and geomorphological factors influence estuary water quality (Becker, Laurenson & Bishop 2009). Most studies focus on monthly-annual scale changes in water quality (e.g. Snow & Taljaard 2007; Schallenberg et al. 2010) rather than event driven changes.

Hydrodynamic processes such as flushing, and mixing are important in determining estuarine water quality. Flushing time is the amount of time it takes for a certain mass of water to be replaced by inflow and/or tidal exchange (Monsen et al. 2002). An estuary is considered to be flushed when 63% of the original water mass has flowed from the estuary basin into the ocean (Monsen et al. 2002; Li 2010). Flushing times are important because flushing removes excess nutrients and replaces stagnant water that can often have poor water quality. Flushing can prevent algal blooms that can lead to anoxic conditions. The time it takes for an IOCE to fully flush usually depends on how much exchange occurs between the ocean and the estuary as well as the amount of inflow from the catchment (Taljaard, van Niekerk & Joubert 2009). Estuarine mixing ensures that the estuary is well oxygenated and prevents stratification of DO, water temperature and salinity, a process that can lead to anoxic conditions in estuaries (Gale, Pattiaratchi & Ranasinghe 2006). Stratification is where there are two distinct layers of water in the water column. More dense saline water sinks to the bottom of the IOCE water column, leaving a freshwater layer on top and a saline water layer at the bottom. It usually occurs when freshwater inflow from upstream flows over the brackish estuary water. Stratification prevents the exchange of thermal heating and oxygen between the two layers (Williams 2014). The bottom layer is usually warmer than the top layer because it is not influenced by the diurnal changes in air temperature (Williams 2014). As oxygen is used up in the benthic zone by biological processes, an oxygen rich top layer and an oxygen poor bottom layer eventually forms in the water column (Gale, Pattiaratchi & Ranasinghe 2006). Stratification can occur during both open and closed periods but tend to occur during periods of limited wind or tidal mixing (Snow & Taljaard 2007). Mixing processes combine the two layers, making salinity, water temperature and DO more uniform throughout the water column. Mixing within IOCE can be influenced by a number of processes including winds, tides, river inflow, solar heating, and gravity (Gale, Pattiaratchi & Ranasinghe 2006). However, it is still relatively unknown which of these processes are the dominant processes in affecting stratification.

IOCE water quality is also impacted by climate change and anthropogenic interventions. Long term studies looking at IOCE water quality have found worrying trends. There have been found to be decreases in salinity and pH in IOCE globally (Russell 2013; Scanes, Scanes & Ross 2020). Overtime, some IOCE have become less saline due to a reduction of river flow (Russell 2013). This reduction of salinity occurs because decreased river inflow translates to longer periods of closure, resulting in less marine exchange which decreases salinity overtime as freshwater flows dilute saline water. In contrast, it is also thought some IOCE may increase in salinity with longer closed periods. For example, Romero et al. (2016) predicted that salinity in the Anglesea River, Victoria will increase with increased closed periods because of higher evaporation rates over summer and very low freshwater inflow. These competing hypotheses illustrate that there still remains uncertainty in how IOCE will change in future and how stratification is impacted by changes in mouth state. It has also been predicted that in the future an increased amount of storms (due to climate change) will increase the frequency of openings in some IOCE (Haines & Thom 2007). Warmer air temperatures on average have caused IOCE water temperatures to increase (Scanes, Scanes & Ross 2020). However, the degree of this warming in individual estuaries is more complex. IOCE with shallow average depths and long residence times tended to have greater increases in water temperature because the water is more exposed to air temperatures and the water has a longer amount of time to heat up (Scanes, Scanes & Ross 2020). Other human influences such as vegetation removal from riparian zones and increased pathed surfaces surrounding the IOCE have also resulted in increases in water temperature overtime (Scanes, Scanes & Ross 2020). Acidity has increased in some estuaries because of a range of factors such as increased air temperature and reduced sea grass area (Scanes, Scanes & Ross 2020). These long-term changes in water quality have the potential to considerably affect the ecology and the functioning of these estuaries. Adams & Niekerk (2020) have found that poor water quality in IOCE has resulted in fish kills, changes in species composition and dieback of some biota. Therefore, it is important to first understand the processes that influence water quality in IOCE to inform future predictions in order to better protect IOCE from climate change.

2.5 Impacts of Mouth State on Water Quality

Changes in the mouth states of IOCE are the fundamental control on the processes that influence water quality (Gale, Pattiaratchi & Ranasinghe 2006; Snow & Taljaard 2007). During closed periods, marine exchange is cut off which decreases salinity overtime (Suzuki et al. 2002). Flushing times can be slow depending on the length of the closure and river inflow (Whitfield et al. 2012) (Fig. 2.6). Flushing can take much longer during closed phases because water cannot be exchanged between the IOCE and the ocean. In closed periods mixing is more controlled by winds and solar heating (Gale, Pattiaratchi & Ranasinghe 2006) and nutrient circulation is determined by biological and biochemical processes (Fig. 2.7) (Taljaard, van Niekerk & Joubert 2009). Stratification can occur when there is a lack of wind mixing (Gale, Pattiaratchi & Ranasinghe 2006).

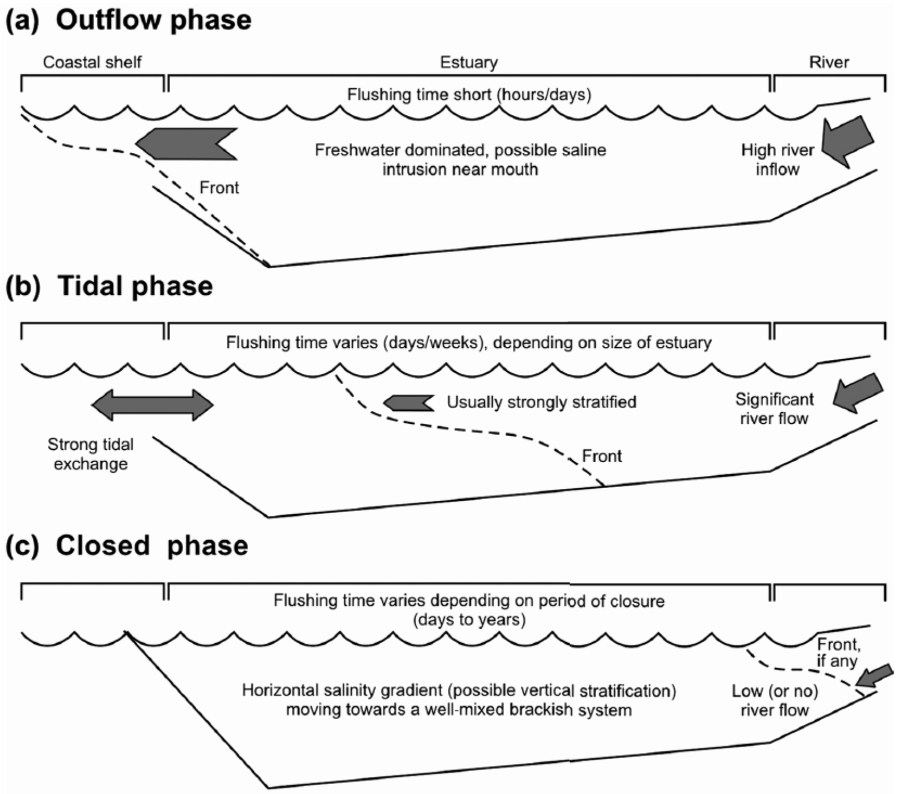

Figure 2.6: Changes in flushing dynamics and stratification from (a) when the estuary is open but strong outflow from the estuary blocks tidal exchange, (b) when outflow reduces and tidal exchange allows marine water to enter the estuary and (c) when the estuary closes and the berm blocks marine exchange (Whitfield et al. 2012).

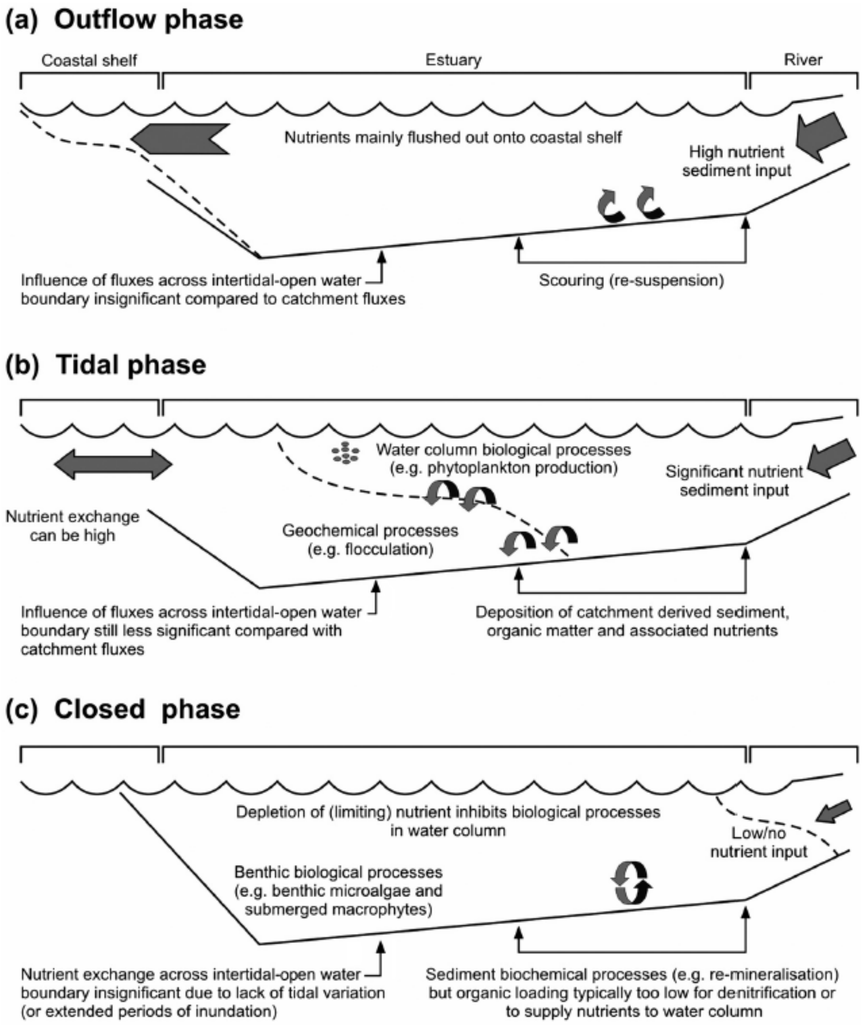

Figure 2.7: Processes of nutrient exchange during (a) outflow phase, (b) tidal phase and (c) closed phase (explained in figure 2.6) (Whitfield et al. 2012).

Meanwhile, during open periods, marine water enters the IOCE and mixes with estuarine water. Stratification of DO, salinity and water temperature can occur when there is strong tidal exchange (Whitfield et al. 2012) (Fig. 2.6). IOCE mixing is more affected by gravitational circulation and tidal currents when the IOCE is open (Gale, Pattiaratchi & Ranasinghe 2006). Nutrient circulation is largely determined by physical processes such as mixing and scouring (Taljaard, van Niekerk & Joubert 2009) (Fig. 2.7). Flushing times during the open state are usually shorter than closed periods because of the influence of tidal flushing (Whitfield et al. 2012).

Despite differences in mixing processes during open and closed periods, estuaries are known to be stratified during both open and closed periods (Gale, Pattiaratchi & Ranasinghe 2007). A key knowledge gap is that we do not fully understand what processes are dominant in affecting stratification and whether these processes shift during open and closed periods.

Draining phases also influence water quality. Strong outflow from IOCE creates a freshwater pulse which prevents marine water from entering the estuary (Fig. 2.6). The draining stage can alter the salinity depth profile in IOCE. Williams (2014) found that when IOCE drain quickly, the water column mixes and stratification of salinity is lost and when the IOCE drains slowly, stratification of salinity is maintained. Scouring of sediment in the basin occurs during draining phases, leading to increases in turbidity (Fig. 2.7). The draining phase is a transitional phase where whilst the mouth is open, little mixing of marine and IOCE water can occur due to high velocity outflow (Bertin et al. 2019). Therefore closed, draining and open phases are three distinct water quality phases as well as geomorphological and hydrodynamic phases. A key limitation on understanding this is the lack of simultaneous morphological and water quality data during and immediately following openings, particularly during the draining phase.

The effect of mouth state on IOCE water quality has been found to be influenced by the volume and morphology of the estuary basin (Schallenberg et al. 2010). The differences between water quality in open and closed phases were found to be more pronounced, with stronger relationships between water quality variables in smaller IOCE than larger IOCE (Schallenberg et al. 2010). This difference was due to tidal flushing occurring more rapidly in the smaller IOCE, meaning that saline water intrusion would have affected water quality more in the smaller IOCE than the larger IOCE (Schallenberg et al. 2010). It has also been found that mixing, circulation, and flushing processes vary between differently sized IOCE (Gale, Pattiaratchi & Ranasinghe 2006; Taljaard, van Niekerk & Joubert 2009; Whitfield et al. 2012). For example, smaller IOCE flush in shorter timeframes compared to large IOCE (Taljaard, van Niekerk & Joubert 2009). Solar heating and gravitational circulation controls mixing in large IOCE whilst winds and tides have a greater affect in smaller IOCE (Gale, Pattiaratchi & Ranasinghe 2006). IOCE with small basins can also be mixed by turbulent flows that occur during openings when the IOCE is draining and propagate upstream from the mouth (Williams 2014). Therefore, it is important to sample a range of different estuary sizes when studying physicochemical and physical processes in estuaries.

2.6 Artificial Estuary Openings

Artificial estuary openings are a management technique where the IOCE is opened to the ocean by digging a channel from the estuary, through the sand barrier and to the ocean (Fig. 2.8). Artificial openings are mainly implemented to mitigate flooding of surrounding infrastructure or more rarely as an attempt to improve estuarine water quality or to promote fish migration and recruitment (Behrens 2008; Stephens & Murtagh 2012). IOCE are also often opened due to public pressure arising when properties are flooded. Pressure to artificially open IOCE is increasing as agricultural and urban areas encroach further onto the floodplains and wetlands surrounding IOCE, resulting in a greater risk of being flooded (Haines, Tomlinson & Thom 2006). This encroachment onto the IOCE floodplain is especially apparent on the Aire River estuary in Victoria. Recently, farmers had roads cut off and their farms were flooded when the Aire River could not be artificially opened for logistical reasons, causing tensions between the estuary managers and the farmers (Bell 2020). As a result, the timing of artificial openings is often determined by water level (Everett 2007).

Figure 2.8: An artificial estuary opening where a channel is dug from the ocean, through the berm to the estuary basin at Painkalac Creek, Aireys Inlet, Victoria, June 2020.

Whilst the hydrology and geomorphology of natural estuary openings have been well studied (e.g. Gordon 1991; Ranasinghe & Pattiaratchi 2003; Parkinson & Stretch 2007; Rich & Keller 2013), there are less studies that specifically focus on artificial openings. Artificial openings tend to have a lower hydraulic head than natural openings because IOCE are usually artificially opened at lower water levels than when they open naturally (Haines 2006). The initial dimensions of the channel that is artificially dug through the berm are important in determining how quickly the IOCE drains (Haines 2006). Most IOCE tend to drain very quickly (approximately 6-48 hours depending on basin volume) following a successful artificial opening (Suzuki et al. 2002). Following the draining period the geomorphology and hydrodynamics of artificial openings and natural openings are otherwise very similar if the artificial opening was successful (Morris & Turner 2010). However, often artificial openings can fail and the IOCE does not drain for a number of reasons such as a lack of outflow or large waves (McSweeney, Kennedy & Rutherfurd 2018). The length of openings following an artificial opening is especially important for IOCE water quality. Artificial openings usually have a smaller hydraulic head and are not as successful at flushing and mixing the IOCE as natural openings (Human, Snow & Adams 2016). Therefore, a longer opening period is needed to ensure the IOCE is well mixed and flushed following an artificial opening. There are many factors that determine the success of an artificial opening in lowering water levels and maintaining or improving the ecology of IOCE. As a result, IOCE managers have now taken more factors into account when determining when to open an estuary (O'Toole et al. 2011).

The ecology of IOCE is important in maintaining its ecosystem function, meaning that the ecological effects of artificial estuary openings are important. The ecological effects of artificial openings have been well researched, with results varying between studies. Most studies have found no significant difference between assemblages of macroinvertebrates (Gladstone, Hacking & Owen 2006), macrobenthic organisms (Dye & Barros 2005), amphibians (Moreira, Knauth & Maltchik 2015) and fish (Griffiths 1999) before and after artificial openings. However, in the case of microbenthic organisms, more noticeable changes have been found to occur on shorter timescales but not on longer timescales following artificial openings (Lill et al. 2012). These studies show that these organisms studied may be resistant to the disturbance of artificial estuary openings or are resilient and are able to recover following artificial openings. However, the composition of macrophytes, macroalgae, and phytoplankton have been found to substantially change as a result of artificial openings. Following artificial openings, macroalgae and phytoplankton have been found to outcompete macrophytes, especially when flows are not high enough to remove nutrients from the IOCE basin (Suzuki et al. 2002; Human, Snow & Adams 2016). Furthermore, large macrophyte mortalities have been linked to artificial openings through a number of mechanisms such as lowered water levels (dos Santos & de Assis Esteves 2002). Increased nutrients can have considerable effects on IOCE water quality and can lead to negative outcomes such as eutrophication because increased biological oxygen demand (the amount of oxygen used by biological organisms in an amount of water over a given period) and decomposition reduces DO levels (Whitfield et al. 2012).

In some cases, changes in estuarine water quality following an artificial estuary opening have resulted in dramatic negative ecological consequences such as mass fish deaths. These are widely referenced in newspaper reports (e.g. MacKenzie 2019) because of the immediate and dramatic effects visible to the community, but are not as widely studied in the literature. The research that has been done has shown that these mass fish deaths are related to changes in water quality following an artificial opening, specifically DO and salinity (Bennett 1985; Becker, Laurenson & Bishop 2009; Stacey et al. 2017). In Victoria, the mass fish deaths following artificial estuary openings that have occurred have been related to drops in DO levels. One of the most extensive studies of a mass fish death was undertaken by Becker, Laurenson & Bishop (2009), who studied a 2005 mass fish death in the Surrey River Estuary in Narrawong, Victoria. They found that the main cause of fish deaths was vertical stratification of DO in the estuary before the artificial opening, with an oxygen rich top layer and an anoxic bottom layer. The high outflow during the draining phase following the artificial opening caused the oxygen rich layer to be 'sheared' off and flow out to sea (Becker, Laurenson & Bishop 2009). The loss of the oxygenated layer caused severe drops in DO levels that were outside the survivable range for fish. Fish deaths were recorded for multiple species, including both freshwater species such as *Galaxias maculatus* (common galaxias) and salt water species such as *Atherinosoma microstoma* (small mouth hardy head) (Becker, Laurenson & Bishop 2009). However, it was found that some species were able to escape the anoxic conditions by escaping to fresher oxygenated water upstream, conditions that suit freshwater and euryhaline organisms. Undertaking artificial openings whilst the IOCE is strongly stratified, with an anoxic bottom layer has been found to be a major factor in contributing to mass fish deaths (Sherwood, Mondon & Fenton 2008). These large changes in stratification and oxygen have been found to occur whilst the IOCE is still draining, where there are large scale and rapid geomorphic changes at the mouth of the IOCE and hydrodynamic changes in the IOCE basin (Becker, Laurenson & Bishop 2009). Despite this, there are few studies that directly measure the changes in stratification during this draining period following an artificial opening and relate this to geomorphic changes at the mouth.

Few studies have specifically focused on the effect of artificial openings on water quality and stratification and linked this to climatic, hydrological, and geomorphological variables such as wind or wave characteristics. Large drops in DO levels have been found to occur following artificial openings (Becker, Laurenson & Bishop 2009; Human, Snow & Adams 2016). Artificial openings have also caused increases in nutrient concentrations because the discharge from artificial openings may not be sufficient enough to scour out sediments and flush out nutrients (Suzuki et al. 2002; Human, Snow & Adams 2016). This is because a high discharge is required to raise the water levels above the berm to incise a channel through the barrier to naturally open the IOCE (Parkinson & Stretch 2007). A high discharge does not usually occur in artificial openings because a channel is incised by machinery and artificial estuary openings tend to be determined by water level and not rainfall or river inflow (Adams & Niekerk 2020).

Three recurring limitations of existing studies on how artificial estuary openings affect water quality and stratification are:

(1) These studies only sample one artificial opening with an intensive research design.

(2) Only one or two estuaries are sampled in each study, often with vastly different sizes or morphologies.

(3) These studies do not sample at finer temporal resolutions (i.e. sub-daily) immediately after an artificial opening and during the draining phase.

Therefore, it is hard to make any substantial conclusions over broader contexts from these studies. This means that measuring a representative sample of artificial openings in multiple IOCE is important. Major changes in water quality seem to occur during the draining phase post artificial openings (e.g. Becker, Laurenson & Bishop 2009). The draining phase is an important phase of the artificial opening and also may be a distinct water quality phase from open and closed periods and should be further studied.

2.7 Conclusion

IOCE are dynamic systems that are influenced by a variety of processes and factors which directly influence water quality and stratification. Overall, wave physical characteristics, tidal processes, hydrodynamic processes, river inflow, climate, ecological composition, and sediment transport are key variables in influencing water quality and stratification in IOCE. However, the exact way in which these variables interact with each other to influence water quality and stratification in IOCE is still relatively unknown or unquantified.

A recurrent theme in existing work is that the connection between entrance state, stratification and water quality has rarely been made and quantified. Natural openings have been well studied but artificial openings have been less studied, with changes in water quality and stratification in response to artificial openings receiving even less attention. The main data gaps in the literature are as follows:

(1) Measuring water quality, in particular depth profiles, immediately after the artificial opening at a finer temporal scale during the draining phase. As a result, the effect of morphological change during the draining stage on water quality and stratification has rarely been quantified.
(2) It is not well known what are the dominant processes that affect stratification and if these processes shift between open and closed periods
(3) In general, the link between mouth state, water quality and stratification is not often made, especially in Victorian IOCE.
(4) Few studies focus on IOCE water quality with an extensive research design that sample a large representative sample of artificial estuary openings over multiple sites.
(5) Few studies have compared IOCE with similar and different morphologies. Usually only 1 or 2 IOCE are studied that have vastly different morphologies which limits comparison.

The literature highlights the importance of sampling IOCE that have varying sizes and studying the temporal and spatial variation in estuarine water quality because they often have different responses to climate and physical variables or exist in varying degrees of infill and have different morphologies. In particular, stratification was found to be a key process in mass fish deaths following artificial estuary openings. Therefore, it will be important to study the conditions and processes that affect stratification in IOCE.

This project will attempt to fill these data and knowledge gaps by:

(1) Measuring water quality depth profiles at hourly scales during the draining phase.

(2) Use secondary data to investigate the link between processes that affect IOCE mouth state and stratification.

(3) Compile data from multiple IOCE and over multiple draining/open/closed cycles to investigate local variability in stratification responses to IOCE mouth state and hydrological, geomorphological, and climatic variables.

(4) Sampling multiple IOCE of different sizes and morphologies.

From existing literature, I have compiled a list of variables that are known to affect stratification in IOCE (they will be referred to as physical-environmental variables) and their expected effects on stratification (Table 2.1):

Table 2.1: A list of physical-environmental variables gathered from existing literature and their expected effect on stratification in IOCE.

