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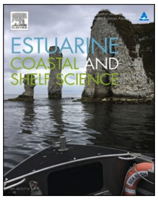

# The influence of geomorphology and environmental conditions on stratification in Intermittently Open/Closed Estuaries

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ABSTRACT

Intermittently Open/Closed Estuaries (IOCE) have entrances that close during periods of low river flow. A major characteristic of IOCE is stratification of salinity, dissolved oxygen and water temperature. After IOCE open (either naturally or artificially), large changes in stratification occur as water drains from the estuary to the ocean. The rapid change in water level and loss of the top oxygenated layer of the water column during drainage often causes fish kills in IOCE globally and is related to stratification. Despite this, there are a lack of studies that statistically analyse the relationships between environmental variables and stratification and that quantify changes to stratification during the draining period across multiple IOCE. To fill these gaps, we (1) analysed the relationships between environmental variables and stratification using distance-based Linear Models (distLM) and distance-based Redundancy Analysis (dbRDA) in five different IOCE across Victoria, Australia, and (2) measured near-continuous physicochemical depth profiles and changes in entrance morphology, fluvial inflows, and estuary water level following four estuary openings.

The distLM results revealed that maximum air temperature, mouth state and fluvial inflows showed statistically significant relationships with stratification in the IOCE studied. The dbRDA suggested that high maximum air temperatures were associated with low values of stratification in small IOCE, more commonly during closed periods. High fluvial inflows were associated with low values of stratification in large IOCE during open periods (except at one site, Curdies River). Field observations of changes in stratification during the draining period revealed two distinct responses. First, a high energy opening with discharge at the mouth between 70 and 182 $m^3s^{-1}$ and fluvial inflows of 0.87–1.85 $m^3s^{-1}$, causing the IOCE water column to mix and become uniform. Second, a low energy opening with discharge from the mouth between 6 and 37 $m^3s^{-1}$ and fluvial inflows of 0.02–0.03 $m^3s^{-1}$, causing the IOCE to remain stratified. These findings were summarised into a conceptual model showing the sequence of changes during openings for different types of IOCE. Over longer timescales (days to years), our results suggest that differences between stratification during open and closed periods are reflected at a shorter time-scale during the draining period (hours to days). These differences further reflect differences in geomorphology and hydrology between IOCE. Our findings will be useful for estuary managers to predict how stratification in different types of IOCE will change during artificial openings and provide a proxy for predicting their response to climate change.

## 1. Introduction

Intermittently Open/Closed Estuaries (IOCE) are estuaries with entrances that close. Periodic entrance closure makes them particularly sensitive to changing environmental conditions. IOCE are globally significant coastal features and are most common on wave-dominated, microtidal coasts where they comprise >15% of all estuaries (McSweeney et al., 2017a). There are three mouth states that occur in IOCE; closed, open and draining (Snow and Taljaard, 2007; Whitfield et al., 2012). A closed state occurs when a subaerial beach berm forms across the mouth. This occurs when onshore sediment transport via waves and flood-tidal currents exceeds the seaward erosional capacity of ebb-tidal currents (Ranasinghe and Pattiaratchi, 2003). IOCE open naturally when the basin water level rises sufficiently to overtop the

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berm crest and outflow scours a channel seaward. Openings commence with a draining phase that extends until the basin water level stabilises at an elevation close to mean sea level (Stretch and Parkinson, 2006). Once drainage finishes, the estuary transitions into an open state with the basin water level often being tidally influenced. In practice, IOCE are often artificially opened by managers before a natural opening threshold is reached, primarily to alleviate localised flooding (Becker et al., 2009). While artificial openings follow a similar sequence of geomorphic change as natural openings, they can lead to sedimentation and shallowing and have often been linked to poor water quality outcomes, especially when the water column is stratified beforehand (Adams and Van Niekerk, 2020).

IOCE are often stratified with an oxygen rich, freshwater layer on top and an oxygen poor, saline bottom layer (Snow and Taljaard, 2007). Dissolved oxygen (DO), water temperature and salinity are the physicochemical variables most affected by stratification, which is a naturally occurring process in many IOCE. There are many environmental variables that have relationships with stratification in IOCE including freshwater inflow, wind, tides, waves and air temperature (Gale et al., 2006; Sherwood et al., 2008; Snow and Taljaard, 2007). Research focussed on South African estuaries have produced useful conceptual models on how water quality and stratification change in IOCE (Snow and Taljaard, 2007; Taljaard et al., 2009; Whitfield et al., 2012). These models suggest that fluvial inflow is important in determining the degree of stratification during open and closed phases. A lack of fluvial inflows can result in freshwater evaporating away, leaving the water column uniformly brackish to saline, which is also common in Australian IOCE (Hoeksema et al., 2018; Sherwood et al., 2008). Initial increases in river inflow overtops the brackish-saline layer, creating two distinct layers in the water column, resulting in stratification. During periods of high river flows, freshwater inflows into the estuary can completely flush estuarine water out of the basin, leaving the IOCE uniformly fresh (Whitfield et al., 2012). Despite this, no robust statistical analysis has been undertaken to analyse the dominance of each environmental variable in explaining stratification across multiple IOCE of different morphologies and catchment sizes.