Physical-Environmental variable	Expected Effect on Stratification	Reference
Rainfall	An indicator of river inflow (as rainfall increases, river inflow is expected to increase). As rainfall increases it is expected stratification will increase as freshwater overtops the saline water layer.	(Taljaard, van Niekerk & Joubert 2009)
Air temperature	As air temperature increases, evaporation increases and the estuary water column will become more uniform, decreasing stratification.	(Snow & Taljaard 2007)
Wind speed and direction	As wind speed increases, stratification will decrease as the estuary basin mixes.	(Gale, Pattiaratchi & Ranasinghe 2006)
Wave significant height, period, and direction	As significant wave height and wave period increases, stratification of salinity will increase as more saline water is enters into the estuary. Wave direction will influence how much of the wave enters the estuary mouth.	(Snow & Taljaard 2007)
Tide height	As tide height increases stratification is predicted to decrease as tides mix the estuary water column.	(Whitfield et al. 2012)
Estuary Water Level	Similar to rainfall, will act as an indicator for river inflow (as river inflow increases, estuary water level is expected to increase).	(Taljaard, van Niekerk & Joubert 2009)
Upstream Discharge	Similar to rainfall and estuary water level.	(Taljaard, van Niekerk & Joubert 2009)
Duration of opening/closure	As duration of closure increases it is expected stratification of DO will increase as benthic processes use up DO at the bottom of the water column. As duration of opening increases stratification of salinity will increase as more saline water is introduced into the estuary	(Gale, Pattiaratchi & Ranasinghe 2006; Everett 2007; Snow & Taljaard 2007)

Mouth state was also found to be a key control on water quality and stratification because it impacts on marine exchange, salinity, water temperature, DO, stratification, and circulation. There are three distinct morphological phases in IOCE: (1) a closed period with limited to no marine influence, (2) a transitional draining period which is dominated by IOCE outflow and (3) an open period with maximum marine connectivity and exchange. The processes controlling water quality and stratification in IOCE change under a closed, draining, or opening state. In light of this, the following effects of mouth state on water quality and stratification are predicted (Table 2.2):

Table 2.2: Different IOCE mouth states and their expected effects on stratification in IOCE.

Mouth State	Prediction	Reference
Closed	Salinity/electrical conductivity will become increasingly stratified when freshwater inflows from rainfall and upstream discharge enter the IOCE basin.	(Schallenberg et al. 2010; Russell 2013)
	Stratification of DO will increase overtime because of low mixing and slow flushing rates promoting biochemical processes that use up DO in the benthic zone.	(Taljaard, van Niekerk & Joubert 2009; Whitfield et al. 2012).
Draining	Salinity/electrical conductivity and water temperature will decrease if the IOCE drains quickly because outflow from the estuary mouth will impede any mixing of marine water in the estuarine basin and freshwater inflows from upstream will further dilute estuarine water. Furthermore, the existing saline layer will be mixed as the IOCE water column de-stratifies whilst draining.	(Everett 2007; Whitfield et al. 2012; Williams 2014)
	If the IOCE drains slowly, the water column will remain stratified with little changes in the water column.	(Williams 2014)
	DO will decrease if the water column is stratified as the top oxygenated layer is lost.	(Becker, Laurenson & Bishop 2009).
	Turbidity will increase because of scouring of sediment from outflow.	(Whitfield et al. 2012)
Open	The stratification of Salinity/electrical conductivity will increase as length of opening increases as more marine water enters the estuary.	(Whitfield et al. 2012).

3 Regional Context

This study focused on a range of IOCE located along the open coast of Victoria (Australia) (Fig. 3.1). IOCE included in this study spanned from the Powlett River west of Wilsons Promontory, to the Curdies River, east of Warrnambool (Fig. 3.1).

3.1 The Victorian Coastline

3.1.1 Marine Conditions

The open Victorian coast is classified as wave-dominated and microtidal with a spring tidal range of 0.80-1.60m (McSweeney et al. 2017). The open west coast (from Portland to Cape Otway) is exposed to consistent high-energy waves generated by strong westerly winds and frontal storm systems propagating northwards from the Southern Ocean (McSweeney 2020). Along this stretch of coastline median significant wave heights vary between 2.5-2.75m (Hemer & Griffin 2010). Wave direction along the west Victorian coastline shows little spatial variability with waves coming from a SSW-WSW direction on average (McSweeney 2020). Mean tidal range is 0.88m at Portland.

The coastline between Cape Otway and Torquay has smaller waves than the open west coast due to sheltering of waves by Cape Otway. The broad and shallow continental shelf also acts to dissipate wave energy. Median significant wave height typically varies between 1.5-1.75m (Hemer & Griffin 2010). Mean tidal range is 1.6m at Lorne.

The coastline between Cape Schanck and Wilson's Promontory is more exposed than the coastline between Cape Otway and Torquay. As a result, median significant wave heights typically vary between 1.75-2.0m with Tasmania blocking waves from the south (Hemer & Griffin 2010). Mean tidal range is 1.2m at Waratah Bay.

3.1.2 Climate and Hydrology

The coastal climate of Victoria is temperate with mean annual rainfall varying between 650mm (at Torquay) to >1400 mm in some parts of the Otway Ranges (Mondon, Sherwood & Chandler 2003; Peel, Finlayson & Mcmahon 2007). Peak rainfall and fluvial discharge in Victoria's catchments occurs during winter and spring and decreases over summer and autumn (Barton & Sherwood 2004).

As well as being seasonally variable, the flow of Victorian rivers and estuaries are also interannually variable, conditions that are characteristic of temperate Australia (Sherwood, Mondon & Fenton 2008; Finlayson 2010). Rivers in the study region supply negligible sediment to the coast because they have a low relief and because estuaries act as a sink for sediment (Davis Jr 1989).

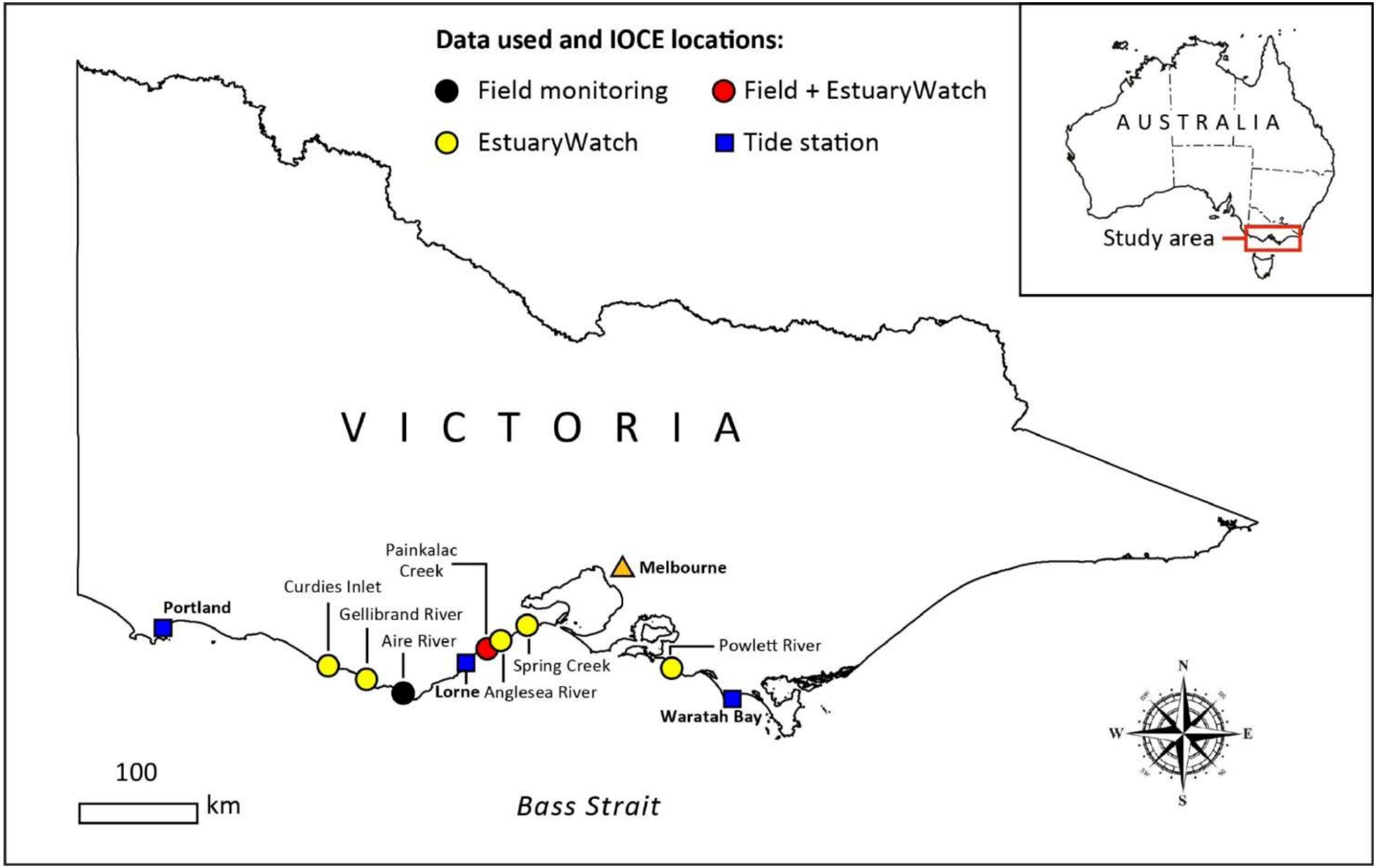

Figure 3.1: A map of study sites that were used as a part of the analysis of secondary data and fieldwork data as well as tide station locations.

3.2 Study Sites

Seven IOCE were selected as study sites to conduct fieldwork and/or to analyse historic data (Fig. 3.1). These IOCE were chosen because they represented a diverse sample of Victorian IOCE with a range of catchment areas and hydrologies (Table 3.1). These sites were also chosen because they have a history of being artificially opened, meaning there is a management interest and regular openings occurring during the timeframe of the study. They also have EstuaryWatch citizen scientist groups that measure physicochemical depth profiles at monthly timescales at multiple locations within their basins. The Aire River was not included in the historical analysis because it does not have an EstuaryWatch group and long-term physicochemical data was not available.

Table 3.1: Characteristics of IOCE studied (Mondon, Sherwood & Chandler 2003; Sherwood, Mondon & Fenton 2008). Spring Creek is not gauged.

IOCE	Catchment Area (km^2)	River Length (km)	Estuary Length (km)	Mean Annual Rainfall (mm)	Estuary Mouth Location	Mean Daily Discharge (ML/day)
Curdies River	1245	66.0	16.0	854	38° 36' 23.05" S 142° 52' 53.33" E	326
Gellibrand River	1184	120.1	7.8	1223	38° 42' 23.07"S 143° 9' 24.33" E	805
Aire River	280	44.0	7.6	1415	38° 48’ 08.40” S 143° 28’ 41.80” E	310
Painkalac Creek	61	20.3	3.25	865	38° 28' 8.62" S 144° 6' 2.89" E	17
Anglesea River	125	20.6	3.5	756	38° 24' 53.01" S 144° 11' 28.80" E	16
Spring Creek	57	27.3	4.0	658	38° 20' 36.42" S 144° 19' 7.20" E	N/A
Powlett River	228	43.0	8.2	938	38° 34' 54.39" S 145° 30' 41.8" E	128

For the IOCE studied, catchment areas range from 57 to 1245km^2 (Table 3.1). The Curdies and Gellibrand Rivers have catchment areas of >1000km^2, Aire and Powlett Rivers have catchment areas of 200-300km^2, and Anglesea River, Spring Creek and Painkalac Creek have catchment areas of <150km^2 (Table 3.1). These IOCE have a range of morphologies and sizes. All IOCE are located west of Melbourne except for Powlett River (Fig. 3.1). Painkalac Creek and Gellibrand River are both dammed in their upper catchment. The Painkalac Creek dam was used to supply Aireys Inlet with freshwater up until 2016. The West Gellibrand Dam is used to supply water to Colac. Anglesea

River had 4.5Ml/day of ground water pumped from a nearby open pit coalmine into the river from the 1970s onward, but this ceased on 31/03/2016 (Romero et al. 2016). All sites have medium-coarse grained sand on the beaches and berms fronting their mouths (Fig. 3.2) (Davis Jr 1989).

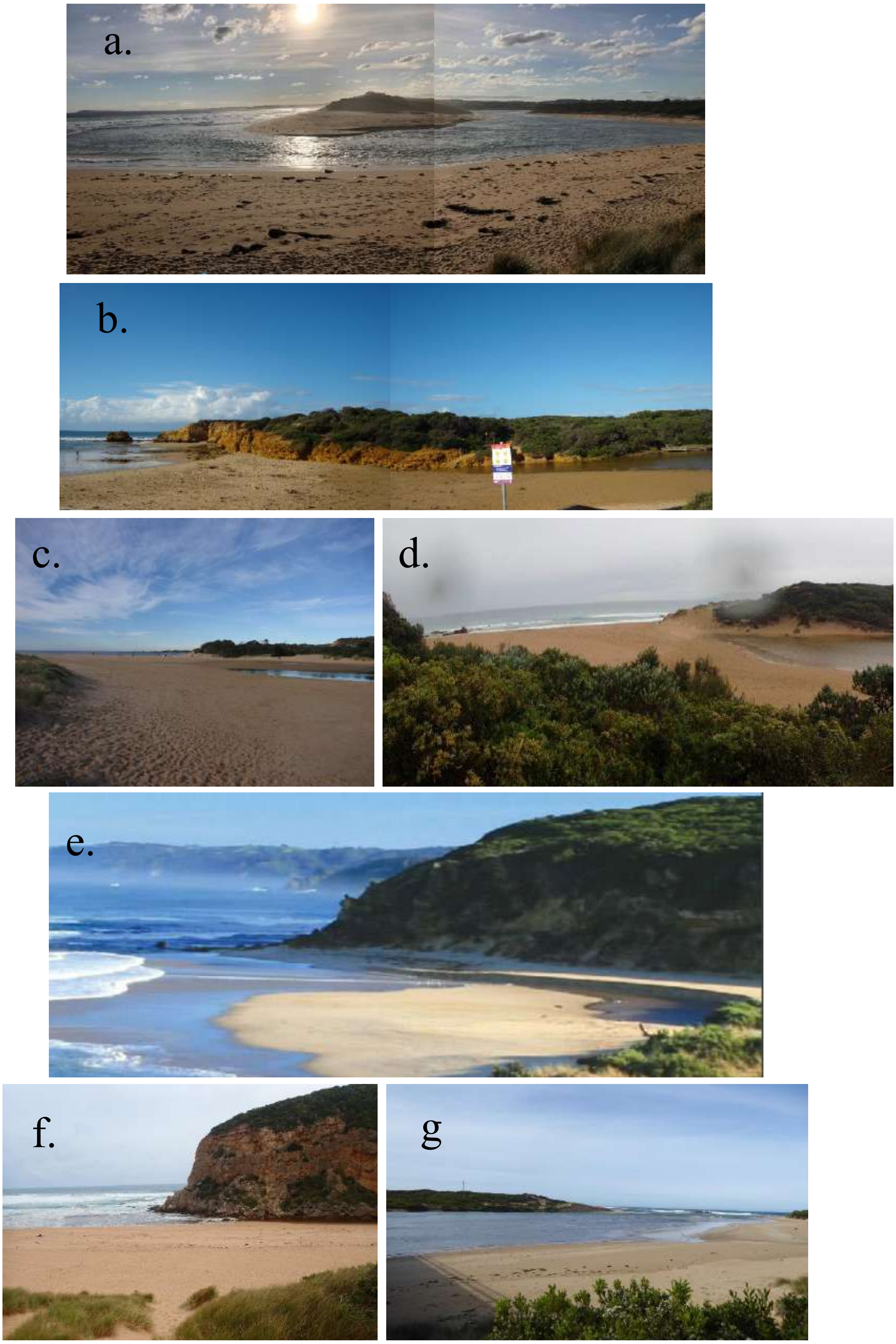

Figure 3.2: Mouths of Powlett River (a), Spring Creek (b), Anglesea River (c), Painkalac Creek (d), Aire River (e), Gellibrand River (f) and Curdies River (g) estuaries.

4 Methods

To achieve the aims and objectives of the project, two methods were used:

(1) Analysis of historic (2007-2020) physicochemical and physical-environmental data to determine the relationships between physical-environmental variables and estuary stratification; and

(2) Fieldwork consisting of measuring depth profiles of physicochemical variables and entrance morphology before an artificial opening and during the draining phase.

4.1 Historic Physicochemical and Physical-Environmental Data Collation

Physicochemical depth profiles and physical-environmental data were gathered for the open and closed periods either side of multiple artificial estuary openings for each IOCE (Table 4.1). Physicochemical data was sourced from the citizen science program EstuaryWatch (Iervasi et al. 2011). The following physicochemical variables were collated:

- pH
- Turbidity (FNU)
- Dissolved oxygen concentration (mg/L)
- Dissolved oxygen percentage saturation (% saturation)
- Salinity (PSU)
- Electrical conductivity (mS/cm)

These physicochemical variables were chosen because they are known to affect the survival of the biota that live in IOCE (Bennett 1985; Pope & Wynn 2007; Becker, Laurenson & Bishop 2009). The EstuaryWatch physicochemical measuring site that had the most observations was selected for each IOCE (Table 4.2). All sites were within 1.6 km of the mouth, being comparable in proximity to the ocean. Stratification of physicochemical variables was calculated by subtracting the top and bottom depth profiles of each variable.

Table 4.1: Data sources and periods of record extracted for analysis for each IOCE studied.

IOCE	Number of open/closed periods assessed	Mouth state and physicochemical data (dataset duration)	Offshore wave data (site and duration)	Offshore tidal data (site and duration)	Climate data (rainfall, wind, and temperature) (site and duration)	Upstream fluvial discharge (site and duration)
Powlett River	5	2015-2020	-39.00, 142.50 2015-2020	San Remo: 2015-2020	Wonthaggi: 2015-2020 Rhyll: 2015-2020	Foster Creek Junction: 2015-2020
Spring Creek	6	2014-2020	-38.50, 144.50 2014-2020	Lorne: 2014-2020	Aireys Inlet: 2014-2020	N/A
Painkalac Creek	14	2007-2020	-38.50, 144.50 2008-2020	Lorne: 2008-2020	Aireys Inlet: 2007-2020	Painkalac Dam: 2007-2020
Anglesea River	28	2011-2020	-38.50, 144.50 2011-2020	Lorne: 2011-2020	Aireys Inlet: 2011-2020	Marshy Creek at Alcoa: 2011-2020
Gellibrand River	16	2007-2020	-39.00, 143.00 2008-2020	Port Campbell: 2007-2020	Nullawarre: 2008-2020 Warrnambool Airport NDB: 2008-2020	Burrupa: 2008-2020
Curdies River	6	2013-2020	-39.00, 142.50 2013-2020	Port Campbell: 2013-2020	Port Campbell: 2013-2020 Warrnambool Airport NDB: 2013-2020	Curdie: 2013-2020
Data source/s:	EstuaryWatch, EEMSS, aerial imagery	EstuaryWatch	NOAA WaveWatch III	BoM	BoM	DELWP

Table 4.2: Characteristics of EstuaryWatch sites chosen for historic data analysis.

IOCE	EstuaryWatch Site	Distance from Mouth (km)	Total number of Physicochemical Observations	Site coordinates
Powlett River	Mouth of Powlett Road Bridge	1.5	171	38°34'25" S 145°30'39" E
Spring Creek	Footbridge upstream of Great Ocean Rd at Torquay	1.0	124	38°20'17" S 144°18'52" E
Anglesea River	Footbridge near Bingley Pde	1.6	148	38°24'7" S 144°11'9" E
Painkalac Creek	Great Ocean Rd Bridge at Aireys Inlet	1.0	167	38°27'53" S 144°5'40" E
Gellibrand River	Old Coach Road Bridge, Princetown	1.3	603	38°41'50" S 143°9'19" E
Curdies River	Dorey St Floating Pontoon	0.6	86	38°36'15" S 142°52'58" E

Using a variety of data sources (Table 4.1), the following physical-environmental variables were collated for each IOCE:

- Climate data including:
    - Daily and 7-day averaged rainfall (mm)
    - Maximum air temperature (°C)
    - Maximum wind gust speed and direction (km/hr)/(°N)
- Offshore wave characteristics including:
    - Significant wave height (m)
    - Wave direction (°N)
    - Wave period (sec)
- Daily maximum tide height (m AHD)
- Estuary water level (m AHD)
- Upstream discharge (m^3/s)
- IOCE mouth condition (open/closed) and duration of mouth state (days)

These physical-environmental variables were chosen because they are known to affect stratification in IOCE (Gale, Pattiaratchi & Ranasinghe 2006; Snow & Taljaard 2007; Taljaard, van Niekerk & Joubert 2009). All physical-environmental variables were adjusted to daily averages. Daily averages were used because the focus of the analysis was over the timescale of change occurring during open and closed periods which is daily (McSweeney, Kennedy & Rutherfurd 2018). Two variables were included for rainfall: (a) a daily average and (b) a 7-day average. A 7-day average was included to be more representative of the rainfall entering the IOCE in the time leading up to the EstuaryWatch physicochemical measurement.

Data from multiple open/closed cycles were gathered for Curdies River, Gellibrand River, Painkalac Creek, Anglesea River, Spring Creek and Powlett River (Table 4.1). The length of open/closed periods were determined by a combination of EstuaryWatch and Estuary Entrance Management Support System (EEMSS) mouth condition data and historic satellite imagery. Satellite imagery was sourced from Planet Labs, Google Earth, and NearMap. Openings that only lasted one day (e.g. failed artificial or illegal openings) were not counted as they did not restart the closed period or cause a decrease in basin water level.

Climate data (wind, rain, and temperature data) was collected from the nearest Bureau of Meteorology (BoM) weather station to the IOCE mouth that had the most complete record for the study period. Offshore wave characteristics were hindcast from the National Oceanographic and Atmospheric Association (NOAA) WaveWatch III model. The model has a resolution of 50km, meaning some IOCE are included within the same grid point (Table 4.1). Hindcasting was used because no permanent wave buoys spanning the data timeframe were available. Upstream discharge was sourced from the Department of Environment, Land Water and Planning (DELWP) discharge gauges and water level was collated from DELWP water level gauges or from EstuaryWatch and EEMSS data if there was no DELWP water level gauge.

4.2 Field Monitoring

4.2.1 Physicochemical Depth Profiles During Draining Phase

Physicochemical depth profiles were taken in the field before an artificial opening and during the draining phase following the opening. Depth profiles included measurements of all physicochemical variables made at the same time and location at varying depths. Measuring depth profiles are important because physicochemical variables can vary greatly at different depths (Snow & Taljaard 2007). At each study site, 3-4 measuring sites were selected for measuring depth profiles to capture the spatial physicochemical variability across the IOCE basin (Fig. 4.1). Distances from the mouth at each measuring site varied between 0.92-3.30km for Painkalac Creek and 1.46-2.65km for Aire River (Fig. 4.1). At each measuring site, using a HI9829 Hanna Instruments Multiparameter Meter, physicochemical variables were measured at 0.5m depth intervals. Total depth of the water and water velocity of the top and bottom of the water column were also measured. Velocity was measured with a Marsh McBurnie flow meter at 80% and 20% depths. An initial depth profile was taken at each measuring site before the artificial opening to determine starting conditions. After the artificial opening depth profiles were taken at each site every 1-3 hours either until the IOCE had finished draining or for as long as logistically possible. The following physicochemical variables were measured:

- Water Temperature (°C)
- Turbidity: (FNU)
- Salinity: (PSU)
- Electrical Conductivity: (mS/cm)
- pH
- Dissolved Oxygen Concentration: (mg/L) and Percentage Saturation (% saturation)

Changes in estuary water level were measured using Solonist water level loggers, corrected for atmospheric pressure using barometric pressure data, and adjusted to Australian Height Datum (AHD).