For IOCE, the draining phase occurs at a much shorter time-scale than open/closed phases with the draining phase persisting over hours to days, rather than over days to years (Gordon, 1991). While the geomorphic changes that occur during the draining phase are well known (Gordon, 1991; Parkinson and Stretch, 2007; Stretch and Parkinson, 2006; Wainwright and Baldock, 2015), a key knowledge gap that remains is how stratification changes during the draining phase. Analysis of changes in stratification during the draining period in Pescadero Estuary, California (U.S.A.), found that stratification broke down in the estuary, and the water column mixed before becoming uniformly fresh due to high freshwater inflow from upstream (Williams, 2014). In contrast, for a subsequent opening, no mixing of the water column occurred when opened with lower freshwater inflow (Williams, 2014). Under low flow conditions in the Great Brak estuary in South Africa, the estuary remained stratified or became more stratified following the draining period (Human et al., 2016) but under high flow conditions the estuary was flushed out with freshwater from upstream (Slinger et al., 2017). These studies suggest a link between the amount of freshwater inflow during the draining period and the physicochemical and hydrodynamic responses in IOCE. However, it is not clear whether these disparate responses to the draining period are unique to these IOCE or whether they are reflected in other IOCE globally. What is needed is a quantification of changes in stratification during the draining period across multiple IOCE of different sizes and morphologies.

This study aims to analyse the key relationships between environmental variables and stratification in IOCE during: (1) open/closed cycles over longer time-scales (weeks to years) and (2) the draining period at a much shorter time-scale (hours to days). It will also investigate whether these relationships change across these different time-scales and between IOCE of different morphologies. We devised three, relatively simple hypotheses that flow directly from previous research (above). First, we predict that fluvial inflows will explain the most variation in stratification in all IOCE studied (H1). Further, we expect a negative correlation between fluvial inflows and stratification (H1a). Secondly, we predict that air temperature (a proxy for evaporation rates) will have a significant relationship with stratification for all IOCE studied (H2), and exhibit a negative correlation due to the evaporation of freshwater overlying brackish to saline water (H2a). Thirdly, during the draining phase we predict that the water column will de-stratify (H3) and become uniformly fresh at the end of the draining period during high fluvial flow conditions (H3a). Conversely, the water column will remain stratified under low fluvial flow conditions (H3b).

By better understanding the variables that affect stratification, we can more robustly predict how stratification changes over a range of temporal-scales and in IOCE with different morphologies. This is important because species such as fish can be killed when extreme changes in stratification occur. For example, dry and hot conditions in Western Australia along with catchment clearing lead to hypersaline water and deoxygenation in estuaries, which caused a fish kill (Hoeksema et al., 2006). Understanding the drivers of stratification in IOCE is also important for estuary managers who often need to artificially open IOCE to alleviate flooding. Immediately after the draining period following artificial openings, mass fish deaths have been observed in Australia (Becker et al., 2009; Stacey et al., 2017; Wilson et al., 2002), South Africa (Whitfield, 1995) and the U.S.A. (Sloan, 2006). Fish are killed during the draining period when the top oxygenated layer shears off and flows out to sea, leaving only the bottom deoxygenated layer behind (Becker et al., 2009) or by fish becoming stranded (Whitfield and Cowley, 2018). By better understanding how stratification changes before and after artificial openings, the risk of fish deaths can be reduced by avoiding implementing openings at times that risk fish deaths occurring.

## 2. Study area

This study focuses on six IOCE located on the wave-dominated, microtidal open coast of Victoria (Australia) (Fig. 1). The open coast of Victoria has a spring tidal range of 0.80–1.60 m (McSweeney et al., 2017b), mixed-semidiurnal tides, and significant wave heights ($H_s$) typically >1.5 m (Hemer and Griffin, 2010). The climate is temperate, with rainfall varying between 650 mm (at Torquay) to >1400 mm at some parts of the Otway Ranges. Victorian catchments experience peak rainfall and fluvial discharge during the Austral winter and spring and decreases over summer and autumn. Rivers supply negligible sediment to the coastline because of their relatively low relief (Harris et al., 2002).

Six IOCE were chosen as study sites because they represented a range of different catchment areas, hydrologies and morphologies (Table 1). The Curdies, Gellibrand and Aire River estuaries are located on the far west Victorian coast, which sees median $H_s$ vary between 2.50 and 2.75 m (Hemer and Griffin, 2010). Painkalac Creek and Anglesea River are located on the central west coast which has median $H_s$ varying between 1.50 and 1.75 m (Hemer and Griffin, 2010). The Powlett River estuary is located on the West Gippsland coast, with a median $H_s$ between 1.75 and 2.00 m (Hemer and Griffin, 2010). All of these sites are artificially opened by estuary managers at least once annually, typically during the austral autumn and winter when flooding is more frequent (Sherwood et al., 2008).