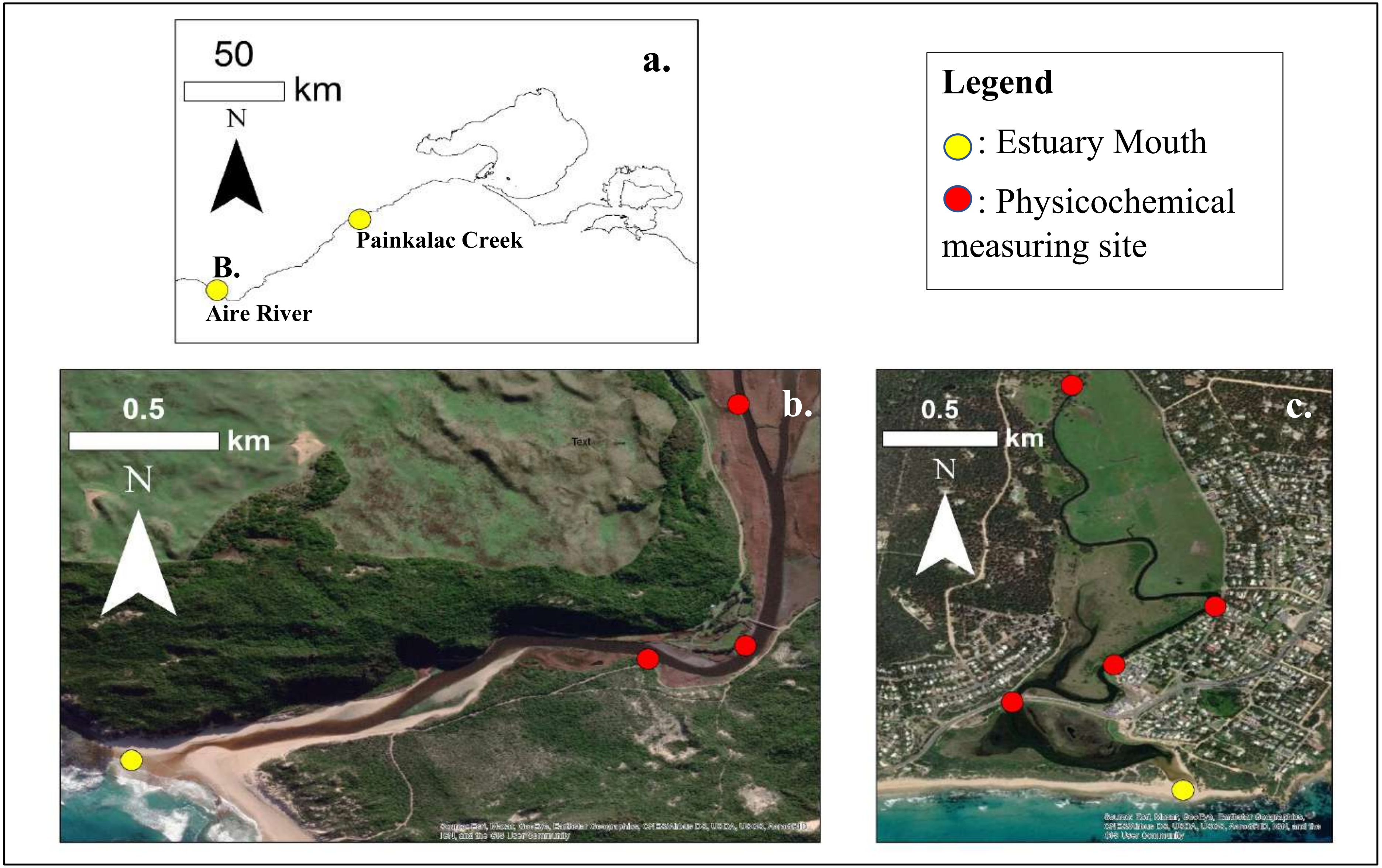

Figure 4.1*:* A map of IOCE analysed using field methods (a) and physicochemical and estuary mouth measuring sites for Aire River (b) and Painkalac Creek (c).

4.2.2 Entrance Morphology

The dimensions of the artificially dug channel, water velocity, and discharge from the IOCE mouth were also measured to capture how the morphology of the channel changed during the draining period (Table 4.3). Whilst it was safe to do so, channel dimensions were measured using a Trimble R6 RTK GPS unit which were referenced to Australian Hight Datum (AHD). When it was not possible or unsafe to survey across the channel, channel width was measured using a laser ranger finder (averaged at least 3 times) and depth was measured using a measuring pole or by estimation. Velocity was measured using the orange method (averaged at least 3 times) (Christensen 1994).

Two artificial openings were measured including a small opening at Painkalac Creek on 30/06/2020 and a large opening at Aire River on 23/07/2020.

Table 4.3: Methods used to measure artificially dug channel dimensions and water velocity and to calculate discharge.

Channel Dimensions/Flow	Unit	Methods of measurement/Calculations
Channel Width	m	RTK GPS, laser ranger finder
Channel Depth	m	RTK GPS, measuring pole, estimation
Water Velocity	m/s	Orange method (Christensen 1994)
Discharge	m^3/s	$Q=A\times V$, where Q=discharge, A=channel cross sectional area and V=water velocity

4.3 Data Analysis

4.3.1 Analysis of Historic Data

The historical data that was gathered for each IOCE was analysed using a Principal Components Analysis (PCA) using a correlation matrix, contained within the stats package in R v. 4.0.2. PCA was chosen because it has no underlying assumptions about the distribution of the data (Jollife & Cadima 2016), and PCAs have been used in similar studies on estuaries (Everett 2007; Schallenberg et al. 2010; Hyman & Stephens 2020). For each IOCE, data was split into open and closed periods which were analysed separately. Before performing the PCA, all variables were scaled to have unit variance. Scaling was done because each variable has different units and a variable with larger values could mask the variance of other variables in the PCA. A PCA variable plot was produced from the PCA results using the autoplot function in the ggfortify package. The PCA biplot and variable loadings were then interpreted to determine the strength of relationships between physicochemical and physical-environmental factors. Only physical-environmental variables with loadings of >0.2 or <-0.2 for principal component 1 were considered important and were analysed (Appendix A). Variable loadings measure how well represented a variable is in the PCA. Past studies that use the same method have used a slightly higher cut-off of ±0.25 (Chatfield & Collins 1981; Peres-Neto, Jackson & Somers 2003). However, a cut-off value for variable loadings of ±0.2 was chosen because it did not remove too many physical-environmental variables from the analysis. The variables that were kept made physical sense as to why they were correlated with stratification of physicochemical variables. Variables are represented as vectors in a PCA plot and a useful feature of PCA is that the cosine of the angle between two variables (vectors) in a PCA plot gives an approximation of the correlation between those variables (Gabriel 1971; Cadima & Jolliffe 1995; Kohler & Luniak 2005). This method has a scale of correlation of 1.00 to -1.00, where 1.00 is the strongest positive correlation between two variables and -1.00 is the strongest negative correlation between two variables. Variables with an angle of 0° between each other have a correlation of 1.00, variables with an angle of 90° between each other have a correlation of 0.00 and variables with an angle of 180° between each other have a correlation of -1.00. This measure of correlation is dimensionless.

4.3.2 Analysis of Fieldwork Data

Depth profiles and geomorphic data for each opening were graphed to visually show the temporal changes in physicochemical variables of different depths as well as mouth morphology. This data was then interpreted to produce a conceptual model. The conceptual model represented two of the different openings studied, one high energy opening and a low energy opening.

5 Results

5.1 Historic Data Analysis Results

Principal Components Analysis (PCA) was undertaken on between 38-242 depth profiles at each of the 6 IOCE between 2008-2020 to determine controls on IOCE stratification during both closed and open states. Turbidity and pH were not included in the analysis of the PCA results because these physicochemical variables were not measured at a high enough frequency in some IOCE (Painkalac Creek and Gellibrand River) and were not well represented enough to make for a robust PCA analysis. Electrical conductivity was grouped very similarly to salinity (except in Curdies River during closed periods, where salinity and electrical conductivity were grouped separately) and dissolved oxygen (DO) percentage saturation was grouped very similarly to DO concentration so both of these physicochemical variables are not referred to in the analysis of the PCA results. Rainfall refers to the 7-day averaged rainfall because it was found to be better represented in majority of PCA (Appendix A). See Appendix A for variable loadings for physical-environmental variables and see Appendix B for records and duration of open and closed periods sampled for each IOCE.

5.1.1 Powlett River

A total of 45 EstuaryWatch depth profiles were analysed during closed periods and 33 depth profiles during open periods between 2015-2020. The two principal components extracted from each PCA captured 49.91% of the total variance of the data for closed periods and 46.61% of the total variance for open periods (Fig. 5.1). During closed periods, stratification of DO, water temperature and salinity were positively correlated with upstream fluvial discharge (DO=1.00, salinity=1.00, water temperature=1.00), estuary water level (DO=0.99, salinity=0.99, water temperature=1.00) and length of closure (DO=0.96, salinity=0.96, water temperature=0.98) and negatively correlated with maximum air temperature (DO=-0.93, salinity=-0.93, water temperature=-0.96) (Fig. 5.1a; Table 5.1). Upstream fluvial discharge was the physical-environmental variable that was most strongly correlated with stratification of water temperature (1.00), salinity (1.00) and DO (1.00) during closed periods (Table 5.1).

Table 5.1: Cosine of angles between physicochemical variables and physical-environmental variables from PCA analysis for Powlett River during closed periods. Only physical-environmental variables with loadings > 0.2 or <-0.2 were measured. Values are dimensionless.

	Upstream Discharge	**Maximum Air temperature**	**Length of Closure**	**Water Level**
DO	1.00	-0.93	0.96	0.99
Salinity	1.00	-0.93	0.96	0.99
Water Temp	1.00	-0.96	0.98	1.00

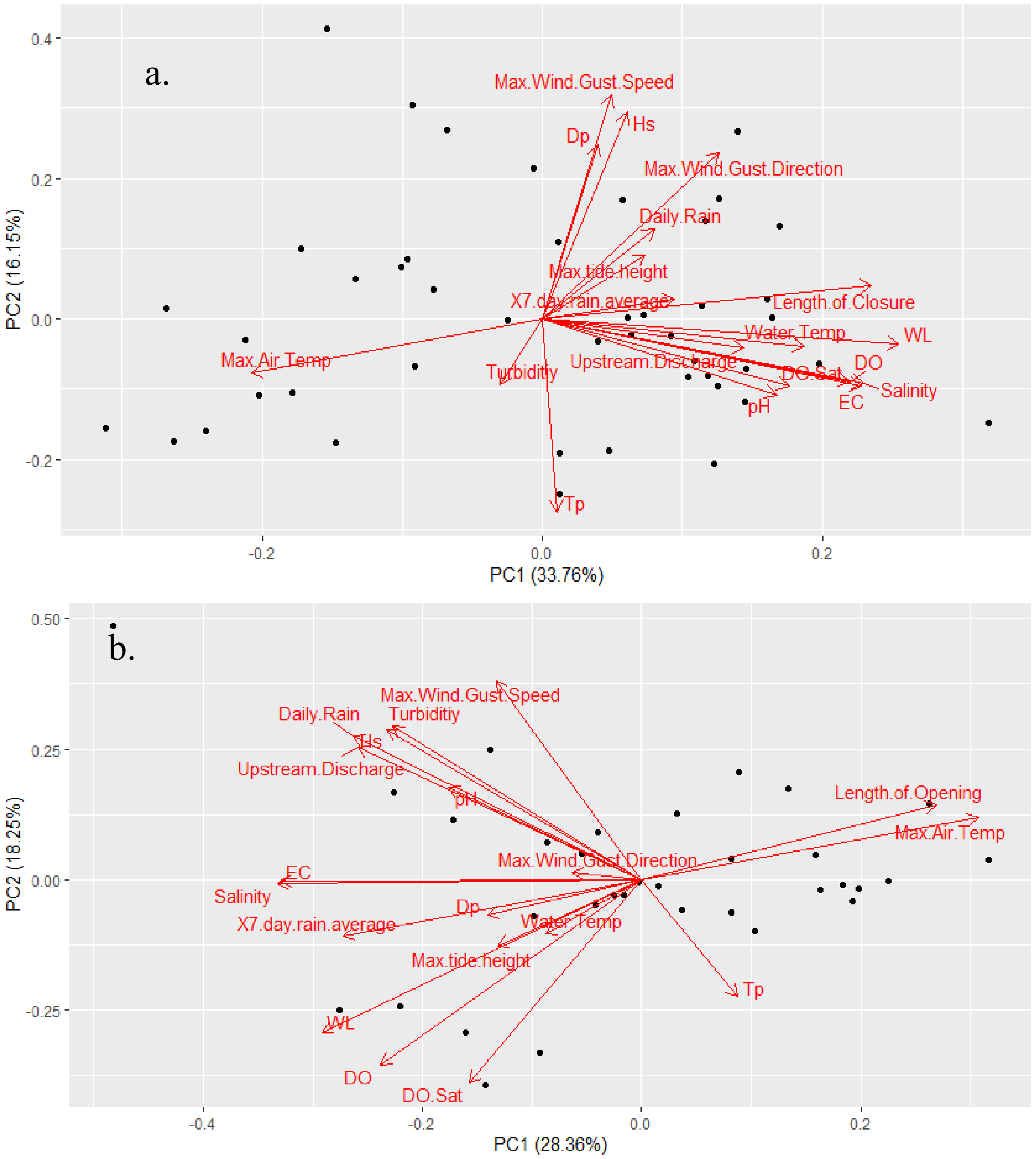

Figure 5.1: PCA biplot for Powlett River during closed periods (a) and open (b) periods. WL is water level, DO is dissolved oxygen, DO Sat is dissolved oxygen percentage saturation, EC is electrical conductivity, Hs is significant wave height, Tp is wave period and Dp is wave direction. All climate and wave variables were averaged daily. Refer to methods for units of variables.

During open periods, stratification of DO, salinity and water temperature were positively correlated with rainfall (DO=0.91, salinity=0.98, water temperature=0.95), estuary water level (DO=0.98, salinity=0.91, water temperature=1.00), significant wave height (Hs) (DO=0.40, salinity=0.85, water temperature=0.49) and upstream fluvial discharge (DO=0.50, salinity=0.91, water temperature=0.59) and negatively correlated with length of opening (DO=-0.93, salinity=-0.97, water temperature=-0.96 and maximum air temperature (DO=-0.91, salinity=-0.98, water temperature=-0.95) (Fig. 5.1b; Table 5.2). Estuary water level was the physical-environmental variable most strongly correlated with stratification of DO (0.98) and water temperature (1.00) (Table 5.2). Maximum air temperature (-0.98) and rainfall (0.98) were the variables most correlated with stratification of salinity during open periods (Table 5.2).

Table 5.2: Cosine of angles between physicochemical variables and physical-environmental variables from PCA analysis for Powlett River during open periods. Only physical-environmental variables with loadings > 0.2 or <-0.2 were measured. Values are dimensionless.

	Upstream Discharge	**Maximum Air Temperature**	**Length of Opening**	**Rainfall**	**Water Level**	**Significant Wave Height**
DO	0.50	-0.91	-0.93	0.91	0.98	0.40
Salinity	0.91	-0.98	-0.97	0.98	0.91	0.85
Water Temp	0.59	-0.95	-0.96	0.95	1.00	0.49

5.1.2 Spring Creek

A total of 25 depth profiles were analysed during closed periods and 13 depth profiles during open periods between 2014-2019. The two principal components extracted from each PCA captured 43.14% of the total variance of the data for closed periods and 49.04% of the total variance for open periods (Fig. 5.2). During closed periods stratification of water temperature, salinity and DO were positively correlated with estuary water level (DO=0.93, salinity=0.95, water temperature=0.92), rainfall (DO=0.77, salinity=0.81, water temperature=0.75) and Hs (DO=0.99, salinity=1.00, water temperature=0.99) and negatively correlated with maximum air temperature (DO=-0.96, Salinity= -0.97, water temperature=-0.95) (Fig. 5.2a; Table 5.3). Hs was the physical-environmental variable most strongly correlated to stratification of DO (0.99), salinity (1.00) and water temperature (0.99) during closed periods (Table 5.3).

Table 5.3: Cosine of angles between physicochemical variables and physical-environmental variables from PCA analysis for Spring Creek during closed periods. Only physical-environmental variables with loadings > 0.2 or <-0.2 were measured. Values are dimensionless.

	Rainfall	**Maximum Air Temperature**	**Water Level**	**Significant Wave Height**
DO	0.77	-0.96	0.93	0.99
Salinity	0.81	-0.97	0.95	1.00
Water Temp	0.75	-0.95	0.92	0.99

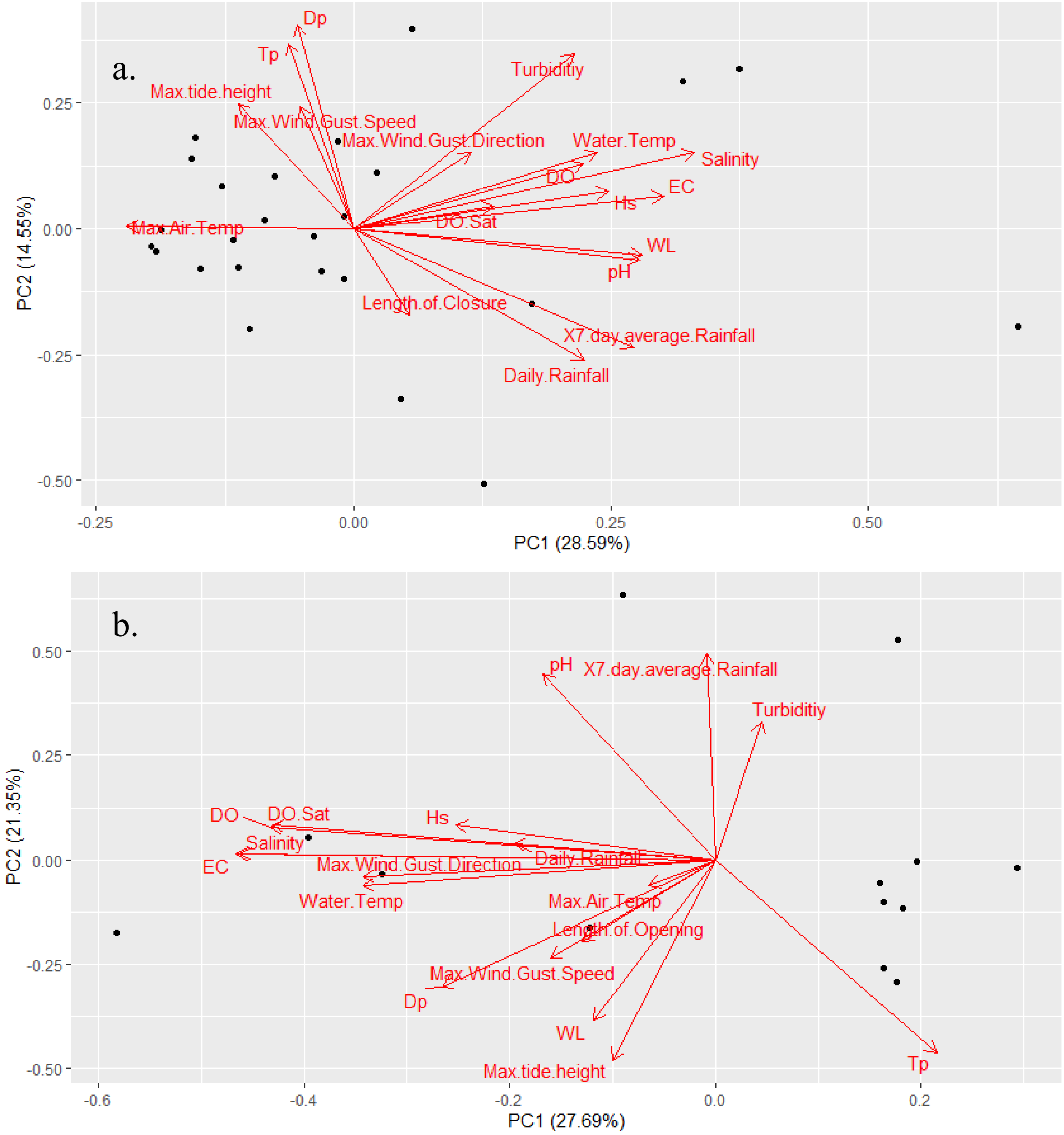

Figure 5.2: PCA biplot for Spring Creek during closed periods (a) and open (b) periods. Refer to Figure 5.1 caption for full variable names and refer to methods for units of variables.

During open periods stratification of DO, salinity and water temperatrure were positively corellated with rainfall (DO=1.00, salinity=1.00, water temperature=0.99), Hs (DO=1.00, salinity=0.99, water temperature=0.98), maximum wind gust direction (DO=0.99, salinity=1.00, water temperature=1.00) and wave direction (Dp) (DO=0.87, salinity=0.91, water temperature=0.93) (Fig. 5.2b; Table 5.4). Rainfall was the physical-enivronmental variable most correlated with stratification of DO (1.00; Table 5.4). Rainfall and maximum wind gust direction were the variables most correlated with salinity (1.00; Table 5.4). Maximum wind gust direction was the variable most correlated with water temperature (1.00) during open periods (Table 5.4).

Table 5.4: Cosine of angles between physicochemical variables and physical-environmental variables from PCA analysis for Spring Creek during open periods. Only physical-environmental variables with loadings > 0.2 or <-0.2 were measured. Values are dimensonless.

	Rainfall	**Significant Wave Height**	**Maximum Wind Gust Direction**	**Wave Direction**
DO	1.00	1.00	0.99	0.87
Salinity	1.00	0.99	1.00	0.91
Water Temp	0.99	0.98	1.00	0.93

5.1.3 Anglesea River

A total of 48 EstuaryWatch depth profiles were analysed during closed periods and 14 depth profiles during open periods between 2012-2019. The two principal components extracted from each PCA captured 41.50% of the total variance of the data for closed periods and 46.43% of the total variance for open periods (Fig. 5.3). During closed periods, stratification of DO, salinity and water temperature were positively correlated with upstream fluvial discharge (DO=1.00, salinity=0.99, water temperature=0.99) and water level (DO=0.98, salinity=0.96, water temperature=0.97) and negatively correlated with maximum air temperature (DO=-0.94, salinity=-0.97, water temperature=-0.96) (Fig. 5.3a; Table 5.5). Upstream fluvial discharge was the variable most correlated with stratification of DO (1.00), salinity (0.99) and water temperature (0.99) during closed periods (Table 5.5).

Table 5.5: Cosine of angles between physicochemical variables and physical-environmental variables from PCA analysis for Anglesea River during closed periods. Only physical-environmental variables with loadings > 0.2 or <-0.2. Values are dimensionless.

	Upstream Discharge	Maximum air Temperature	Water Level
DO	1.00	-0.94	0.98
Salinity	0.99	-0.97	0.96
Water Temp	0.99	-0.96	0.97

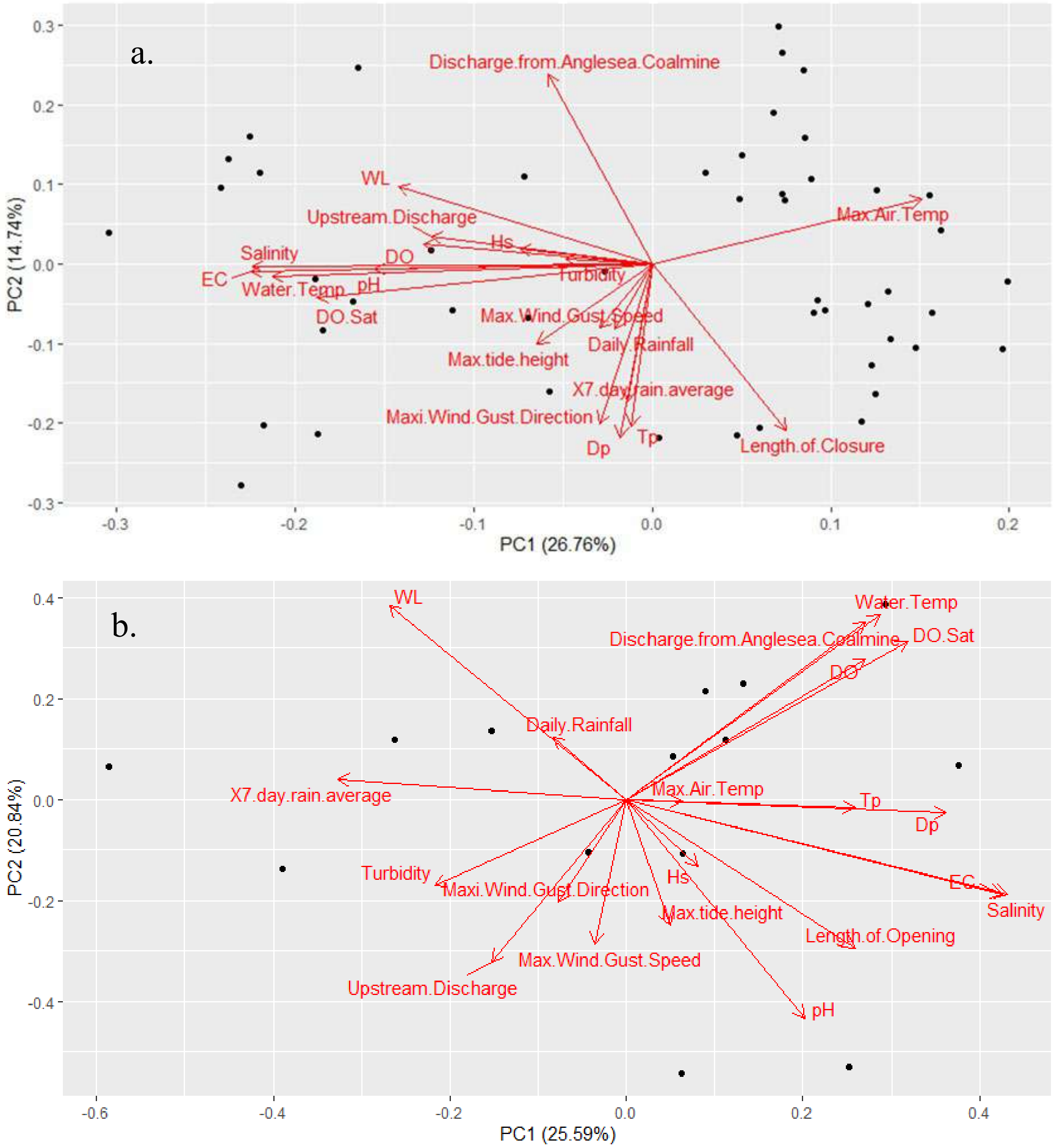

Figure 5.3: PCA biplot for Anglesea River during closed periods (a) and open (b) periods. Refer to Figure 5.1 caption for full variable names and refer to methods for units of variables.

During open periods stratification of DO, salinity and water temperature were positively correlated with Dp (DO=0.84, salinity=0.98, water temperature=0.78), discharge from Anglesea coalmine (DO=1.00, salinity=0.66, water temperature=1.00), length of opening (DO=0.45, salinity=0.95, water temperature=0.35) and wave period (Tp) (DO=0.84, salinity=0.98, water temperature=0.79) and negatively correlated with rainfall (DO=-0.83, salinity=-0.98, water temperature=-0.77) and estuary water level (DO=-0.36, salinity=-0.91, water temperature=-0.24) (Fig. 5.3b; Table 5.6). Discharge from Anglesea coalmine was the physical-environmental variable most correlated with stratification of DO (1.00) and water temperature (1.00) during open periods (Table 5.6). Rainfall was the variable most correlated with stratification of salinity (-0.96; Table 5.6).

Table 5.6: Cosine of angles between physicochemical variables and physical-environmental variables from PCA analysis for Anglesea River during open periods. Only physical-environmental variables with loadings > 0.2 or <-0.2 were measured. Values are dimensionless.

	Wave Direction	Rainfall	Discharge from Anglesea Coalmine	Water Level	Wave Period	Length of Opening
DO	0.84	-0.83	1.00	-0.36	0.84	0.45
Salinity	0.98	-0.98	0.66	-0.91	0.98	0.95
Water Temp	0.78	-0.77	1.00	-0.24	0.79	0.35

5.1.4 Painkalac Creek

A total of 76 EstuaryWatch depth profiles were analysed during closed periods and 16 depth profiles during open periods between 2009-2019. The two principal components extracted from each PCA captured 37.11% of the total variance of the data for closed periods and 44.16% of the total variance for open periods (Fig. 5.4). During closed periods, stratification of DO, salinity and water temperature were positively correlated with estuary water level (DO=0.99, salinity=0.99, water temperature=0.95) and negatively correlated with length of closure (DO=-0.98, salinity=-0.99, water temperature=-1.00) and maximum air temperature (DO=-0.88, salinity=-0.86, water temperature=-0.75) (Fig. 5.4a; Table 5.7). Estuary water level was the physical-environmental variable most correlated with stratification of DO (0.99) during closed periods (Table 5.7). Length of closure was the variable that was most correlated with stratification of salinity (-0.99) and water temperature (-1.00) (Table 5.7).

Table 5.7: Cosine of angles between physicochemical variables and physical-environmental variables from PCA analysis for Painkalac Creek during open periods. Only physical-environmental variables with loadings > 0.2 or <-0.2 were measured. Values are dimensionless.

	Water Level	**Length of Closure**	**Maximum Air Temperature**
DO	0.99	-0.98	-0.88
Salinity	0.99	-0.99	-0.86
Water Temp	0.95	-1.00	-0.75

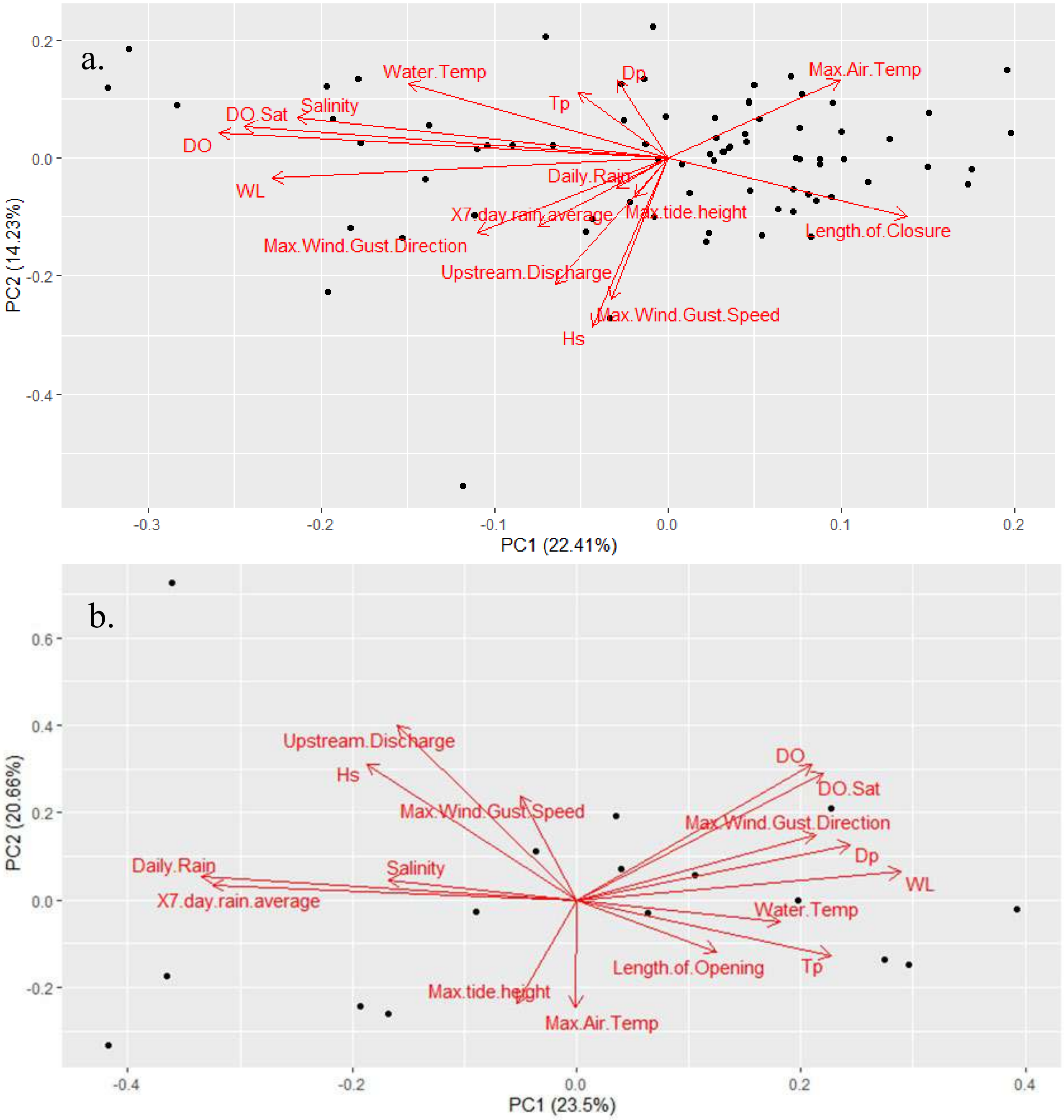

Figure 5.4: PCA biplot for Painkalac Creek during closed (a) and open (b) periods. Refer to Figure 5.1 caption for full variable names and refer to methods for units of variables.

During open periods stratification of DO and water temperature were positively correlated with estuary water level (DO=0.91, water temperature=0.98), Dp (DO=0.95, water temperature=0.96), Tp

(DO=0.74, water temperature=0.99) and maximum wind gust direction (DO=0.97, water temperature=0.93) and negatively correlated with rainfall (DO=-0.85, water temperature=-1.00) and Hs (DO=-0.45, water temperature=-0.89) (Fig. 5.4b; Table 5.8). Meanwhile, stratification of salinity was positively correlated with rainfall (1.00) and Hs (0.89) and negatively correlated with water level (-0.98), Dp (-0.96), Tp (-0.99) and maximum wind gust direction (-0.93) (Fig. 5.4b; Table 5.8). Rainfall was the physical-environmental variable most correlated with stratification of salinity (1.00) and water temperature (-1.00) during open periods (Table 5.8). Maximum wind gust direction was the variable most correlated with stratification of DO (0.97; Table 5.8).

Table 5.8: Cosine of angles between physicochemical variables and physical-environmental variables from PCA analysis for Painkalac Creek during open periods. Only physical-environmental variables with loadings > 0.2 or <-0.2 were measured. Values are dimensionless.

	Rainfall	**Water Level**	**Wave Direction**	**Wave Period**	**Significant Wave Height**	**Maximum Wind Gust Direction**
DO	-0.85	0.91	0.95	0.74	-0.45	0.97
Salinity	1.00	-0.98	-0.96	-0.99	0.89	-0.93
Water Temperature	-1.00	0.98	0.96	0.99	-0.89	0.93

5.1.5 Gellibrand River

A total of 91 EstuaryWatch depth profiles were analysed during closed periods and 151 depth profiles during open periods between 2008-2019. The two principal components extracted from each PCA captured 33.94% of the total variance of the data for closed periods and 36.77% of the total variance for open periods (Fig. 5.5). During closed periods stratification of DO was positively correlated with water level (0.59), upstream discharge (0.56), rainfall (0.62), length of closure (0.71) and Hs (0.16) and negatively correlated with maximum air temperature (-0.59) (Fig. 5.5a; Table 5.9). Stratification of salinity was positively correlated with estuary water level (0.17), upstream fluvial discharge (0.12), rainfall (0.21) and length of closure (0.31) and negatively correlated with maximum air temperature (-0.17) and Hs (-0.31) (Fig. 5.5a; Table 5.9). Stratification of water temperature was positively correlated with maximum air temperature (0.89), and negatively correlated with estuary water level (-0.89), upstream discharge (-0.91), rainfall (-0.87), length of closure (-0.81) and Hs (-0.98) (Fig.

5.5a; Table 5.9). Length of closure was the physical-environmental variable most correlated with stratification of DO (0.71) during closed periods (Table 5.9). Hs (-0.31) and length of closure (0.31) were the variables most correlated with stratification of salinity (Table 5.9). Hs was the variable most correlated with water temperature (-0.98; Table 5.9).

Table 5.9: Cosine of angles between physicochemical variables and physical-environmental variables from PCA analysis for Gellibrand River during closed periods. Only physical-environmental variables with loadings > 0.2 or <-0.2 were measured. Values are dimensionless.

	Water Level	**Upstream Discharge**	**Rainfall**	**Length of Closure**	**Maximum Air Temperature**	**Significant Wave Height**
DO	0.59	0.56	0.62	0.71	-0.59	0.16
Salinity	0.17	0.12	0.21	0.31	-0.17	-0.31
Water Temperature	-0.89	-0.91	-0.87	-0.81	0.89	-0.98

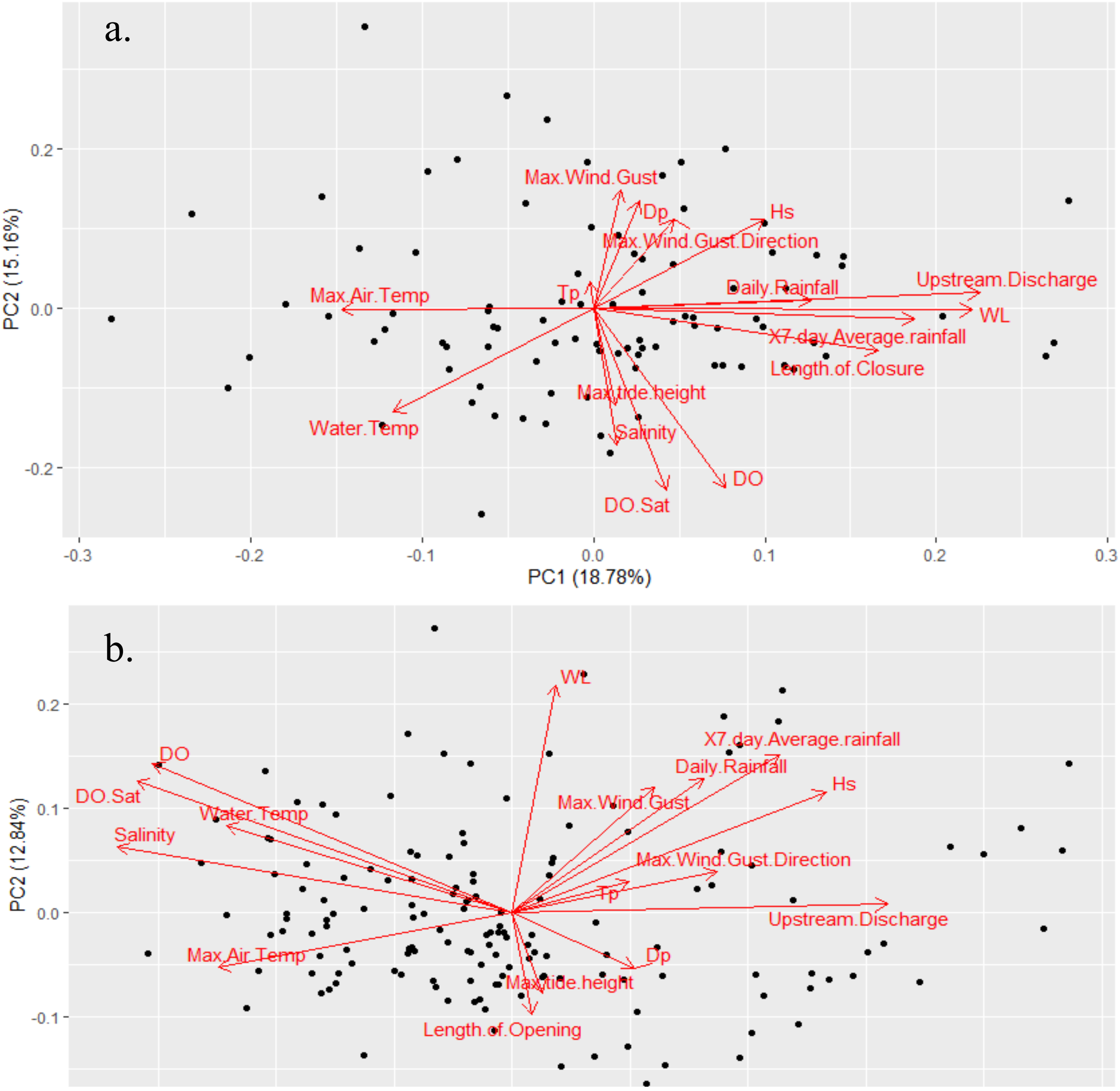

Figure 5.5: PCA biplot for Gellibrand River during closed (a) and open (b) periods. Refer to Figure 5.1 caption for full variable names and refer to methods for units of variables.

During open periods, stratification of DO, salinity and water temperature were positively correlated with maximum air temperature (DO=0.81, salinity=0.93, water temperature=0.87) and negatively correlated with upstream discharge (DO=-0.90, salinity=-0.98, water temperature=-0.94), Hs (DO= -0.68, salinity=-0.84, water temperature=-0.75) and rainfall (DO=-0.56, salinity=-0.74, water temperature=-0.64) (Fig. 5.5a; Table 5.10). Upstream discharge was the physical-environmental variable most correlated with stratification of DO (-0.90), salinity (-0.98) and water temperature (-0.94) during open periods (Table 5.10).

Table 5.10: Cosine of angles between physicochemical variables and physical-environmental variables from PCA analysis for Gellibrand River during open periods. Only physical-environmental variables with loadings > 0.2 or <-0.2 were measured. Values are dimensionless.

	Upstream Discharge	**Maximum Air Temperature**	**Significant Wave Height**	**Rainfall**
DO	-0.90	0.81	-0.68	-0.56
Salinity	-0.98	0.93	-0.84	-0.74
Water Temp	-0.94	0.87	-0.75	-0.64

5.1.6 Curdies River

A total of 32 EstuaryWatch depth profiles were analysed during closed periods and 19 depth profiles during open periods between 2014-2020. The two principal components extracted from each PCA captured 36.40% of the total variance of the data for closed periods and 46.16% of the total variance for open periods (Fig. 5.6). During closed periods DO, electrical conductivity (EC) and water temperature were positively correlated with maximum air temperature (DO=0.89, EC=0.53, water temperature=0.93) and negatively correlated with Hs (DO=-0.77, EC=-0.34, water temperature= -0.83), maximum wind gust speed (DO=-0.80, EC=-0.37, water temperature=-0.86) and upstream discharge (DO=-0.91, EC=-0.56, water temperature=-0.95) (Fig. 5.6a; Table 5.11). Salinity was positively correlated with Hs (0.73), rainfall (0.78), maximum wind gust speed (0.71) and upstream discharge (0.54) and negatively correlated with maximum air temperature (-0.57) (Fig. 5.6a; Table 5.11). Upstream discharge was the physical-environmental variable most correlated with DO (-0.91), electrical conductivity (-0.56) and water temperature (-0.95) during closed periods (Table 5.11). Rainfall was the variable most correlated with salinity (0.78; Table 5.11).

Table 5.11: Cosine of angles between physicochemical variables and physical-environmental variables from PCA analysis for Curdies River during closed periods. Only physical-environmental variables with loadings > 0.2 or <-0.2 were measured. Values are dimensionless.

	Significant Wave Height	**Rainfall**	**Maximum Wind Gust Speed**	**Maximum Air Temperature**	**Upstream Discharge**
DO	-0.77	-0.73	-0.80	0.89	-0.91
Salinity	0.73	0.78	0.71	-0.57	0.54
Electrical Conductivity	-0.34	-0.28	-0.37	0.53	-0.56
Water Temperature	-0.83	-0.80	-0.86	0.93	-0.95

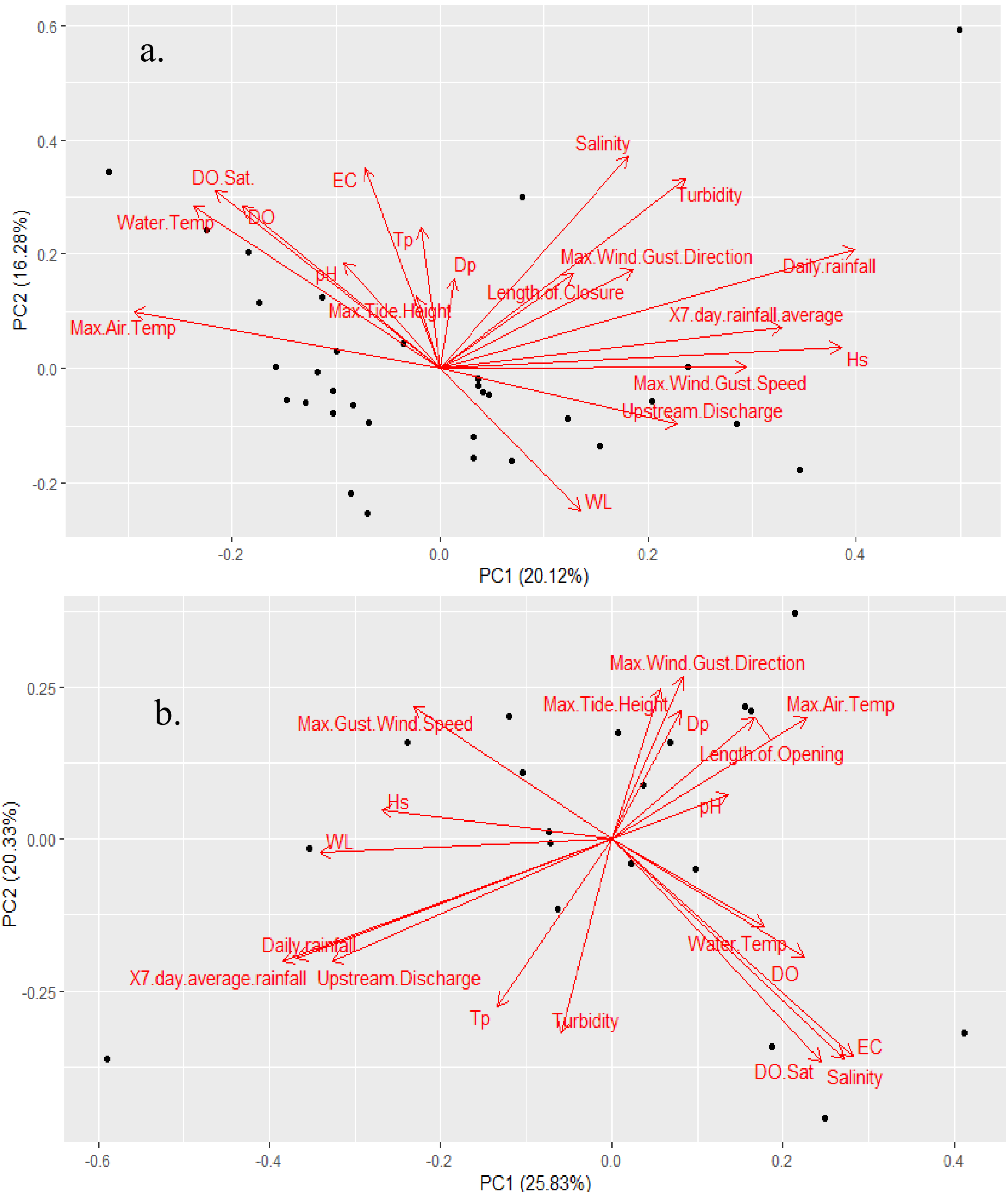

Figure 5.6: PCA biplot for Curdies River during closed (a) and open (b) periods. Refer to Figure 5.1 caption for full variable names and refer to methods for units of variables.