The geomorphic classification system of Mondon et al. (2003) is useful in grouping these estuaries by catchment area and the relative stage of sedimentary infill of the central basin, which is helpful to differentiate between different IOCE morphologies. This method of classifying estuaries builds upon work done by Cooper (2001) and Roy et al. (2001) and is similar to the classification method used by McSweeney et al. (2017b) (Table 2). The classification method used by Mondon et al. (2003) was chosen because it was directly applied to almost all IOCE chosen for this study, is simple and can be easily applied

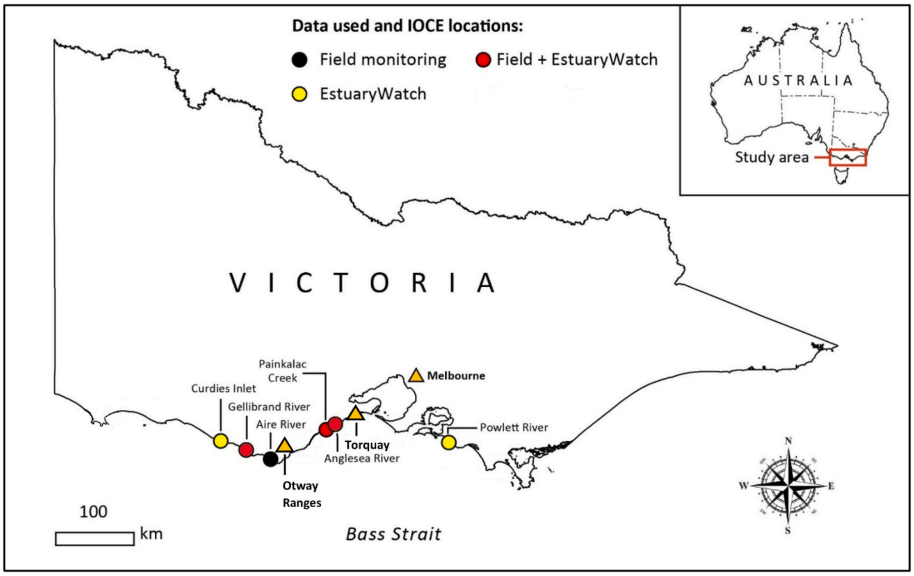

**Fig. 1.** Location and the type of data gathered for each IOCE included in the study with points of interest shown. Data are described in detail in the Methods section.

**Table 1**
Characteristics of all IOCE included in study. Discharge was taken from the gauge that captured the most flow into the estuary, and so is an estimate. Rainfall data were taken from the location with the most complete rainfall record located within the catchment.

| IOCE | Catchment Area ($km^2$) | River Length (km) | Estuary Area ($km^2$) | Mean Annual Rainfall (mm) | Estuary Mouth Location (DMS) | Mean Daily River Discharge into Estuary ($m^3s^{-1}$) |
|---|---|---|---|---|---|---|
| Curdies River | 1124 | 66.0 | 3.61 | 876.0 | 38° 36′ 23.05″ S, 142° 52′ 53.33″ E | 3.77 |
| Gellibrand River | 1184 | 120.1 | 0.29 | 1077.0 | 38° 42′ 23.07″S, 143° 9′ 24.33″ E | 9.32 |
| Aire River | 280 | 44.0 | 0.61 | 1081.5 | 38° 48′ 8.40″ S, 143° 28′ 41.80″ E | 3.58 |
| Painkalac Creek | 61 | 20.3 | 0.16 | 623.7 | 38° 28′ 8.62″ S, 144° 6′ 2.89″ E | 0.20 |
| Anglesea River | 125 | 20.6 | 0.11 | 658.6 | 38° 24′ 53.01″ S, 144° 11′ 28.80″ E | 0.19 |
| Powlett River | 228 | 43.0 | 0.22 | 938 | 38° 34′ 54.39″ S, 145° 30′ 41.8″ E | 2.64 |

to other IOCE overseas. According to the classification system used by Mondon et al. (2003), the Aire, Powlett, Curdies and Gellibrand estuaries are classified as estuaries with moderate catchment areas of 200–1200 $km^2$ and substantial estuarine wetland or lagoon areas (Type 2). Painkalac Creek is classified as a small river or creek with catchment area between 5 and 60 $km^2$ with sand-barred entrances and wetland or lagoonal areas along estuaries (Type 3b) (Mondon et al., 2003). Anglesea River is classified as a small river with a catchment area of 20–125 $km^2$ with sand-barred entrances and channelised estuaries (Type 3a) (Mondon et al., 2003). All sites have medium-coarse grained sand on the beaches and berms fronting their mouths (Davis Jr, 1989).

## 3. Materials and methods

### *3.1. Long term analysis of environmental and stratification of physicochemical variables*

Long term physicochemical and environmental data at each IOCE were analysed to determine which environmental variables are strongly associated with stratification and whether these change between IOCE of different morphologies.