During open periods, stratification of DO, salinity and water temperature were positively correlated with maximum air temperature (DO=0.56, salinity=0.37, water temperature=0.56) and negatively correlated with rainfall (DO=-0.69, salinity=-0.53, water temperature=-0.71), upstream discharge (DO=-0.66, salinity=-0.48, water temperature=-0.67), estuary water level (DO=-0.87, salinity=-0.74, water temperature=-0.89), maximum wind gust speed (DO=-1.00, salinity=-0.99, water temperature= -1.00) and Hs (DO=-0.93, salinity=-0.84, water temperature=-0.93) (Fig. 5.6b; Table 5.12). Maximum wind gust speed was the physical-environmental variable most correlated with stratification of DO (-1.00), salinity (-0.99) and water temperature (-1.00) during open periods (Table 5.12).

Table 5.12: Cosine of angles between physicochemical variables and physical-environmental variables from PCA analysis for Curdies River during open periods. Only physical-environmental variables with loadings > 0.2 or <-0.2 were measured. Values are dimensionless.

	Rainfall	Upstream Discharge	Water Level	Maximum Wind Gust Speed	Maximum Air Temperature	Significant Wave Height
DO	-0.69	-0.66	-0.87	-1.00	0.56	-0.93
Salinity	-0.53	-0.48	-0.74	-0.99	0.37	-0.84
Water Temperature	-0.71	-0.67	-0.89	-1.00	0.56	-0.93

5.1.7 Differences Between Sites

The main difference in correlations of physicochemical and physical-environmental variables between IOCE were found between larger catchment area IOCE and smaller catchment IOCE. Smaller catchment IOCE including Powlett River (Table 5.1-5.2), Spring Creek (Table 5.3), Anglesea River (Table 5.5) and Painkalac Creek (Table. 5.7) had a positive correlation between stratification of DO, salinity and water temperature and either rainfall, upstream fluvial discharge, and estuary water level during open and/or closed periods. These IOCE also consistently showed a negative correlation between maximum air temperature and stratification of DO, salinity and water temperature. In contrast, larger catchment IOCE including the Gellibrand (Table 5.10) and Curdies Rivers (Table 5.11-5.12) had a positive correlation between maximum air temperature and stratification of physicochemical variables during closed and/or open periods. These estuaries had a negative correlation between either rainfall, upstream fluvial discharge and estuary water level and stratification.

5.2 Fieldwork Results

Two estuary openings were monitored at two IOCE (Aire River and Painkalac Creek) during 2020. Measuring sites refer to the physicochemical monitoring sites upstream from the mouth at each IOCE and does not refer to the IOCE mouth (Fig. 4.1). Turbidity was not referred to in the Painkalac Creek results because bottom turbidity readings were affected by the water quality multi-meter hitting the bottom of the water column. pH was not referred to because no interpretable results could be extracted for both Painkalac Creek and Aire River (Appendix C). DO percentage saturation and electrical conductivity were not referred to because the changes were very similar to DO concentration and salinity respectively for both Painkalac Creek and Aire River. Refer to Appendix C for raw physicochemical data from Painkalac Creek and Aire River.

5.2.1 Painkalac Creek Artificial Opening

Painkalac Creek was opened on 30/06/2020 at 12:00, approximately 30 minutes after low tide. The estuary water level was 1.90m AHD before the opening and the weather was partly cloudy with a maximum air temperature of 14.5°C. The berm length was approximately 100m. Winds were 20km/h from the N to NNW during the day with a maximum wind gust of 59km/h at 23:30. Between 1.05-1.47Ml/day of water was released from Painkalac Dam between 30/06/2020-04/07/2020. Estuary water level at Painkalac Creek dropped by 0.30m to reach 1.60m AHD between 30/06/10:00 to 02/07/10:00 (Fig. 5.7). Physicochemical measurements were measured from 30/06/2020-02/07/2020 and geomorphic measurements from 30/06/2020-01/07/2020.

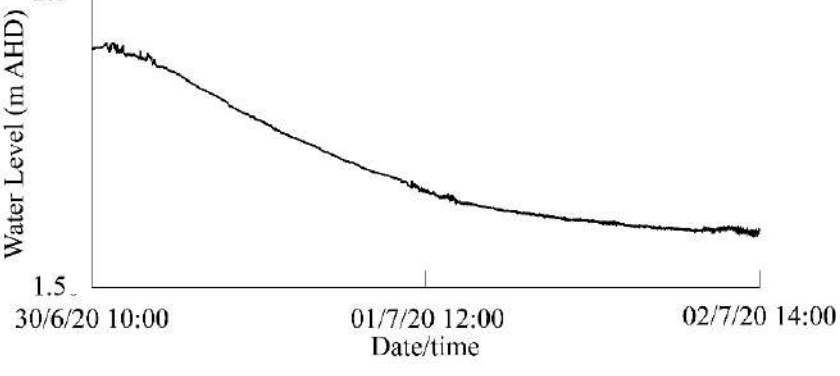

Figure 5.7: Water level of Painkalac Creek between 30/06/2020 10:00 to 02/07/2020 14:00. Estuary was open at 12:00 on 30/06/2020.

5.2.1.1 Geomorphic Change

The artificially dug channel transitioned from a straight channel to a meandering channel (by 01/07/7:00), increasing the channel length by 90m (Fig. 5.8). Channel width peaked at 11.97m 22 hours after opening (Fig. 5.9a). Channel water depth peaked at 0.50m approximately 3 hours after opening (Fig. 5.9b). Discharge from the mouth peaked at 5.46m^3/s also approximately 3 hours after the opening before declining (Fig. 5.9c). Upstream water velocity peaked at 0.01-0.02m/s (Table 5.13).

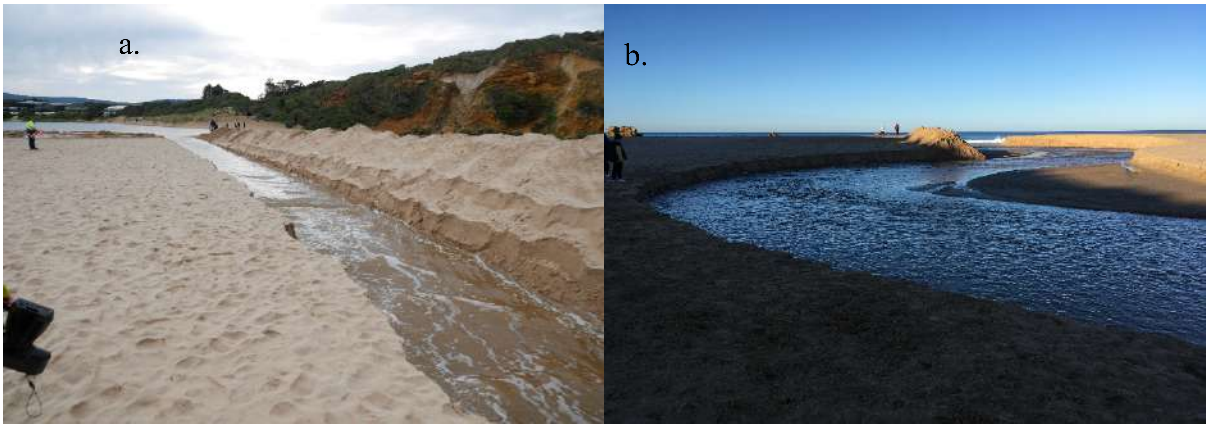

Figure 5.8: Artificially dug channel immediately after opening, 30/06/2020 (a) and artificially dug channel the next morning, 01/07/2020 (b).

Table 5.13: Timing and magnitude of water velocity at the top and bottom of the water column at each measuring site at Painkalac Creek.

Measuring Site	Maximum Top Water Velocity (m/s)	Timing of Maximum Top Water Velocity (hours after opening)	Maximum Bottom Water Velocity (m/s)	Timing of Maximum Bottom Water Velocity (hours after opening)
Painkalac Lower	0.01	1.5	0.02	4.5
Painkalac Lower	0.01	1.75	0.00	N/A
Painkalac Upper	0.02	Before opening	0.01	Before opening
Painkalac Upper	0.02	Before opening	0.01	Before opening

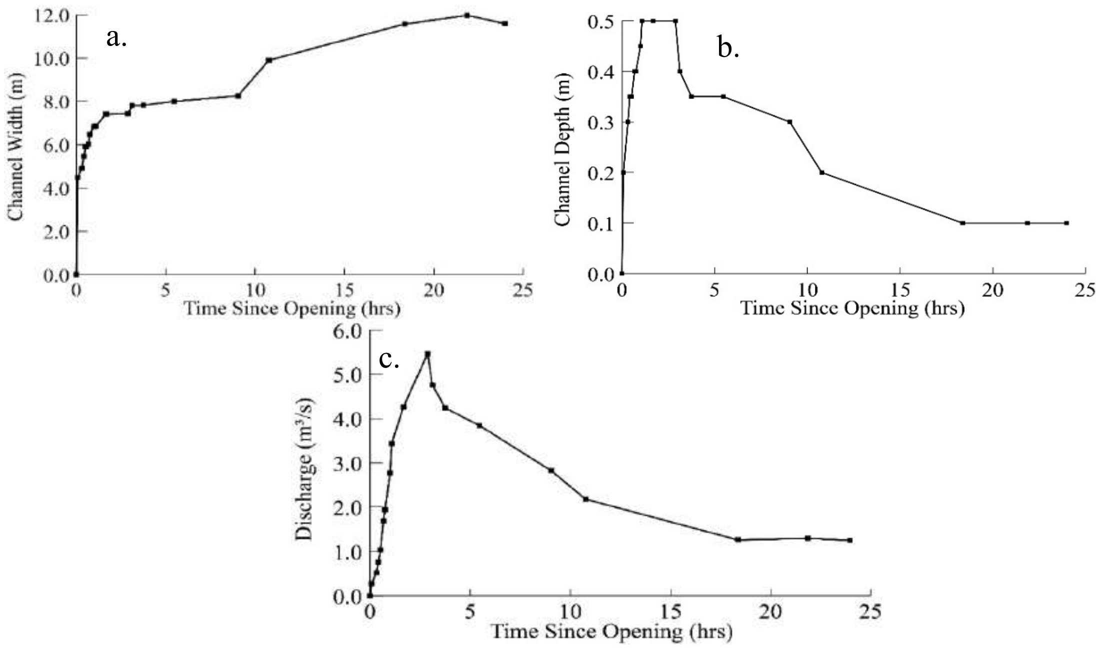

Figure 5.9: Changes in channel width (a), channel depth (b) and discharge (c) of the artificially dug channel throughout the artificial opening.

5.2.1.2 Salinity

Salinity was weakly stratified before the opening with absolute differences between top and bottom salinity of 1.84 PSU at Painkalac Upper (Fig 4.1c; Fig. 5.10j), 3.63 PSU at Painkalac Upper Middle (Fig 4.1c; Fig. 5.10g), 2.59 PSU at Painkalac Lower Middle (Fig 4.1c; Fig. 5.10d) and 2.49 PSU at Painkalac Lower (Fig. 4.1c; Fig. 5.10a). Salinity remained stratified throughout the whole measurement period. The top three depths (0.1-1.0m depth) became less uniform as water level decreased. For example, at Painkalac Lower the absolute difference between salinity at 0.1m-1.0m depths was 0.01 PSU before the opening and increased to 2.22 PSU by depth profile 6 (22 hours after opening) (Fig. 5.10a). Salinity at the top two depths (0.1-0.5m) generally decreased throughout the measurement period. This decrease in top salinity was especially the case at Painkalac Upper Middle (Fig. 5.10g) and Painkalac Upper (Fig. 5.10j) with decreases of top salinity between depth profiles 1 and 7 (0-52 hours after opening) of 1.78 PSU and 5.59 PSU, respectively. Salinity at 1.0m depth generally increased throughout the measurement period, especially at Painkalac Lower (Fig. 5.10a) and Lower Middle (Fig. 5.10d) where salinity at 1.0m depth increased by 2.09 PSU and 2.26 PSU respectively between depth profiles 1-6 (0 to 26 hours after opening). There was no marked change in bottom salinity at any measuring site.

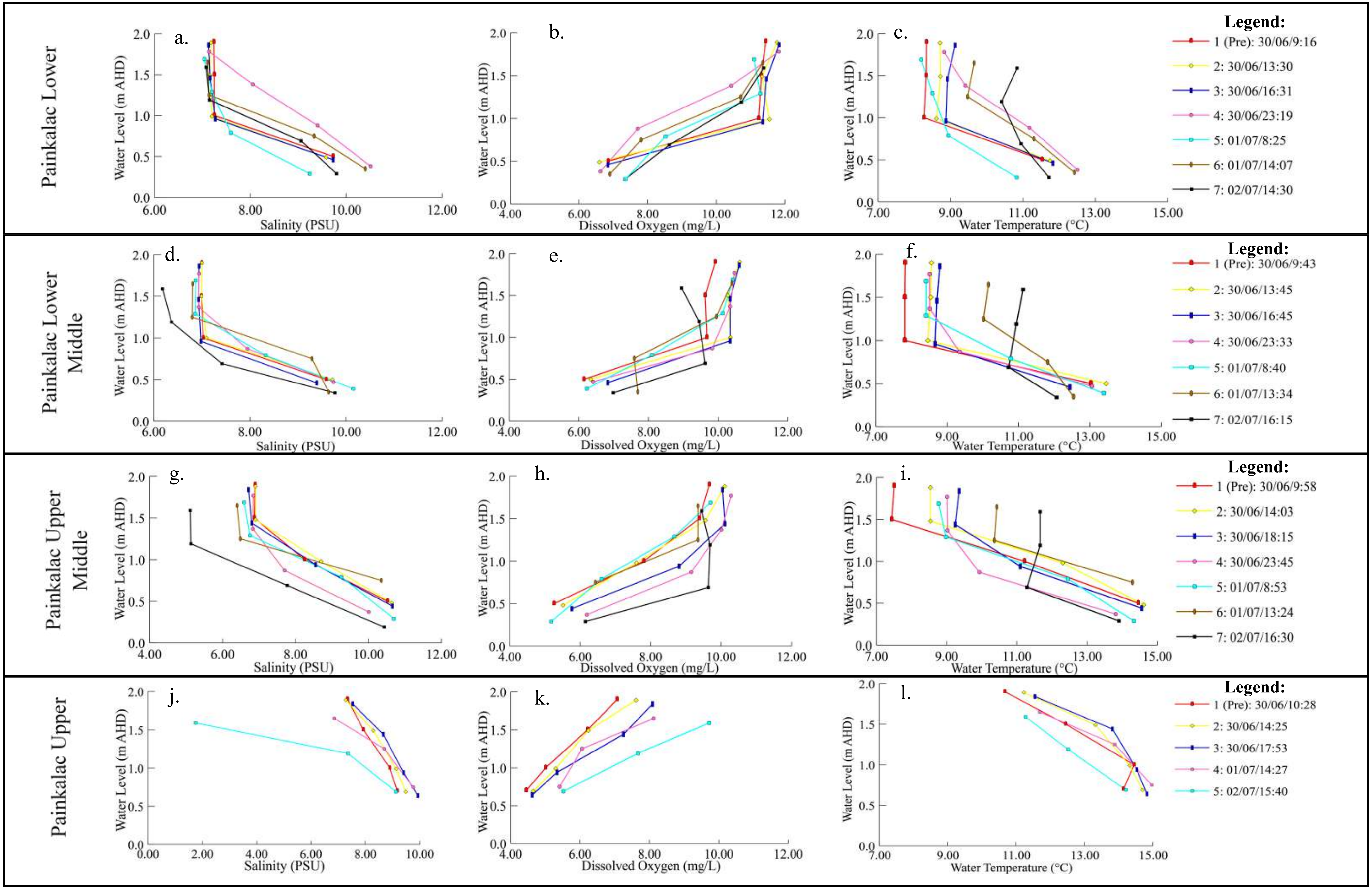

Figure 5.10: Physicochemical depth profiles taken at Painkalac Creek at Painkalac Lower (a-c), Painkalac Lower Middle (d-f), Painkalac Upper Middle (g-i) and Painkalac Upper (j-l) measuring sites (refer to Chapter 4.2.1 for location of field sites) between 30/06/2020 9:16-02/07/2020 16:30. The estuary was artificially opened on 30/06/2020 at 12:00. Note the different axes used for salinity used in Painkalac Upper and Painkalac Upper Middle.

5.2.1.3 Dissolved Oxygen (DO)

DO concentration was stratified before the opening with differences between top and bottom DO of 2.62mg/L at Painkalac Upper (Fig. 5.10k), 4.41mg/L at Painkalac Upper Middle (Fig. 5.10h), 3.77mg/L at Painkalac Lower Middle (Fig. 5.10e) and 4.59mg/L at Painkalac Lower (Fig. 5.10b). DO remained stratified throughout the whole measuring period. Generally, top DO increased during the day and decreased overnight. DO at 1.0m depth at each depth profile at Painkalac Lower (Fig. 5.10b) and Painkalac Lower Middle (Fig. 5.10e) decreased as water level lowered. DO at 1.0m depth between profiles 1 and 6 (0-26 hours after opening) decreased by 3.42mg/L at Painkalac Lower (Fig. 5.10b) and by 2.09mg/L at Painkalac Lower Middle (Fig. 5.10e).

5.2.1.4 Water Temperature

Water temperature was stratified at each measuring site before the opening, with absolute differences between top and bottom water temperature of 3.47°C at Painkalac Upper (Fig. 5.10l), 6.95°C at Painkalac Upper Middle (Fig. 5.10i), 5.21°C at Painkalac Lower Middle (Fig. 5.10f) and 3.19°C at Painkalac Lower (Fig. 5.10c). Water temperature remained stratified throughout the whole opening at all measuring sites. Top water temperature generally increased during the day and then decreased overnight at all measuring sites. Similar to salinity, the 1.0m depth of each profile mostly increased during the measuring period at Painkalac Lower (Fig. 5.10c) and Painkalac Lower Middle (Fig. 5.10f). Water temperature increased at 1.0m depth by 3.03°C at Painkalac Lower (Fig. 5.10c) and 4.01˚C at Painkalac Lower Middle (Fig. 5.10f). Water temperature at 0.1-1.0m depths became more uniform between depth profiles 6 and 7 (25.3-53 hours after opening) at Painkalac Lower, Lower Middle and Upper Middle.

5.2.2 Aire River Artificial Opening

Aire River was opened on 23/07/2020 at 12:00, approximately 30 minutes before high tide. The water level was 1.57m AHD before the opening and the weather was fine, partly cloudy with a top of 11.8°C and winds NNW to WSW between 11-28km/h. The berm length was approximately 46m. On

24/07/2020 at 10:00 water level had dropped 1.05m to 0.52m AHD (Fig. 5.11). Geomorphic and physicochemical measurements were carried out between 23/07/2020-24/07/2020.

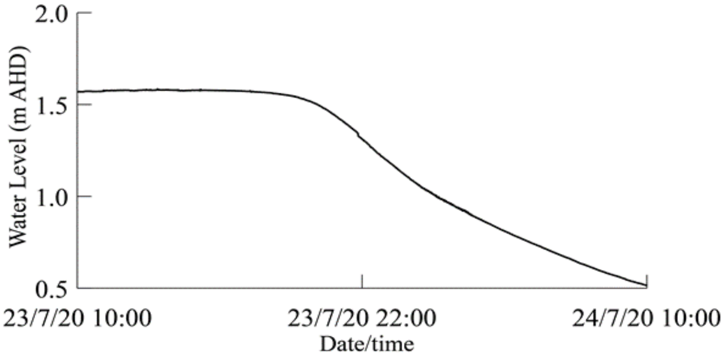

Figure 5.11: Water level of Aire River between 23/07/2020/10:00 to 24/07/2020 10:00. Artificial estuary opening was completed at 12:00 on 23/07/2020.

5.2.2.1 Geomorphic Change

The artificially dug channel started off narrow (7.66m) and shallow (0.32m) before transitioning into a deep and wide channel approximately 8 hours after opening (Fig. 5.12). Maximum channel width (34.82m) occurred 19.9 hours after opening (Fig. 5.13a) and maximum channel water depth (1.50m) occurred 11.3 hours after opening (Fig. 5.13b). Discharge from the mouth peaked at 189.20m^3/s 11.3 hours after opening (Fig. 5.13c). Upstream water velocity peaked at 0.16-0.29m/s at the top of the water column and 0.08-0.18m/s at the bottom of the water column at each measuring site (Table 5.14). Maximum upstream velocity occurred just before maximum discharge from the mouth (9.1-10.6 hours after opening) at all sites except for bottom velocity at Aire Upper (Table 5.14).

Table 5.14: Timing and magnitude of maximum water velocity at the top and bottom of the water column at each measuring site at Aire River.

Measuring Site	Maximum top water velocity (m/s)	Timing of top maximum water velocity (hours after opening)	Maximum bottom water velocity (m/s)	Timing of bottom maximum water velocity (hours after opening)
Aire Lower	0.23	9.1	0.16	9.1
Aire Middle	0.29	9.5	0.18	9.5
Aire Upper	0.16	10.6	0.08	20.5

Figure 5.12*:* Artificially dug channel immediately after the artificial opening, July 23, 2020 (a) and the next morning, July 24, 2020 (b).

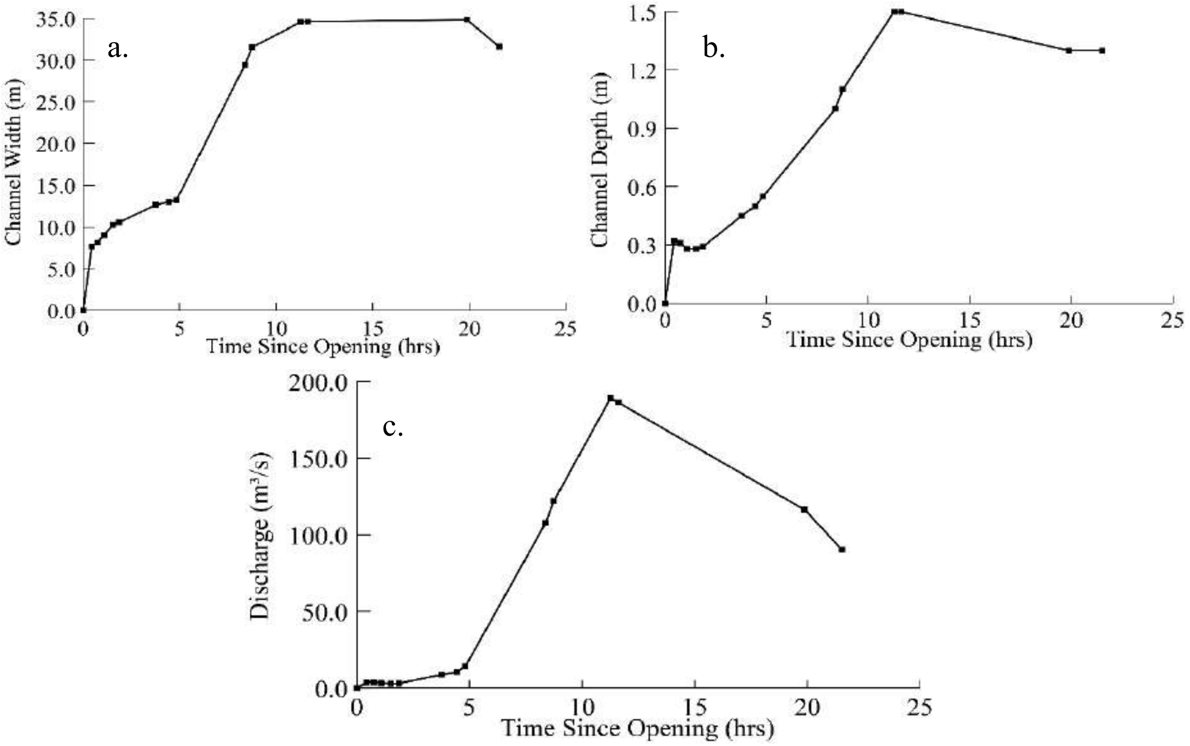

Figure 5.13*:* Changes in channel width (a), channel depth (b) and discharge (c) of the artificially dug channel throughout the artificial opening.

5.2.2.2 Salinity

Salinity was stratified before the opening at all measuring sites with absolute differences in top and bottom salinity of 4.36 PSU at Aire Upper (Fig. 4.1b; Fig. 5.14i), 14.96 PSU at Aire Middle (Fig. 4.1b; Fig. 5.14e) and 11.17 PSU at Aire Lower (Fig. 4.1b; Fig. 5.14a). Salinity became relatively uniform at all measuring sites between depth profile 4 (Fig. 5.14i) and 5 (Fig. 5.14a, e) (9.6-11.6 hours after opening). Salinity became uniform in depth profile 4 with an average salinity of 2.30 PSU at Aire Upper (9.6 hours after opening) (Fig. 5.14i), depth profile 5 with an average salinity of 3.44 PSU at Aire Middle (11.6 hours after opening) (Fig. 5.14e) and depth profile 5 with an average salinity of 3.38 PSU at Aire Lower (10.8 hours after opening) (Fig. 5.14a). After salinity became uniform, salinity increased in the top two depths (0.1-0.5m) of Aire Lower (Fig. 5.14a) and the whole water column of Aire Middle (Fig. 5.14e) and Aire Upper (Fig. 5.14i) between depth profiles 4 and 5 (9-11.6 hours after opening) and then decreased between depth profiles 5 and 6 (10.6-20.5 hours after opening). For example, at Aire Upper, average salinity increased from increased from 2.30 PSU to 3.63 PSU between depth profiles 4 and 5 and decreased to 1.27 PSU at depth profile 6 (Fig 5.14i).

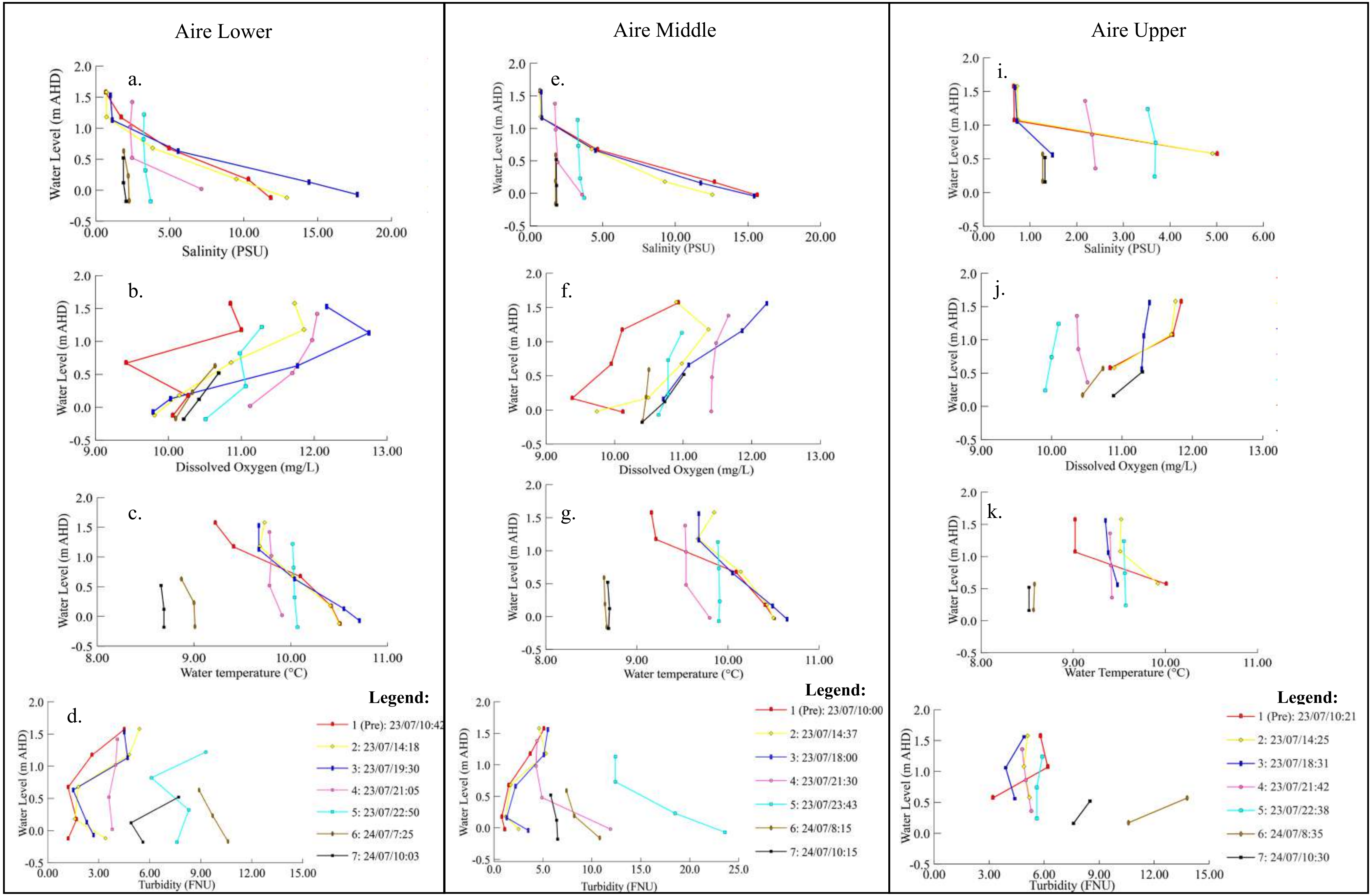

Figure 5.14: Physicochemical depth profiles taken at Aire River Lower (a-d), Aire River Middle (e-h) and Aire River Upper (i-l) measuring sites (refer to Chapter 4.2.1 for location of measuring sites) between 23/07/2020 10:00-24/07/2020 10:30. The estuary was artificially opened at 23/07/2020 12:00. Note the different axes for salinity (c) used for Aire Upper and turbidity (l) used for Aire Middle.

5.2.2.3 Dissolved Oxygen

DO concentration was weakly stratified at all measuring sites with absolute differences between top and bottom DO of 1.01mg/L at Aire Upper (Fig. 5.14j), 0.81 mg/L at Aire Middle (Fig. 5.14f) and 0.79mg/L at Aire Lower (Fig. 5.14b). Top DO increased during the daytime and then decreased overnight at all measuring sites except Aire Upper which decreased throughout the first day. DO became uniform by the depth profile 4 at Aire Upper (9.6 hours after opening) (Fig. 5.14j), Aire Middle (9.5 hours after opening) (Fig. 5.14f) and Aire Lower (9 hours after opening) (Fig. 5.14b).

5.2.2.4 Water Temperature

Before the opening water temperature was weakly stratified with absolute differences between top and bottom water temperature of 0.99°C at Aire Upper (Fig. 5.14k), 1.35°C at Aire Middle (Fig. 5.14g) and 1.29°C at Aire Lower (Fig. 5.14c). Water temperature became uniform by depth profile 4 at Aire Upper (9.6 hours after opening) (Fig. 5.14k) and depth profile 5 at Aire Middle (10.8 hours after opening) (Fig. 5.14g) and Aire Lower (11.6 hours after opening) (Fig. 5.14c). Water temperature increased throughout the water column between depth profiles 4 and 5 (9-11.6 hours after opening) at all measuring sites before decreasing overnight between depth profiles 5 and 6 (10.6-20.5 hours after opening).

5.2.2.5 Turbidity

Turbidity was low at all measuring sites before the opening with Aire Upper having an average turbidity of 5.1 FNU (5.14l), Aire Middle 2.4 FNU (Fig. 5.14h) and Aire Lower 2.2 FNU (Fig. 5.14d). Average turbidity increased at all sites and peaked between depth profiles 5 and 6 (10.6-20.5 hours after opening) at 12.2 FNU at Aire Upper (Fig. 5.14l), 16.7 FNU at Aire Middle (Fig. 5.14h) and 9.7 FNU at Aire Lower (Fig. 5.14d).

5.2.3 Comparison Between Sites

At Painkalac Creek, discharge from the mouth peaked earlier (3 hours after opening) but was much smaller than Aire River (Fig. 5.9c). Upstream, there was very little variation in physicochemical depth profiles throughout the measurement period at each of the measuring sites with very low water velocities (Fig. 5.10; Table 5.13). Meanwhile at Aire River, discharge from the mouth took longer to reach its maximum (11.5 hours) but was over 30 times larger than Painkalac Creek, representing one order of magnitude difference (Fig. 5.13c). As discharge from the mouth started to reach its maximum at Aire River, surface salinity (Fig. 5.14a, e, i) and water temperature (Fig. 5.14c, g, k) increased but the depth profiles became more uniform, before becoming completely uniform at each measuring site. Turbidity also increased as discharge from the mouth increased (Fig. 5.14d, h, l) and increases in top and bottom velocity at all measuring sites were observed coinciding with this increase in discharge (Table 5.14; Appendix C). Overall, the magnitude of changes in mouth morphology and physicochemical depth profiles were much larger at the Aire River opening than the Painkalac Creek opening.

6 Discussion

6.1 Analysis of Historic Data

6.1.1 Closed Periods

At all IOCE included in the PCA, rainfall, upstream fluvial discharge, and estuary water level were consistently important controls on stratification of dissolved oxygen (DO), salinity and water temperature during closed periods (Table 5.1, 5.5, 5.7, 5.9 and 5.11). These physical-environmental variables are all indicators of river inflow. Estuary water level is an indicator of river inflow because water level tends to be higher during periods of high river inflow. At Powlett River (Fig. 5.1a), Spring Creek (Fig. 5.2a), Anglesea River (Fig. 5.3a) and Painkalac Creek (Fig. 5.4a), river inflow was positively correlated with stratification of DO, salinity and water temperature. These results are consistent with the prediction made that increased river inflow will increase stratification of physicochemical variables (Table 2.2) and agrees with findings from previous studies (Barton & Sherwood 2004; Taljaard, van Niekerk & Joubert 2009; Whitfield et al. 2012). Increased river inflow increases stratification because of density differences between saline water and freshwater (Snow & Taljaard 2007). Freshwater from river inflow reduces the salinity at the top of the water column, eventually leading to increases in stratification of salinity, DO and water temperature (Snow & Taljaard 2007).

Maximum air temperature proved to also be an important physical-environmental variable in affecting stratification during closed periods. Stratification of DO, salinity and water temperature were negatively correlated with maximum air temperature at Powlett River (Table 5.1), Spring Creek (Table 5.3), Anglesea River (Table 5.5) and Painkalac Creek (Table 5.7). Increases in maximum air temperature usually coincide with reduced river inflow, especially over summer in Victoria (Sherwood, Mondon & Fenton 2008). Increases in air temperature also result in greater rates of evaporation. If there is not enough river inflow to replace the freshwater that is being lost to evaporation, then the estuary water column becomes uniformly saline (Taljaard, van Niekerk & Joubert 2009). Therefore, as maximum air temperature increases and river inflow decreases, the water column becomes uniformly saline with consistent DO and water temperature, decreasing stratification as predicted (Table 2.1). For IOCE of similar sizes, morphologies and climatic conditions in South Africa, Snow & Taljaard (2007) also found that during low to no river inflow periods, the freshwater layer evaporates away leaving, the water column with uniform salinity, DO and water temperature (Fig. 6.1). This process is likely to also be observed in Victorian IOCE and other similar IOCE globally in semi-arid climates where evaporation exceeds inflow (Cameron & Pritchard 1963; Snow & Taljaard 2007).

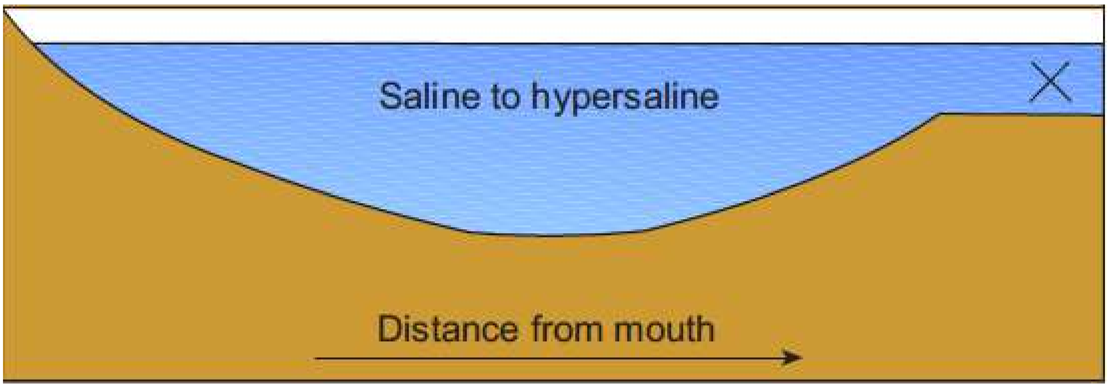

Figure 6.1: When there is little to no river inflow during closed periods, the freshwater layer evaporates away, leaving a uniformly saline water column (Snow & Taljaard 2007).

Stratification of DO and salinity were poorly represented in the Gellibrand River PCA during closed periods (Fig 5.5a). It was found that there was little variation in stratification of salinity and DO during the analysis period. This occurred because Gellibrand River was consistently closed over summer or autumn for nine out of the eleven years of the data period for between 18-51 days (Appendix B). During this time, the water column was constantly stratified with little variation in the degree of stratification. Stratification of water temperature varied more throughout the analysis period and was better represented in the PCA. Stratification of water temperature was negatively correlated with water level, upstream discharge and rainfall and positively correlated with maximum air temperature (Table 5.9).

At Curdies River, stratification of DO, electrical conductivity and water temperature were negatively correlated with freshwater inflow and positively correlated with maximum air temperature (Fig. 5.6a) during closed periods. However, salinity and electrical conductivity were grouped differently and had different relationships to physical-environmental variables unlike at all other IOCE that measured electrical conductivity. There was little variability in stratification of salinity, possibly due to the EstuaryWatch site being close to the mouth and therefore being less influenced by river inflow. Electrical conductivity is more sensitive to changes and was better able to capture changes in stratification than salinity at Curdies River. These results indicate that stratification at Curdies River responds differently to Powlett River, Spring Creek, Anglesea River and Painkalac Creek.

Other physical-environmental variables such as significant wave height, maximum wind gust speed and length of closure had some degree of correlation with stratification. However, none of these variables were consistently correlated with stratification at all IOCE and there was no consistent correlation between these variables and stratification of DO, salinity and water temperature. It is more likely that significant wave height and maximum wind gust speed increase at the same time as river inflow increases rather than directly affecting stratification in IOCE as predicted (Table 2.1). Maximum wind gust speed and significant wave height tend to increase during storms when there is also high rainfall and river inflow (e.g. McSweeney, Kennedy & Rutherfurd 2018). Vertical stratification during closed periods has been attributed to waves entering the basin by overtopping the berm in IOCE of similar sizes and settings in South Africa such as the Diep and Palmiet estuaries (Snow & Taljaard 2007; Taljaard, van Niekerk & Joubert 2009). This may not have been observed in my results because the EstuaryWatch measuring sites chosen were located >1.0km upstream from the mouth except at Curdies River. These sites may have been located too far upstream to be affected by waves overtopping the berm. My results do not rule out that waves can affect stratification in IOCE during closed periods. Length of closure is also more likely to be indicative of a change in river inflow and maximum air temperature rather than affecting stratification as predicted (Table 2.2). As the length of closure increases, the IOCE will experience higher rainfall and river flow as we move into autumn and spring. The length of closure may affect stratification of DO by reducing bottom DO as biochemical processes use up oxygen (Sherwood, Mondon & Fenton 2008). This process has been observed in many IOCE such as Wamberal Lagoon and Smiths Lake in Australia (Gale, Pattiaratchi & Ranasinghe 2006) and Diep Estuary in South Africa (Whitfield et al. 2012) which are of a similar sizes and settings. This process cannot be proven with certainty from my results because there was no consistent correlation between length of closed periods and stratification of DO across all IOCE. Therefore, my results cannot prove the prediction made that stratification of DO increases as the length of closure increases (Table 2.2), but this process could still occur in the IOCE studied.

Overall, during closed periods, stratification of DO, salinity and water temperature are most affected by evaporation and river inflow (i.e. estuary water level, rainfall, upstream fluvial discharge). Stratification at Powlett River, Spring Creek, Anglesea River and Painkalac Creek increases when there is greater river inflow and decreases when evaporation is greater. In contrast, there is little variation in stratification at Gellibrand and Curdies Rivers during closed periods. My results indicate that stratification increases when river inflow decreases and when evaporation is greater, in contrast to processes observed in the smaller basin IOCE (i.e. Powlett River, Spring Creek, Anglesea River and Painkalac Creek). The results from the Gellibrand and Curdies Rivers are opposite to the prediction made that increased river inflow increases stratification (Table 2.2) which indicates that there is a diversity in how stratification at different IOCE respond to river inflow, likely influenced by size and morphology.

6.1.2 Open Periods

During open periods river inflow (i.e. water level, rainfall, and upstream discharge) and evaporation (i.e. maximum air temperature) were important physical-environmental variables in determining the degree of stratification of IOCE, similar to closed periods.

The Gellibrand (Fig. 5.5b) and Curdies Rivers (Fig. 5.6b) showed much greater variation in stratification of salinity, DO and water temperature during open periods than closed periods. This led to much stronger relationships between stratification and physical-environmental variables during open periods. Stratification of salinity, DO and water temperature were negatively correlated with river inflow and other hydrological variables (e.g. water level, upstream discharge, and rainfall) and positively correlated with maximum air temperature at these IOCE. This decrease in stratification occurred because high river inflow during open periods can be sufficient to completely flush out more saline/brackish estuarine water and make the water column uniformly fresh (Snow & Taljaard 2007). Then when river inflow decreases, the IOCE returns to being stratified. These results do not support the prediction made that increased river inflow increases stratification (Table 2.1-2.2). In agreement with my findings, Sherwood, Mondon & Fenton (2008) also found that the water column at Gellibrand River was completely fresh at times. When open, the Gellibrand and Curdies Rivers correspond to the freshwater dominated state described by Taljaard, van Niekerk & Joubert (2009) (Fig. 6.2).

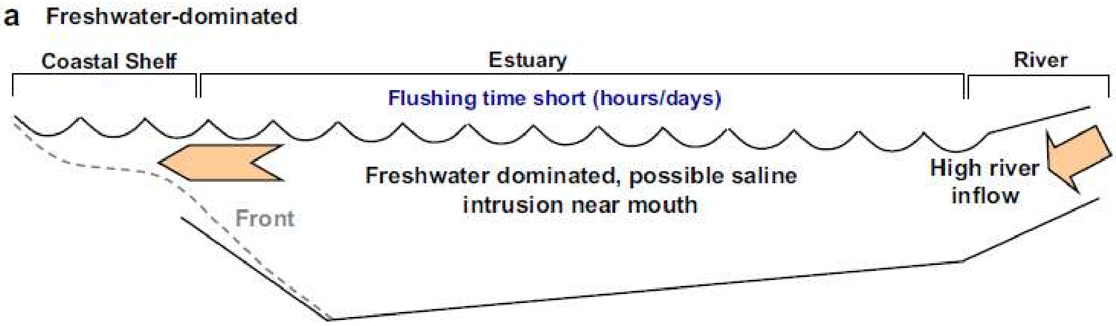

Figure 6.2: Freshwater dominated state where high river inflow flushes brackish-saline estuary water out to sea, leaving the water column uniformly fresh (Taljaard, van Niekerk & Joubert 2009).

The Powlett River had similar relationships between stratification and physical-environmental variables during open and closed periods (Fig. 5.1b). Stratification of DO, salinity and water temperature were positively correlated with river inflow and negatively correlated with maximum air temperature during open periods. These results align with the findings of others who observed a similar process in South African IOCE (Snow & Taljaard 2007; Taljaard, van Niekerk & Joubert 2009; Whitfield et al. 2012). For example, Snow & Taljaard (2007) found that increased river inflow, especially during open phases, increases stratification of physicochemical variables (Fig. 6.3).

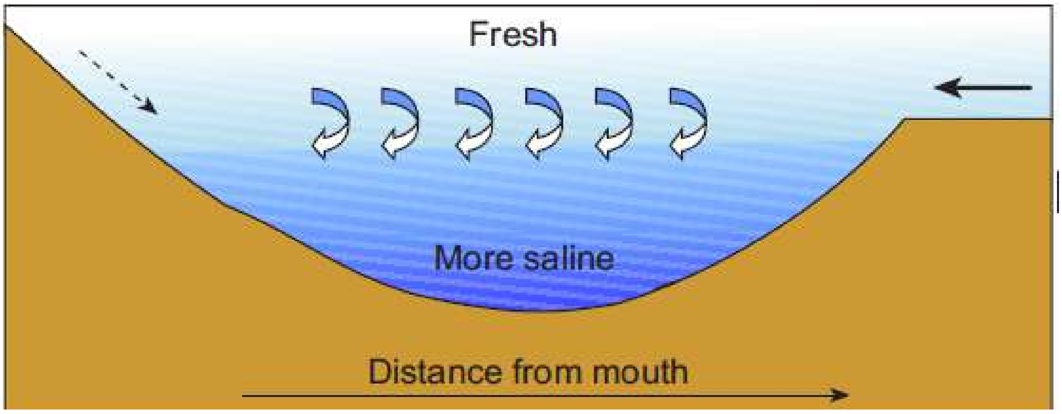

Figure 6.3: Freshwater inflow from upstream causing a greater salinity gradient between the top and bottom of the water column (Snow & Taljaard 2007).

The relationships between stratification and physical-environmental variables during open periods were more difficult to analyse in smaller IOCE including Spring Creek (Fig. 5.2b), Anglesea River (Fig 5.3b) and Painkalac Creek (Fig. 5.4b) for several reasons. First, IOCE with smaller catchment areas only stay open for a short amount of time (i.e. weeks vs months) because they have less fluvial energy to keep the estuary open (Appendix B). For example, Anglesea River only stays open on average for 14 days (McSweeney, Kennedy & Rutherfurd 2016). Second, while the temporal scale of measurements for EstuaryWatch is fortnightly to monthly on average, there are less frequent measurements taken during open periods. This is likely because when the estuary is already open, there is less risk of poor water quality and the need for monitoring is reduced. Given the available data, my work is less likely to get a representative sample of physicochemical measurements for open periods. There is also less emphasis placed on open periods by estuary managers because open periods do not cause management problems such as flooding.