### *3.1.1. Depth profiles and time series data*

Physicochemical depth profiles and environmental time series data were collated for each IOCE spanning 8–13 years. Physicochemical depth profile data were sourced from EstuaryWatch (Pope and Wynn, 2007). EstuaryWatch is a citizen science program whereby citizen scientists measure physicochemical depth profiles at multiple measuring sites in a longitudinal profile at an estuary at monthly to fortnightly intervals. The data are quality controlled by Catchment Management Authorities (CMA) before being made freely available to the public (Pope and Wynn, 2007). The EstuaryWatch physicochemical measuring site with the most observations at each IOCE was chosen for the analysis. All were within 2 km of the mouth. Only choosing one site per IOCE meant that longitudinal variability in stratification was not captured but this was necessary to simplify the statistical analyses and was not needed to test the hypotheses. The period of record for each EstuaryWatch site ranged from 8 years at Curdies Inlet to 14 years at Gellibrand River, Painkalac Creek and Anglesea River. During this period, annual rainfall ranged from 200 mm below average rainfall to 180 mm above average rainfall at each IOCE (Bureau of Meteorology, 2022). Water temperature (°C), DO concentration (mg/L) and salinity (using the Practical Salinity Scale), were included in the analysis.

The environmental variables chosen for analysis were maximum air temperature (°C) (Bureau of Meteorology, 2022), maximum wind gust speed (km/h) (Bureau of Meteorology, 2022), maximum tide elevation (m MSL) (Bureau of Meteorology, 1991b), fluvial inflows ($m^3s^{-1}$) (Department of Environment, Land, Water and Planning, 2022), IOCE mouth state (open/closed) (Pope and Wynn, 2007), offshore $H_s$ (m), offshore wave period (seconds) and offshore wave direction (°N).

**Table 2**

A summary of estuary classification studies and how each IOCE is classified under these studies.

| IOCE | Mondon et al., (2003) | Cooper (2001) | Roy et al., (2001) | McSweeney et al., (2017b) |
|---|---|---|---|---|
| Curdies | Type 2 large catchment area with large wetland/lagoon area | Normally closed, water level perched | Type IVa Intermittent, low infill | Type A Large IOCE, close 1–2 times per year, monthly opening/closure duration (low infill) |
| Gellibrand | Type 2 large catchment area with large wetland/lagoon area | Normally closed, water level perched | Type IVd Intermittent, high infill | Type A Large IOCE, close 1–2 times per year, monthly opening/closure duration (high infill) |
| Aire | Type 2 large catchment area with large wetland/lagoon area | Normally closed, water level perched | Type IVd Intermittent, high infill | Type B1 Medium Size IOCE, close several times per-year, weeks-months opening/closure duration |
| Painkalac | Type 3b small catchment area with wetland lagoon area | Normally closed, water level perched | Type IVd Intermittent, high infill | Type B3 Medium Size IOCE, close several times per year, weeks-months opening/closure duration (high infill) |
| Anglesea | Type 3a small catchment area with channelised estuary | Normally closed, water level perched | Type IVc Intermittent, moderate infill | Type B3 Medium Size IOCE, close several times per year, weeks-months opening/closure duration (high infill) |
| Powlett | Type 2 large catchment area with large wetland/lagoon area | Normally open, water level perched | Type IVc Intermittent, moderate infill | Type B3 Medium Size IOCE, close several times per year, weeks-months opening/closure duration (high infill) |

Painkalac Creek has a dam close to the estuary that controls fluvial inflows into the estuary, and Anglesea River had $0.05m^3s^{-1}$ of freshwater released into the river from a nearby coalmine until March 2016 with irregular releases from the coalmine following 2016 (Romero et al., 2016). Therefore, daily rainfall (mm) (Bureau of Meteorology, 2022), was also included as an environmental variable in these IOCE. Due to the absence of operational wave buoys, offshore wave data were hindcast using NOAA's WAVEWATCH III (WWIII) model v.3.14 on a global 30 arcmin grid. WWIII is accepted as a reliable source of hindcast data (Browne et al., 2007) and shows good agreement with buoy data in Australia (Hemer et al., 2007). Environmental variables were chosen because they were known to have relationships with stratification of water temperature, DO and salinity in IOCE (Gale et al., 2006; Snow and Taljaard, 2007), and data for each variable were easily and freely accessible (with the exception of wind data).

### 3.1.2. Statistical analysis

To investigate the relationships between environmental conditions and stratification, we used distance-based Linear Models (distLM) to test which environmental variables explain variation in stratification in each estuary. distLM, which uses distance-based Redundancy Analysis (dbRDA), was originally conceived for testing hypotheses about the causes of variation in abundances of multiple species across multiple locations (Legendre and Anderson, 1999) but is suitable for other types of questions where the dependent variables comprise similarly multivariate data. In this approach, multivariate data are first converted to a triangular, resemblance matrix, which comprises all possible pair-wise comparisons between data points using an appropriate similarity index. Regression is used to test whether one or more continuous or discrete predictor variables explain variation in the similarity matrix. *P*-values for hypothesis tests are generated using permutation methods. This method was chosen because it does not require variables to approximate a normal distribution, which is an important assumption of more traditional parametric multivariate methods such as Principal Components Analysis.