Other variables such as length of opening, significant wave height, wave direction, wave period, maximum wind gust speed and maximum wind gust direction had some degree of correlation with stratification. However, none of these variables were consistently correlated with stratification at all IOCE and there was no consistent correlation between these variables and stratification of DO, salinity and water temperature. These variables tended to only appear in IOCE that had a low amount of physicochemical observations (i.e. Spring Creek, Anglesea River and Painkalac Creek). Similar to length of closure, length of opening is more likely to reflect seasonal changes in river inflow and air temperature rather than affecting stratification as predicted (Table 2.2). Maximum wind gust direction and speed would more likely change during storms coinciding with increased river inflow, rather than directly affecting stratification. Changes in wave height, direction and period could have an effect by influencing the amount of saline water that is introduced into the IOCE during open periods (Snow & Taljaard 2007). It is also possible that the correlations capture the seasonal changes in ocean wave climate, rather than showing that they directly affect stratification. Whilst marine water entering the estuary has been found to influence stratification (Gale, Pattiaratchi & Ranasinghe 2007; Snow &

Taljaard 2007; Taljaard, van Niekerk & Joubert 2009), there is not enough evidence to support the prediction made that marine water entering the estuary increases stratification of salinity (Table 2.1-2.2) but this process could still be occurring in Victorian IOCE.

6.1.3 Effect of Catchment Area

There were large differences in the responses of stratification of DO, salinity and water temperature to river inflow and maximum air temperature between larger IOCE with catchment areas of >1000km^2 (i.e. Gellibrand River and Curdies River) and smaller IOCE with catchment areas of <250km^2 (i.e. Powlett River, Spring Creek, Anglesea River and Painkalac Creek). The most noticeable differences were that stratification in IOCE with smaller catchments had a positive relationship with river inflow and other hydrological variables (i.e. rainfall, water level and upstream fluvial discharge) and a negative relationship with maximum air temperature. In contrast, stratification in IOCE with large catchment areas had a negative relationship with river inflow and a positive relationship with maximum air temperature.

My study provides the first quantification of the effect of catchment area on stratification processes in a range of IOCE. Very few studies have measured multiple IOCE across a wide range of catchment areas and similar analyses tend to focus on a comparison between one large and one small estuary (e.g. Gale, Pattiaratchi & Ranasinghe 2006; Schallenberg et al. 2010). Catchment area affects stratification because rivers and estuaries with larger catchment areas tend to have a larger discharge. This phenomena is captured in the specific discharge equation, a metric that divides actual discharge by the catchment area of a river or estuary (Ophori & Tóth 1990; Kennard et al. 2010). This equation shows that larger catchment area rivers and estuaries tend to have a greater discharge even when scaling discharge to catchment area (Burgers, Schipper & Hendriks 2014). This relationship is further supported by the fact that the catchments of the larger basin IOCE in this study (Curdies and Gellibrand River) are located in areas of higher rainfall than the other IOCE studied. As a result, Curdies and Gellibrand Rivers have enough river inflow to flush out brackish to saline estuary water, leaving the water column uniformly fresh. This happens often enough to be captured by EstuaryWatch measurements (which have a sampling frequency of 4 weeks on average). Flushing out of saline water may still happen in the smaller estuaries studied on rare occasions. However, these IOCE do not have enough river inflow to flush out the estuary water often enough to be captured by EstuaryWatch measurements. Therefore, catchment area is an important variable when considering stratification in IOCE.

6.1.4 Seasonal Trends in Stratification

My results reflect annual and seasonal variations in river inflow, evaporation, and stratification in Victorian IOCE rather than differences between mouth states. Over winter and spring there is increased inflow from the catchments. In smaller catchment IOCE, this increased river inflow is only enough to freshen the top, freshwater layer of the water column, increasing stratification. Meanwhile, in larger catchment IOCE, this increased river inflow is enough to flush out the saline water in the water column, making the water column uniformly fresh and decreasing stratification. As maximum air temperature and evaporation increases and river inflow decreases over summer, the freshwater layer evaporates away in smaller catchment IOCE, decreasing stratification. Meanwhile in larger catchment IOCE, there is no longer enough river inflow to flush out the saline estuary water. However, there is still enough river inflow to maintain a freshwater layer over summer, increasing stratification. There may be other factors that affect stratification in IOCE, but they may not be captured at the fortnightly-monthly temporal scale that is measured by EstuaryWatch.

The seasonal variation in stratification that was captured at Gellibrand and Curdies Rivers can be applied to a conceptual model of stratification described by Bantow, Rashleigh & Sherwood (1995) for large catchment Victorian estuaries (Fig. 6.4). It was found that saline water is flushed out over winter when flows increase, then over summer, when river inflow decreases, the salt wedge stagnates, resulting in higher saline conditions and stratification in the water column (Bantow, Rashleigh & Sherwood 1995). Sherwood, Mondon & Fenton (2008) have observed that larger estuaries in Victoria become completely fresh over winter and spring, during peak river discharge and that high freshwater inflow completely flushes out brackish estuary water, leading to the water column to be uniformly fresh. This phenomena has also been observed in IOCE of similar sizes and settings overseas such as the Great Berg estuary in South Africa (Taljaard, van Niekerk & Joubert 2009). A key knowledge gap that my work has addressed is that small IOCE in Victoria do not follow this same cycle. In fact, my findings indicate that smaller IOCE can often lack the river inflow to completely flush out saline waters unless there is a large amount of rain. Therefore, the annual hydrodynamic cycle in these IOCE is better reflected by two distinct seasonal periods of stratification (Fig. 6.5):

1. During winter and spring, increased river discharge results in freshwater overtopping saline water, increasing the difference in salinity between the top and bottom layer, eventually leading to increases stratification of DO and water temperature.
2. Over summer, river discharge drops to low flow or no flow in some cases. As a result, there is no longer enough freshwater inflow to replace the freshwater that is being lost to evaporation. This causes the water column to become uniformly saline with uniform DO and water temperature.

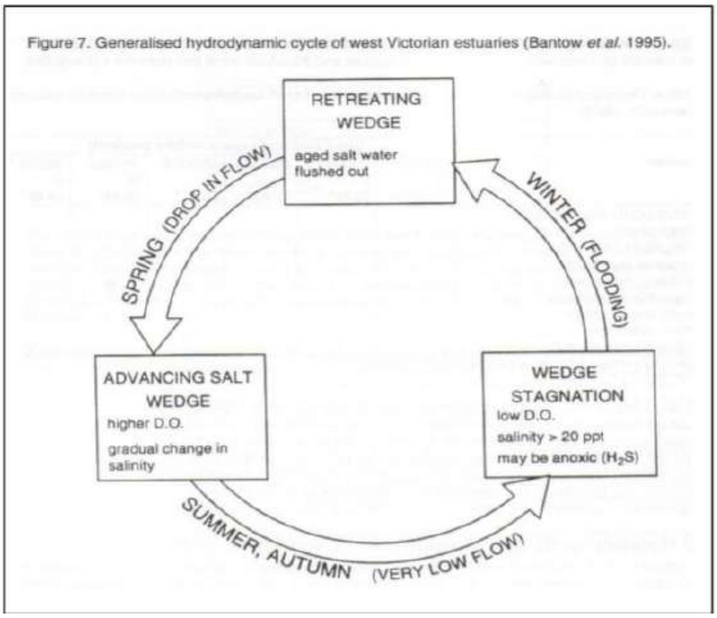

Figure 6.4: A generalised conceptual model of stratification in Western Victorian estuaries (Bantow, Rashleigh & Sherwood 1995) over Summer-Autumn (December-May), Winter (June-August) and Spring (September-November).

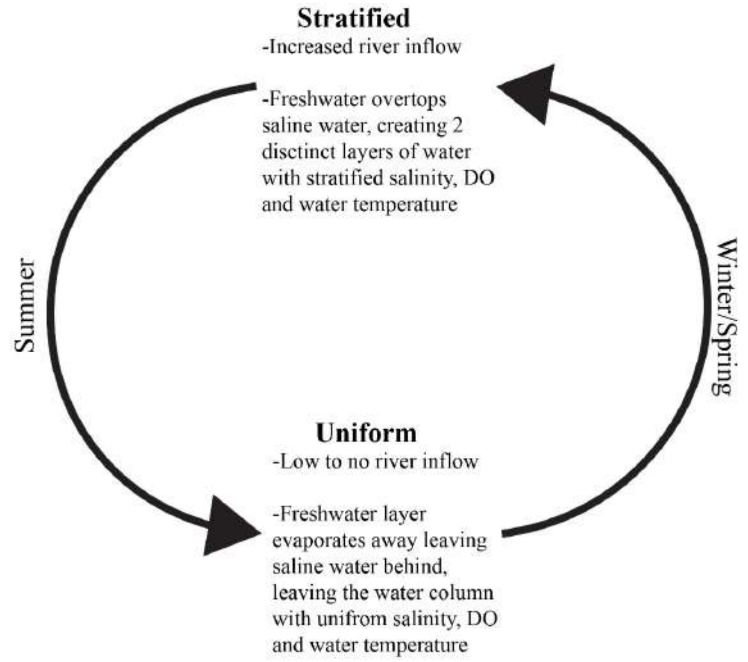

Figure 6.5: A generalised conceptual model of seasonal changes stratification for smaller catchment estuaries in Victoria between summer (December-February) and Winter-Spring (June-November).

These results show that IOCE scale and morphology, such as catchment area, and physical-environmental variables such as river inflow and air temperature have large effects on stratification in these smaller IOCE.

6.2 Analysis of Fieldwork Data

6.2.1 Painkalac Creek

6.2.1.1 Geomorphic Changes

At Painkalac Creek, channel depth (0.50m) and discharge (5.46m^3/s) peaked 3 hours after opening before decreasing for the rest of measurement period, whilst channel width increased throughout the measurement period (Fig. 5.9). These results indicate that the artificial opening lost energy within hours of the opening. A further morphological indicator of the low energy nature of the opening was that the channel transitioned from a straight to a meandering channel (Fig. 5.8). The channel becoming longer, shallower, and wider meant that the water encountered more friction, reducing outflow velocity and discharge from the mouth. Long, wide and shallow artificial channels are typical of low energy artificial openings which is what was observed at Painkalac Creek (McSweeney, Kennedy & Rutherfurd 2016). There was little draw down of water from upstream caused by the draining phase, indicated by a low water velocity (0.00-0.02m/s) at all measuring sites (Table 5.13).

The low energy opening could have happened for several reasons including:

- Long distance between estuary basin and ocean.
    - Longer distances between the estuary basin and the ocean means there is a reduced hydraulic gradient due to a lower hydraulic head over a longer berm width (Stretch & Parkinson 2006).
- Opening was completed at a rising tide.
    - As the tide rises, the difference between sea level and water level reduces, reducing the hydraulic head (Stretch & Parkinson 2006).
- Large sand piles adjacent to the channel introduced too much sediment into the channel (Fig. 5.8a).
    - More energy was required for the water to transport the extra sediment, rather than scour out the channel, reducing discharge from the mouth. (Lane 1955).

6.2.1.2 Physicochemical Changes

Overall, three main changes in physicochemical depth profiles were captured during the measuring period at Painkalac Creek:

(1) Increases in water temperature and DO during the day and decreases overnight.
(2) Freshwater inflow from water released from Painkalac Dam, reducing salinity of the depth profiles at all measuring sites.
(3) A reduction in the depth of the freshwater layer.

The first two changes were not directly caused by the artificial opening whilst the third change was directly caused by the artificial opening. Water temperature, especially closer to the surface, increases during the day as air temperature increases. DO also normally increases throughout the day because with more sunlight, sub-aqueous plants are better able to photosynthesise and produce more oxygen that then dissolves into the water column (Pope & Wynn 2007). These changes in water temperature and DO are not caused by the artificial opening and would happen naturally regardless of mouth state (Pope & Wynn 2007).

The gradual freshening of surface salinity occurred at all measuring sites and was particularly apparent at sites further from the mouth during the measurement period. This reduction in salinity occurred after a release of water from Painkalac Dam was authorised to occur after 30/06/2020 at 13:30 until July 4. The reduction in surface salinity was most obvious by 50.5-52.5 hours after opening. Again, this change in surface salinity was not directly caused by the draining period and would have still occurred regardless of the artificial opening. The dam increased base flows compared to if there was no water released. However, the draining of the estuary may have aided the drawdown of the freshwater being released from the dam.

The reduction in water level was directly caused by the artificial opening which caused a drop of approximately 0.3m over three days. The 0.3m reduction in water level represents a loss of the upper freshwater layer of the water column by surface flows out of the estuary. This reduction of the freshwater layer was shown in the depth profiles as a reduction in the uniformity of the top three depth profiles (0.1-1.0m depths) during the measurement period.

Overall, there was very little change in the physicochemistry of the water column throughout the opening. Surface flow out of the estuary reduced the thickness of the freshwater layer, but the water column of each measuring site remained stratified in water temperature, salinity and DO throughout the whole opening (Fig. 5.10). This happened for two reasons:

(1) There was not enough freshwater being drawn down from upstream to flush out the estuary.
(2) Flow from out of the mouth was not great enough to cause mixing by turbulent flows that could propagate upstream into the basin.

There were no obvious changes in top and bottom water velocity at any of the measuring sites, indicating that the opening was causing little draw down of water from upstream. This directly contrasts to the turbulence that was captured at the Aire River opening at sites up to 2.65km upstream. Flows from upstream were also insufficient to increase the thickness of the freshwater layer or mix the water column.

The results from the Painkalac Creek opening support the prediction made that the IOCE remains stratified if it drains slowly (Table 2.2). These findings are consistent with previous studies done. At Pescadero Estuary in USA, Williams (2014) also found that in low energy artificial openings, the estuary water column does not mix or flush but only results in surface flow out of the estuary. As a result, the estuary remains stratified during a low energy artificial opening. It takes a high amount of river inflow to break down stratification in an estuary (Taljaard, van Niekerk & Joubert 2009; Whitfield et al. 2012) and low energy artificial openings do not draw down enough upstream water to achieve de-stratification.

There were no substantial drops in DO in the water column throughout the measurement period despite DO being stratified in the water column. This is consistent with previous research where large drops in DO were observed in openings with large drops in water level (>1m), corresponding to high energy openings (Becker, Laurenson & Bishop 2009; Stacey et al. 2017). For example, a large decrease in DO (>6.0mg/L) occurred after an opening at Surrey River, Victoria, where the water level dropped by over 1.2m within 2 days (Becker, Laurenson & Bishop 2009). This result is important because it means that mass fish deaths are unlikely to occur from low energy openings where there is only a small drop in water level (0.3m).

6.2.2 Aire River

6.2.2.1 Geomorphic Changes

In the two first hours after the opening, there were only small changes in the channel morphology (Fig. 5.13). Channel depth (Fig. 5.13b) and discharge (Fig. 5.13c) remained relatively consistent and channel width (Fig. 5.13a) increased slowly in the first two hours post opening. Discharge from the mouth began increasing between 4-5 hours after the opening as the berm was eroded down and the channel started to widen and deepen. Discharge dramatically increased between 5-8 hours after opening as the channel widened and deepened at a rapid rate before reaching its maximum dimensions with a maximum channel width of 34.82m and depth of 1.50m which resulted in maximum velocity (3.65 m/s) and discharge from the mouth (189.20m^3/s) 11-12 hours after opening (Fig. 5.13). Around this time, water velocity peaked upstream at the measuring sites at between 0.16-0.29m/s at the top of the water column and 0.08-0.18m/s at the bottom of the water column (Table 5.14). The channel width stabilised after this point as water level dropped further (Fig. 5.11), with a decrease in discharge as water level and the hydraulic head decreased.

These geomorphic changes at the mouth are similar to those described by Stretch & Parkinson (2006) where initially there is little change in channel dimensions and little change in water level. Then when the opening kicks off, there are rapid changes in channel width, depth and outflow and water level decreases rapidly (Stretch & Parkinson 2006). Finally as the hydraulic head decreases, water velocity and rate of scour decreases, causing decreases in channel cross-sectional area and discharge (Stretch & Parkinson 2006).

The artificial opening at Aire River was an example of a high energy opening. The maximum discharge from the mouth was 189m^3/s (Fig. 5.13c), over 30 times greater, an order of magnitude higher than the maximum discharge from Painkalac Creek mouth (5.46m^3/s) (Fig. 5.9c).

The artificial opening was able to reach a high energy state and cause a rapid decrease in water level for a number of reasons:

- There was a high hydraulic head and a short berm.
  - A large difference between estuary water level and sea level means the estuary water has greater potential energy (Stretch & Parkinson 2006). When this energy is spread over a shorter berm width (46 m), this translates to an increased hydraulic gradient.
- The opening was completed on a falling tide.

- As the channel initially develops, the difference between sea water level and estuary water level increases as the tide falls, increasing the hydraulic head which increases potential energy and the size of the opening (Stretch & Parkinson 2006).

6.2.2.2 Physicochemical Changes

The following major changes were captured during the measurement period at Aire River:

(1) Increases in water temperature and DO during the day and decreases overnight.
(2) De-stratification of DO, water temperature and salinity.
(3) Increases in Salinity in the top three depths of the water column after de-stratification followed by decreases.
(4) Increases in turbidity, peaking between 11.7-20.5 hours after opening.

Similar to the Painkalac Creek opening, the increases in surface DO and water temperature during the day and decreases overnight are not attributed to the opening itself but to the natural diurnal cycle of increasing DO and water temperature during the day as air temperature and sunlight increases (Pope & Wynn 2007).

Initially there were few changes in the water column as the flow from the mouth was low. The water column was still stratified in the first three depth profiles for Aire Lower (0-7.5 hours after opening) and Middle (0-6.0 hours after opening) and the first two profiles for Aire Upper (0-2.5 hours after opening) (Fig. 5.14). Afterwards, the water column began to de-stratify as water was drawn down from upstream, increasing the depth of the freshwater layer first at Aire Upper, then at Aire Middle and Aire Lower (Fig. 5.14a, e, i). Between depth profiles 3 and 5 (6.0-11.6 hours after opening), salinity at the top three depths increased at each measuring site as turbulent flows mixed the water column and brought up saline water from the bottom depths upstream. Mixing from turbulent flow was also observed at Aire Lower 9.1 hours after opening where there were erratic readings for salinity at the bottom depth (Fig. 5.14a). At the same time, turbidity was increasing throughout the water column at each study site as flows were strong enough to erode and transport sediment (Fig. 5.14d, h, l). This period roughly corresponded to increasing discharge and eventually peak discharge from the mouth (Fig. 5.13c). Around this time, top water velocity at Aire Lower and Middle peaked at 0.23-0.29m/s and bottom velocity peaked at 0.16-0.18m/s (Table 5.14). This high upstream water velocity indicates that there was a lot of water being drawn down from upstream and water was flowing throughout the water column. As water level decreased further overnight (Fig. 5.11), saline water was replaced by freshwater from upstream and by the next morning, the water column had a salinity that was similar to the top two depths of the water column before the opening. The water column was uniformly freshwater shown by the salinity being consistently below 5 PSU which represents the threshold for freshwater (Pope & Wynn 2007). There was little change in the water columns at each measuring site between the last two profiles as flow from the mouth was decreasing and losing energy.

These changes were especially captured in the changes in water temperature and salinity. The freshwater layer had much lower salinity and water temperature than the saline layer before the opening, then becoming uniform. DO was mostly consistent throughout the opening with small changes due to the amount of sunlight during the day and overnight so the changes were not as obvious.

Overall, there were large changes in the physicochemistry of the water column. These changes were caused by:

(1) Large drawdown of freshwater from upstream, enough to flush out saline water closer to the bottom of the estuary.

(2) Turbulent flows at the basin mixing the water column and bringing up more saline water from the bottom depths upstream.

(3) Sufficient flow velocity at the basin and upstream to erode and transport sediment downstream.

Salinity in all except the surface sections of the water column decreased as freshwater from upstream was drawn down by the opening. Water velocity at upstream measuring sites were much higher than at Painkalac Creek and was high at both the top and bottom of the water column. There was evidence of mixing of the water column during the opening, most likely caused by turbulent flow. This mixing was shown by salinity in the surface of the water column increasing during the opening. Then surface salinity by the final measurement was still greater than before the opening.

These results support the predictions made for the draining phase (Table 2.2). As predicted, average salinity dropped in the water column compared to before the opening. The water column also mixed with surface salinity increasing during the opening before saline water was flushed out of the estuary. Finally, turbidity increased in the water column as sediment was eroded away then transported. However, there was no major drop in DO during this opening as predicted. This could have been because there was high DO throughout the whole water column. As found in previous studies (Sherwood, Mondon & Fenton 2008; Becker, Laurenson & Bishop 2009) these results confirm that it is important to have high DO at the bottom layer of the water column when conducting artificial openings.

6.2.3 Conceptual Model

The conceptual models of both openings link the geomorphic changes at the mouth of the IOCE to the changes in stratification upstream from the mouth. The low energy opening at Painkalac Creek consists of three stages, with the draining stage only occupying the second stage (Fig. 6.6):

1. **Pre-opening:** The estuary is closed, and the water column is stratified. The top layer is freshwater with high DO and low salinity and water temperature. The bottom layer has higher salinity and water temperature but lower DO (Fig. 6.6a).
2. **Initially after the opening, there is only small outflow from the artificial channel, which at this stage is narrow and shallow (approx. 5-10m wide and 0.2-0.5m deep).** Little water is being drawn down from upstream, resulting in only surface flow from the mouth. Water from the freshwater layer is flowing out from the mouth, but there is not enough surface flow

to completely shear off the freshwater layer. There is not enough energy at the mouth to erode the berm down, which is higher than the saline water layer. Physicochemistry and stratification is largely unchanged excluding changes that happen naturally during the day. Water level is lowering slowly (Fig. 6.6b).

3. **At the mouth, the channel has widened, and shallowed (approx. 10-15m wide, 0.1-0.2m deep) and water level has dropped slightly.** The drop in water level has been taken off the freshwater layer by surface flows and the estuary remains stratified. There is no longer enough outflow to remove sediment that is transported onshore by waves and tides. A secondary berm forms, closing the estuary (Fig. 6.6c).