To quantify stratification, we used the absolute difference between the values of the surface and bottom measurements for each physicochemical variable on each day; thus, large values signal greater stratification. This is similar to the method of quantifying stratification used by Sherwood et al. (2008) but without dividing by total depth because we did not require a gradient. Daily data are likely to be temporally autocorrelated, which violates an assumption of the statistical models that data points are independent. To overcome this problem, we calculated seven-day running averages and used these values. These data were normalised to a common scale and then converted into a resemblance matrix using Euclidean distance, which is an appropriate similarity index for environmental data (Anderson et al., 2008). The predictor variables were inspected for outliers and, where necessary, variables were appropriately transformed to reduce effects of outlying values (fluvial inflows was fourth-root transformed for Gellibrand, Curdies and Powlett Rivers and square root transformed for Painkalac Creek). Associations among independent variables were examined to test for multi-collinearity, but all correlations were well below the suggested threshold (0.95) that would render one or more of them fully redundant (Anderson et al., 2008). Aire River was not included in the statistical analysis due to a lack of regular long term physicochemical data during open and closed periods.

We used step-wise selection to test which variables explain significant variation in the similarity matrices, as adjudged by significant *P*-values of $<0.05$, and the AIC selection criterion to determine the best overall model for each estuary. *P*-values were generated using 999 permutations. All analyses were conducted using the statistical package PERMANOVA+ (Version 6, PRIMER-E Ltd, Plymouth, UK). Because different methods of variable selection may deliver different results, we also used the Best procedure, which examines all possible combinations of predictor variables and reports the best models for a given number of variables, to check whether it delivered the same outcomes. We illustrate outcomes by using dbRDA to perform an ordination of the fitted values from the model, which constrains the arrangement of data points to reflect combinations of the environmental variables that explained the most variation.

## 3.2. Field measurements during the draining period

At all sites aside from the Powlett and Curdies Rivers, changes in estuary entrance morphology, water level, and basin physicochemical conditions were monitored prior to and near-continuously during artificial openings. From these data, we linked morphological change at the mouth to physicochemical and hydrodynamic changes in the basin.

### 3.2.1. Physicochemical depth profiling

At each IOCE, physicochemical depth profiles were collected at 0.5m depth intervals at two to three different measuring sites along the longitudinal profile of the estuary (Table S1). DO (mg/L) and salinity (using the Practical Salinity Scale) were measured using a Hanna Instruments HI9829 water quality multimeter. Depth profiles were taken at each site within 5 days before each artificial opening and then at regular intervals after the opening until the IOCE finished draining or for as long as logistically possible. Monitoring of depth profiles during the draining period were timed to coincide with major changes in entrance morphology and discharge at the mouth, being taken sub-hourly on average during periods of rapid geomorphic change.

The estuary basin water level was continuously logged at a 30-s interval using Solonist pressure transducers (LevelLogger30001 model). Water level data were corrected for atmospheric pressure and adjusted to mean sea level (MSL). Water level data (at a 15-min interval) from the Department of Environment, Land, Water & Planning's stream gauge network (Department of Environment, Land Water and Planning, 2022) were used to supplement the data obtained from the level loggers. Fluvial inflow data were taken from the closest discharge gauge to the estuary (Department of Environment, Land, Water and Planning, 2022). Hourly tide heights were retrieved from tidal charts and corrected from chart datum to be relative to mean sea level. Water velocity at each physicochemical measuring site was measured using a Marsh McBurnie Flow Meter at 20% and 80% depths of the water column at the same time as each depth profile was measured.

### *3.2.2. Entrance morphology*

Changes in IOCE entrance morphology were measured during the draining period following artificial openings. While the channel remained safe to wade, the channel width and depth were measured at a repeat cross-section using a Trimble R6 Real Time Kinematic (rtk) GPS unit (referenced relative to MSL). When it was unsafe to survey the mouth, channel width was measured using a laser ranger finder (with readings averaged multiple times) and channel depth was measured using a measuring (i.e. stadia) pole. Cross sectional area was calculated either from the surveyed profiles or by assuming a trapezoidal channel when the channel could not be surveyed. Water velocity from the mouth was measured using the orange method (Christensen, 1994) and averaged three times. Discharge at the mouth was calculated by multiplying the cross-sectional area of the channel by water velocity.

## 4. Results

### *4.1. The relationships between environmental variables and stratification*

Analysis of long-term data showed that fluvial inflows had statistically significant effects on stratification in all estuaries except Anglesea River, but only in the Gellibrand River did fluvial inflows explain the most variation (Table 3). Additionally, in other estuaries fluvial inflows were statistically significant but explained only small amounts of variation (<5%). Thus, hypothesis 1 (H1) was rejected. Maximum air temperature was a statistically significant variable for Gellibrand River, Painkalac Creek, Powlett River and Anglesea River but not Curdies River so hypothesis 2 (H2) was rejected (Table 3). Additionally, only in Anglesea River did maximum air temperature explain a meaningful amount of variation (27%) with all others <10%.

The dbRDA for Gellibrand River illustrated that fluvial inflows was strongly aligned with stratification, with high values of fluvial inflows associated with low values of stratification, thus supporting H1a (Fig. 2a & S1). These low values of stratification only occurred during open periods, with high values of stratification occurring more often during closed periods (Fig. S1). For Curdies River, the model did not explain much of the variance (vectors are not aligned with the data: Fig. 2b and S2). For Painkalac Creek (Fig. 2c & S3), Powlett River (Fig. 2d and S4) and Anglesea River (Fig. 2e & S5), maximum air temperature was aligned with stratification such that high values of maximum air temperature were associated with weak stratification (H2a supported). In Painkalac Creek and Anglesea River, higher values of stratification were more common during open mouth states than closed (Figs. S3 and S5). In contrast, high values of maximum air temperature were associated with low values of stratification during both open and closed periods in Powlett River. During open mouth states, in some cases large values of fluvial inflows also resulted in low values of stratification for Powlett River (Fig. S4). For Painkalac Creek, during open periods, increased fluvial inflows resulted in greater stratification of salinity (Fig. 2c) but this was less the case with stratification of water temperature and DO (Figs. S3b–c).

### *4.2. Fieldwork results*

### *4.2.1. Aire River*

Aire River was artificially opened on 05/03/21 at 14:50, 2 h before high tide. Peak discharge at the mouth was 82.84$m^3s^{-1}$ and was reached 21 h after opening (Fig. 3a). At a distance of 2 km upstream, water velocity reached a maximum of 0.35 $ms^{-1}$ at the top of the water column and 0.23 $ms^{-1}$ at the bottom, occurring 20 h after opening (Table S2). When the basin ceased draining, the water level had dropped by at least 0.72m (Fig. 3b). Fluvial flows into the estuary averaged 0.87$m^3s^{-1}$ during the draining period.

Aire River was stratified before the opening with a difference of 4.94 mg/L between top and bottom DO (Fig. 3c) and a difference of 24.4 between top and bottom salinity at the middle physicochemical measuring site (Fig. 3d). The top 1.5m of the depth profile was more

**Table 3**
distLM results, using stepwise selection of variables for all estuaries including the cumulative AIC of the model when each variable is added, the P-value of each variable, the proportion of variance each variable and the cumulative proportion explained by the model as each variable is added. Note that the results of the Best selection procedure produced the same results as shown here.

| Estuary | Variable | Cumulative AIC | *P*-value | Proportion Explained | Cumulative Proportion |
|---|---|---|---|---|---|
| Gellibrand River | Fluvial Inflows | 375.83 | 0.001 | 0.32 | 0.32 |
| | Mouth State | 346.00 | 0.001 | 0.04 | 0.36 |
| | Maximum Air Temperature | 341.68 | 0.003 | 0.008 | 0.37 |
| | Maximum Tidal Elevation | 338.04 | 0.004 | 0.007 | 0.37 |
| Curdies River | Mouth State | 85.28 | 0.002 | 0.07 | 0.07 |
| | Fluvial Inflows | 84.19 | 0.067 | 0.04 | 0.10 |
| Painkalac Creek | Mouth State | 139.28 | 0.001 | 0.16 | 0.16 |
| | Maximum Air Temperature | 130.24 | 0.001 | 0.06 | 0.22 |
| | Fluvial Inflows | 126.90 | 0.009 | 0.03 | 0.25 |
| | Rainfall | 125.45 | 0.023 | 0.02 | 0.27 |
| Powlett River | Maximum Air Temperature | 164.76 | 0.001 | 0.09 | 0.09 |
| | Mouth State | 153.36 | 0.001 | 0.07 | 0.16 |
| | Fluvial Inflows | 147.27 | 0.001 | 0.04 | 0.20 |
| Anglesea River | Maximum Air Temperature | 83.61 | 0.001 | 0.27 | 0.27 |
| | Mouth State | 78.19 | 0.002 | 0.05 | 0.32 |
| | Rainfall | 76.22 | 0.015 | 0.03 | 0.34 |