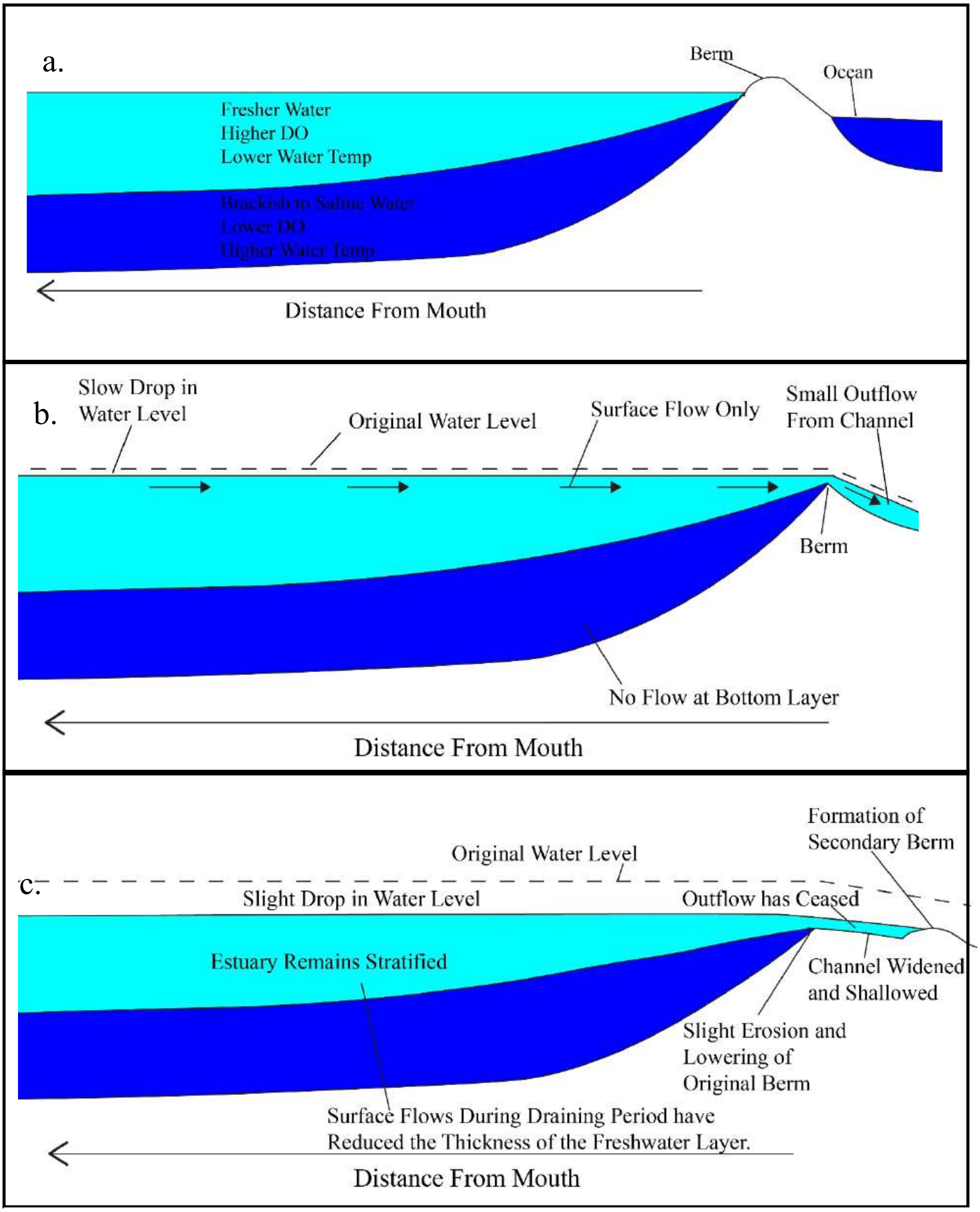

Figure 6.6: Conceptual model of the initial conditions before the artificial estuary opening at Painkalac Creek (a), during the draining period (b) and when draining has ceased due to closure (c).

The high energy opening consists of six stages, with the same first two stages as the low energy opening. However, this opening has the energy to transition to transition to stages 3 and 4 before continuing onto stages 5-6 (stage 6 was not captured at the Aire River opening but is based on existing literature and prior knowledge):

1. **Pre-opening:** The estuary is closed, and the water column is stratified**.** The top layer is freshwater with high DO and low salinity and water temperature. The bottom layer has higher salinity and water temperature but lower DO (Fig. 6.7a).
2. **Initially after the opening, there is only small outflow from the mouth, which at this stage narrow and shallow (approx. 5-10m wide and 0.2-0.5m deep).** Only surface flow is occurring and water from the freshwater layer is flowing out from the mouth. Physicochemistry and stratification is largely unchanged excluding changes that happen naturally during the day. Water level is lowering slowly (Fig 6.7b).
3. **Water erodes away sediment at the mouth and the berm starts being eroded down, which initiates the channel to deepen and widen and discharge starts increasing from the mouth.** This increase in discharge causes more water to be drawn down from upstream, increasing the thickness of the freshwater layer. However, the water column is still stratified (Fig. 6.7c).
4. **The channel is reaching its maximum dimensions and discharge as the berm is further eroded down (approx. 30m wide and 1.5m deep).** Flow has transitioned from surface flow to flow throughout the entire water column. Turbidity is increasing as sediment is eroded and transported. Freshwater is being transported from upstream. However, turbulent flow is causing mixing between the two layers, reducing stratification as saline water is mixed with freshwater. Surface salinity is increasing, and bottom salinity is decreasing as the water column is starting to become more uniform. Water level is dropping rapidly (Fig. 6.7d).
5. **The hydraulic head is decreasing as the water level reaches mean sea level and the opening is starting to lose energy.** At the mouth, channel width and depth are stabilising and

discharge from the mouth starts to decrease. By this stage, the water column is uniform as estuary water has been flushed out to sea and replaced by freshwater from upstream. As a result, DO, salinity and water temperature are now uniform (Fig. 6.7e)

6. **The estuary finishes draining as the estuary basin reaches sea level and the hydraulic head is removed** (Stretch & Parkinson 2006; McSweeney, Kennedy & Rutherfurd 2018). The estuary is now in the open phase and marine water can now re-enter the estuary (Fig. 6.7f).

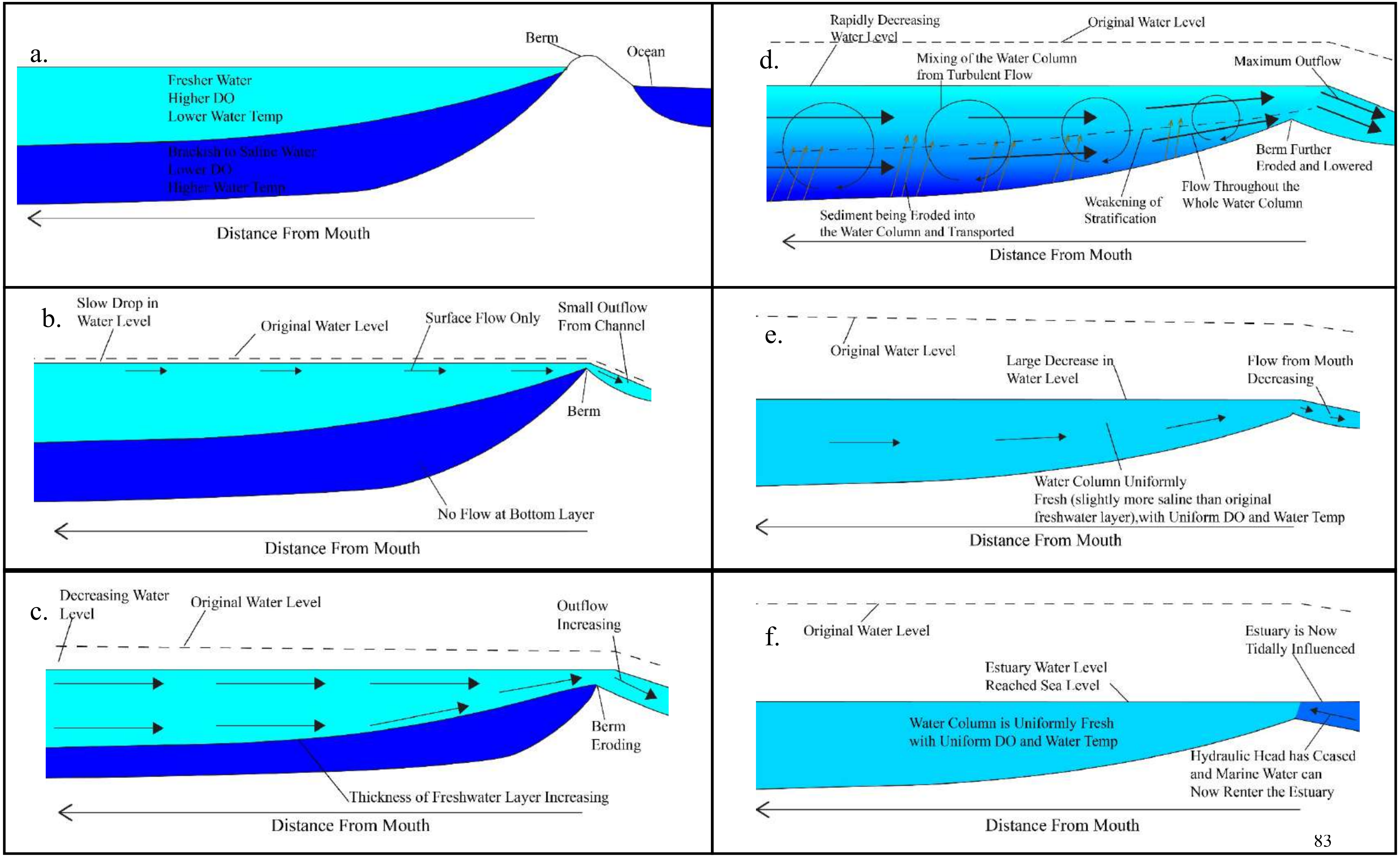

Figure 6.7: Conceptual model of the initial conditions before the artificial opening at Aire River (a), the draining period (b-e) and the transition to the open period (f).

Results indicate that the top layer of the water column does not always necessarily shear off as described in previous studies (Becker, Laurenson & Bishop 2009). Large openings have enough energy from outflow to also mix the water column. This is the first time that this mechanism of physicochemical change in the water column has been captured in Victorian IOCE. Williams (2014) also found that openings that were large enough, had the energy to mix the water column in the Pescadero Estuary, USA.

These changes were caused by upstream processes. However, the geomorphic changes at the mouth caused water from upstream to be drawn down, leading to dramatic changes in physicochemistry of the water column. Evidence from the two openings show that the size of the opening is directly related to the rates and magnitude of changes in physicochemistry in the water column. The energy of the opening is controlled by the geomorphic changes at the mouth following the artificial opening. Therefore, the changes in physicochemistry in the water column are related to the changes in the mouth of the morphology during the draining phase. This link between mouth morphology and physicochemistry during the draining phase has never been made before.

6.3 Implications

The findings of my project have direct application to a myriad of issues related to estuary entrance management. The results of the secondary data analysis reveal that stratification is seasonally variable, with further variation between estuaries of differing catchment areas. These findings are of direct application to management as they illustrate that not all IOCE operate the same and as such they should not be managed the same. For larger IOCE with larger catchment areas, the water column tends to de-stratify over winter and spring as estuarine water is flushed out. It would be ideal to artificially open an estuary at this time because the estuary is well oxygenated and there is less risk that the opening will deoxygenate the water column (Sherwood, Mondon & Fenton 2008). This knowledge will help prevent mass fish deaths into the future for larger catchment IOCE.

Smaller catchment area IOCE that were studied do not typically de-stratify due to river inflow over winter. My work has shown that these estuaries de-stratify over summer when the freshwater layer evaporates away, causing the water column to become uniformly saline. If an opening did have to occur in summer, likely due to flashy rainfall events and flooding, a lower energy opening may be more appropriate for these smaller systems because it means that the water column does not mix and deoxygenate the top layer. Since a large artificial opening was not sampled in a small catchment area IOCE, it is uncertain whether large openings would also cause mixing of the water column. However, Human et al. (2018) found that small, shallow IOCE tend to mix easier than larger, deeper IOCE, indicating that these smaller IOCE could also be mixed similarly during the draining period. Nevertheless, the results confirm it is very important to monitor DO levels before undertaking an artificial opening in smaller catchment IOCE so we can quantify these changes and better understand how these more vulnerable systems function.

My results from the PCA could also provide an indication of how stratification in IOCE may change in the future. It is predicted that in the future annual rainfall will decrease, and air temperature will increase in southern Australia (Hope et al. 2015; Grose et al. 2020). Increases in the variability (i.e. frequency and magnitude) of extreme rainfall and high temperature days are also predicted in southern Australia (Grose et al. 2020). These changes in climate will affect the amount of river inflow to estuaries, and the rate of evaporation, two factors which my work indicates directly affect stratification in IOCE. Increased extreme rainfall events could result in estuaries being flushed out more often or reduced rainfall could reduce overall river inflow, changing the timing and magnitude of stratification. Smaller catchment IOCE may be vulnerable to increases in air temperature, with increased evaporation and reduced river inflow, increasing the period where these IOCE are uniformly saline. However, more study is needed to confirm these predictions.

An important finding from this research was that mouth morphology and estuary physicochemistry are linked during the draining phase. For estuary managers, this is an important step towards predicting how basin physicochemistry will change with different opening styles so they can anticipate risk. There were two types of openings captured:

(1) A high energy opening where there is a large, rapid drop in water level with large artificial channel dimensions. Initially there is mixing between the water column as it de-stratifies and eventually saline estuary water is flushed out of the estuary.
(2) A low energy opening where there is a small, gradual drop in water level with lower outflow from the mouth resulting in little change in stratification of the water column. Surface flow reduces the thickness of the freshwater layer.

The initial channel morphology such as the length, hydraulic head, width and depth play an important role in determining the size of the artificial opening (Stretch & Parkinson 2006; Parkinson & Stretch 2007). The timing of the opening is also important in determining the size of the opening. For example, if an opening occurs during a falling tide, the hydraulic head increases as the estuary drains, increasing the size of the opening and vice versa during a rising tide (Stretch & Parkinson 2006). Therefore, the timing of the opening and the way in which the channel is manually dug is important in determining what sort of opening, a high energy or low energy occurs. These variables can be manipulated by estuary managers who dig out the artificial channels. For example, channels could be deliberately dug with multiple bends to make the channel longer, reducing the energy of the opening. Alternatively, opening the IOCE at a falling tide increases the energy of the opening. There may be cases where stagnant water may need to be flushed out of the estuary, requiring a larger opening. Lower energy openings are more appropriate to mitigate flooding or to reduce drawdown of hypoxic and nutrient enriched water from floodplains which can also cause mass fish deaths (Stacey et al. 2017). This is especially important when IOCE are strongly stratified and the bottom layer of the water column is severely oxygen depleted, making it undesirable for the water column to mix (Sherwood, Mondon & Fenton 2008). This has known to cause mass deaths in both freshwater and saltwater fish species (Becker, Laurenson & Bishop 2009). Mass fish death events particularly affect fish species that have a limited ability to escape the anoxic waters, such as fish species that are stenohaline and cannot escape upstream (Becker, Laurenson & Bishop 2009). The results of the fieldwork component of this project confirm the need to measure DO depth profiles before opening, especially for large openings. If the water column is well oxygenated, then there is very little change in DO during the draining period, regardless if it is a high energy or low energy opening. These results can assist estuary managers on deciding whether it is appropriate to artificially open an estuary or not. Victorian IOCE provide habitat to many important freshwater and saltwater fish species (Pope, Barton & Quinn 2015). Protecting these fish species from large drops in DO will have ecological benefits by maintaining the food web and economic benefits from maintaining recreational fishing.

6.4 Limitations

6.4.1 Historic Data Analysis

A major limitation to the analysis of historic data was that it was not possible to test the statistical significance of the relationships between stratification of physicochemical variables and physical-environmental variables. The distribution of the stratification of physicochemical variables violated the assumption of a normal distribution and therefore could not be tested. The violation of normal distribution still occurred after data transformations were performed (e.g. square root and log transformations). This is largely due to the stochastic nature of the data. Future studies could use a different method to measure stratification such as analysing top and bottom salinity separately. Alternatively, more observations are needed to help the variables achieve a more normal distribution which reinforces the need for an increased sampling and monitoring frequency.

Analysing physical relationships using PCA can prove difficult in separating cause and effect. For example, it was difficult to determine whether wave characteristics had a direct effect on stratification or whether the PCA was picking up how wave characteristics change over winter and summer. In future, a sophisticated time series analysis may complement the PCA to help to analyse temporal variability.

A limitation of sampling open and closed periods separately is that in some estuaries, the stratification physicochemical variables does not vary much over open or closed periods. This lack of variation is especially the case for estuaries that are seasonally open. For example, the Gellibrand River closes mainly over the summer months (Appendix B). As a result, the water column is constantly stratified, with little variation in the degree of stratification.

Finally, a lot of different data sets were used in the data analysis, with most of them having missing data from them. If a row had one column of data missing, then the whole row had to be deleted to ensure the PCA worked. Missing data resulted in less observations which reduced the quality of representation of the data that was analysed. In future studies, more observations and using other data sources to fill data gaps will help to negate that limitation.

6.4.2 Fieldwork

The main limitation of the fieldwork measurements was that physicochemical depth profiles were taken off fishing platforms. This meant that the whole water column could not be measured because these platforms were closer to the bank and away from the thalweg. In future studies, it is recommended that measurements are taken over the thalweg of the estuary so that the whole water column can be measured using some sort of watercraft. Measuring over the thalweg will ensure that changes over the whole water column will be captured.

There were no large artificial openings sampled from smaller catchment IOCE and there were no small artificial openings sampled from larger catchment IOCE. As a result, the physicochemical response of IOCE of different catchment areas to different sized draining periods could not be captured. Ideally more artificial openings would have been sampled for this study. However, due to restrictions on field work due to CoVID19, this was not possible. A greater number of artificial openings will increase the validity of the results and confirm the conceptual model.

6.5 Future Opportunities

There is a great opportunity to measure physicochemical depth profiles at more artificial estuary openings. >10 artificial openings occur per year in Victoria on average and >20 sites are artificially opened making this a common practice at estuary mouths in Victoria (Pope, Barton & Quinn 2015). Sampling more artificial openings would also increase the validity of the results. Ideally, a large artificial opening at a small catchment IOCE and a small artificial opening at a large catchment IOCE will provide a good dataset to compare the responses of IOCE of different catchment areas to the size of the draining period. It is also important for future studies to measure estuaries with similar catchment sizes as well as different. This helps to determine whether similar sized estuaries respond similarly to the same sized opening. In future studies, it will also be important to measure the physicochemical depth profiles over the whole water column. To do this, a boat will need to be used to measure the depth profile over the thalweg. Measuring the deepest part of the estuary water column ensures that the full water column is measured. This comprehensive measurement of physicochemical depth profiles during the draining period will help further inform management actions for estuaries.

Mass fish deaths occur in some IOCE and not others. The majority of these fish deaths occur due to sharp drops in DO during the draining period (Becker, Laurenson & Bishop 2009; Stacey et al. 2017). But it is still unclear why this happens in some IOCE and not others. Existing research suggests that mass fish deaths occur due to extremely low DO levels in the bottom layer of the water column at the time of opening (Sherwood, Mondon & Fenton 2008; Becker, Laurenson & Bishop 2009). However, further research is required to determine the exact mechanism and physical process that causes this drop in DO. It is uncertain whether it is the top oxygenated layer shearing off during the opening, or whether mixing in the water column, mixes the oxygenated and the deoxygenated layer, lowering DO in the water column to dangerous levels. My results indicate that turbulent mixing could play a greater role in this process than discussed in prior work, but more artificial openings are needed to be sampled to answer this question.

Another future research direction is to study how stratification in estuaries will change under future climate change scenarios. My results have given an indication of how climate change will affect stratification in IOCE in the future (Chapter 6.3). However, these competing processes leave a lot unknown and highlight the importance of improving our understanding and predictive capacity of how these climatic changes will affect water quality in estuaries, in particular stratification. Previous studies have used long term data sets to see how water quality has changed over periods of >20 years (Russell 2013; Scanes, Scanes & Ross 2020). However, less studies have used this long-term data to see how stratification has changed over interannual timescales and predict how stratification will change into the future. This study has demonstrated the importance of considering multiple depths in the water column, not just one point, or an average. Long term physicochemical data sets such as EstuaryWatch will be vital in being able to capture these changes in estuaries. Studies on this area will be important in ensuring that estuaries remain in good condition for years to come.

7 Conclusion

Stratification of IOCE in Victoria is linked to both seasonal variability in environmental conditions and the energy environment occurring during the draining phase of artificial entrance openings. Analysis of historic physicochemical and physical-environmental data identified that changes in IOCE stratification tend to reflect seasonal differences rather than changes in mouth state (i.e. open/closed) as predicted (Table 2.2). The two most important factors were found to be (1) indicators of river inflow (i.e. upstream fluvial discharge, rainfall, and estuary water level), and (2) maximum air temperature. IOCE showed two different responses to seasonal changes in river inflow and temperature depending on the catchment area of the estuary and the connecting river:

(1) Smaller catchment IOCE (<250 km^2):
  - Over winter and spring: become stratified when freshwater from river inflow flows over the top of brackish-saline estuary water, creating two distinct layers, a freshwater layer, and a more saline layer in the water column.
  - Over summer: become uniformly saline when river inflow becomes insufficient to replace the freshwater being lost to evaporation, leaving the water column uniformly saline.

(2) Larger catchment IOCE (>1000 km^2):
  - Over winter and spring: become uniformly fresh when high river inflow flushes out more saline estuarine water.
  - Over summer: become stratified when river inflow is no longer great enough to flush out the estuary but enough to maintain a freshwater layer.

The results for the smaller catchment IOCE supported the prediction that increased river inflow increases stratification, but the results of the larger catchment IOCE did not support this prediction (Table 2.1-2.2). In some IOCE, stratification of dissolved oxygen (DO) was positively correlated with length of closure, but this could not be proven to be caused by biochemical processes as predicted (Table 2.2). It could also not be proven that marine water entering IOCE through waves and tides had a major effect on stratification of salinity during open periods as predicted (Table 2.1-2.2). This was possibly due to the distance of the EstuaryWatch sites from the mouth. Wind speed and direction also was found to not have a large effect on stratification from results as predicted (Table 2.1).

These models of seasonal variation in stratification could potentially be applicable to estuaries overseas that are of similar scale and in similar temperate climate zones. These results directly contribute to estuary entrance management decision making because they enable managers to identify what conditions lead to periods of high stratification, and when there are high risk periods for mass fish deaths so they can adjust the timing of artificial openings accordingly.

Additionally, my results can be used to predict how stratification will change under future climate change. My results predict that as air temperature increases and river inflow decreases into the future, smaller catchment IOCE may become uniformly saline for longer periods of time. Increased high rainfall events and storms may mean that saline water in IOCE is flushed out at a higher frequency. Understanding how stratification will change in the future will be vital in keeping IOCE in good condition into the future.

Through the gathering of multiple physicochemical depth profiles throughout the draining period of two artificial entrance openings there was found to be two changes in stratification of physicochemical variables depending on the size of the opening:

(1) A large, high energy opening where the water column mixes and de-stratifies and estuarine water is eventually flushed out and replaced by freshwater from upstream.
    - As predicted the water column mixed and salinity and water temperature decreased as saline estuary water was flushed out of the estuary and replaced by fresher, cooler water from upstream (Table 2.2).
    - Turbidity increased as predicted because the flow upstream was great enough to erode and transport sediment.
    - DO did not decrease as predicted except for natural decreases overnight because the whole water column was well oxygenated.

(2) A small, low energy opening where there is little change in stratification, and surface flow reduces the thickness of the freshwater layer.
    - As predicted, there were little changes in stratification and physicochemistry during this opening (Table 2.2).

These results have identified, for the first time, the change in IOCE stratification that occurs during entrance openings and how these changes vary between openings of different magnitude. These results have also linked changes in stratification to changes in mouth morphology during the draining phase. Importantly, changes in morphology at the mouth are affected by (1) the timing of the artificial opening and (2) the initial channel dimensions. These variables can be easily manipulated by estuary managers. By having better control of the magnitude of the opening, large drops in DO can be prevented, preventing mass fish deaths.

This project provides us with a much stronger understanding of stratification processes occurring in estuaries during and immediately after entrance openings. This fills an important knowledge gap and will help estuary managers better understand how stratification can translate to a loss of DO after openings in different estuary types.

My findings will ultimately help reduce the amount of mass fish deaths in the future after artificial openings by:

(1) Identifying conditions that lead to a high degree of stratification in IOCE and high risk periods for mass fish deaths.

(2) Better understanding how stratification changes when IOCE start draining following an artificial opening and how this can be potentially controlled.

By filling in knowledge and data gaps in literature, there is now a better understanding of the processes that affect stratification before artificial openings and during the draining phase following artificial openings. With this knowledge, estuary managers can prevent fish deaths in the future by avoiding conditions that cause large drops in DO following artificial openings.

8 References

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