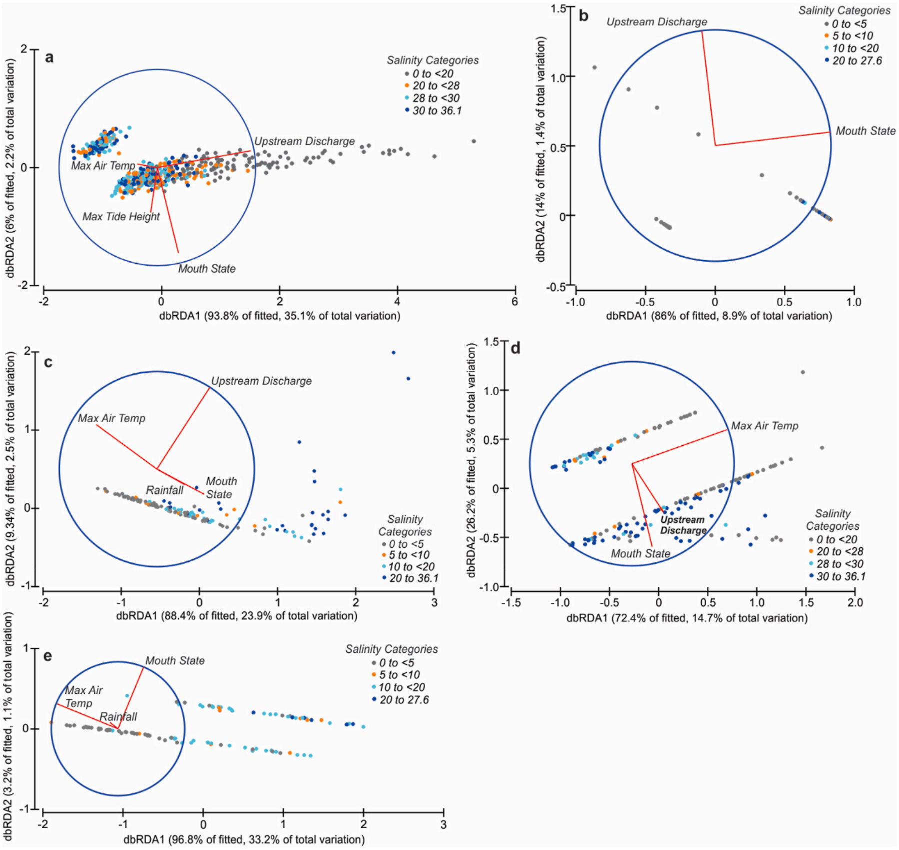

**Fig. 2.** Ordination using distance-based redundancy analyses (dbRDA), which illustrate the outcomes of fitting distLM to reveal which environmental variables explain significant variation in measures of estuary stratification in (a) Gellibrand River, (b) Curdies River, (c), Painkalac Creek, (d) Powlett River and (e) Anglesea River. Axis labels supply the percentage of fitted and total variation explained by each model. Significant environmental variables are shown as vectors (red lines) whose direction and length indicate the strength and sign of their correlation with the dbRDA axes. The relative size and position of the unit circle (blue) is arbitrary. Each vector begins at the circle origin and terminates at the coordinates describing its correlation with the two axes. Data points reflect differences between salinity values at the top and bottom of the water column, hence larger values indicate greater stratification. See Figs. S1–S5 for illustration of the same plots using other response variables that capture stratification. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

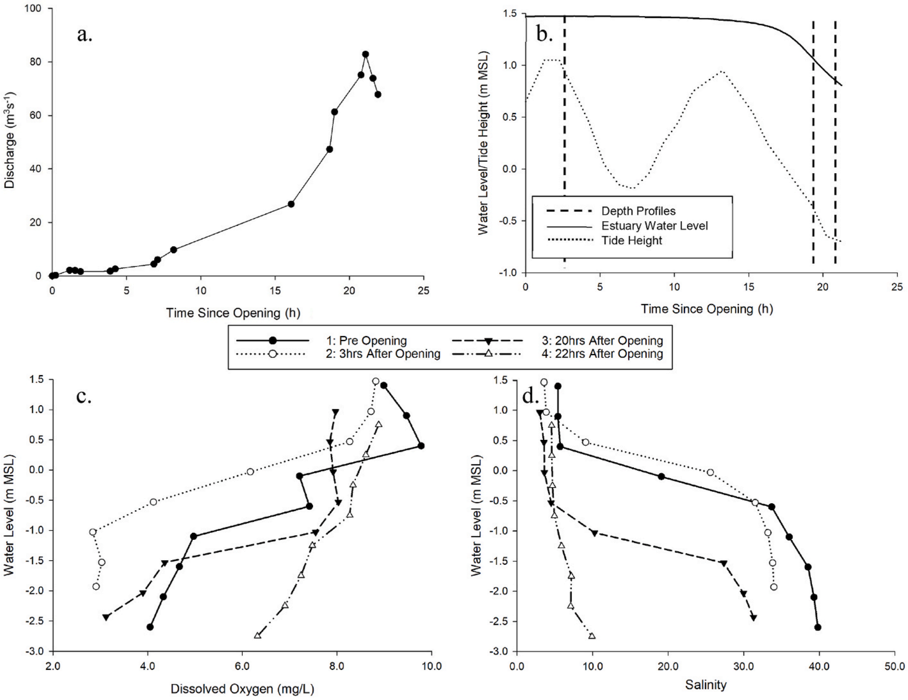

**Fig. 3.** Discharge from the mouth (a), water level, offshore tidal height and timing of depth profiles (b), DO depth profiles (c) and salinity depth profiles (d) during an artificial opening at Aire River. The depth profiles in this figure were taken from the middle measuring site. The estuary was opened on 05/03/21/14:50.

uniform 20 h after opening (Fig. 3c and d). At the same time, approximately 20 h after opening, discharge at the mouth (Fig. 3a) and top and bottom water velocity at the upstream measuring sites (Table S2) had reached their maximum. By the end of the measuring period (22 h after opening), both DO and salinity were much more uniform with a difference of 5.44 between top and bottom salinity and a difference of 2.56

mg/L between top and bottom DO at the middle measuring site (Fig. 3c and d). The lower physicochemical measuring site was also stratified before the opening and became more uniform during the draining period (Figs. S6a–b). The upper measuring site was slightly stratified in salinity and uniform in DO during the opening and shifted to uniform salinity and continued to have uniform DO during the draining period (Figs. S6c–d).

### 4.2.2. Gellibrand River

Gellibrand River was artificially opened on March 18, 2021 at 8:30, 1 h before low tide. Peak discharge at the mouth was 170.14 m$^3$s$^{-1}$, which was reached approximately 13.5 h after opening (Fig. 4a). Upstream 1.3 km of the mouth, water velocity reached a maximum of 0.46 ms$^{-1}$ at the top of the water column and 0.22 ms$^{-1}$ at the bottom, 12 h after the opening (Table S3). The draining period caused a 1.41 m drop in water level (Fig. 4b). Fluvial flows into the estuary averaged 1.85 m$^3$s$^{-1}$ during the draining period.

Gellibrand River was stratified before the opening with a difference of 4.32 mg/L between top and bottom DO and a difference of 27.38 between top and bottom salinity at the lower physicochemical measuring site (Fig. 4c and d). At the fifth depth profile, 12 h after opening, the top 2.5 m of the depth profile had become more uniform (Fig. 4c and d). Also at this point, top and bottom water velocity had reached its maximum (Table S3). Maximum discharge from the mouth was reached at approximately 15 h after opening (Fig. 4a). By the sixth depth profile, approximately 22.5 h after the opening, the water column became uniform with a difference of 0.27 between top and bottom salinity and 1.67 mg/L between top and bottom DO. By the end of the measuring period, stratification increased slightly (Fig. 4c and d). At the middle and upper measuring site, the water column was uniform before the opening and remained uniform during the draining period (Fig. S7).

### 4.2.3. Painkalac Creek

Painkalac Creek was artificially opened on October 02, 2020 at 11:20, 1 h before high tide. Maximum discharge from the mouth was recorded at 37.20 m$^3$s$^{-1}$ and was reached 6.5 h after opening (Fig. 5a). Upstream 0.9 km of the mouth, the maximum water velocity was 0.05 ms$^{-1}$ at the top of the water column and 0.02 ms$^{-1}$ at the bottom, 7 h after opening (Table S4). The draining period caused a drop of 0.99 m in water level (Fig. 5b). An average discharge of 0.07 m$^3$s$^{-1}$ was released from Painkalac Dam (~5 km upstream) during the draining period.

Painkalac Creek was slightly stratified before the opening with a difference of 1.90 mg/L between top and bottom DO and a difference of 3.59 between top and bottom salinity at the lower physicochemical measuring site (Fig. 5c and d). Approximately 6 h after opening, discharge from the mouth (Fig. 5a) and water velocity at the upstream measuring sites (Table S4) reached their maximum. At the end of the measuring period there was a difference of 2.10 mg/L between top and bottom DO a difference of 4.31 between top and bottom salinity (Fig. 5c and d). Bottom salinity increased to 8.99 at the end of the measuring period with saltwater intrusion from tides (Fig. 5d). DO increased during the day before decreasing overnight. The middle and the upper measuring sites were similarly stratified before the opening and remained stratified throughout the whole draining period (Fig. S8).

### 4.2.4. Anglesea River

Anglesea River was opened on July 15, 2021 at 11:30, approximately 4 h before high tide. Maximum discharge at the mouth was recorded at 6.47 m$^3$s$^{-1}$ and was reached 10.6 h after opening (Fig. 6a). Upstream of the mouth 1.0 km, maximum water velocity was recorded at 0.04 ms$^{-1}$ at the top of the water column and 0.02 ms$^{-1}$ at the bottom, 11 h after opening (Table S5). The draining period caused a drop of 0.48 m in water level. Fluvial flows into the estuary averaged 0.03 m$^3$s$^{-1}$ during the draining period.

Anglesea River was stratified before the opening with a difference of 3.39 mg/L between top and bottom DO and 10.21 between top and bottom salinity (Fig. 6c and d). Maximum discharge from the mouth (Fig. 6a) and water velocity at the upstream measuring sites (Table S5) were reached approximately 12 h after the opening. By the end of the measuring period, Anglesea River was still stratified with a difference of 7.79 mg/L between top and bottom DO and 12.19 between top and bottom salinity (Fig. 6c and d). The top 1.5 m of the depth profile

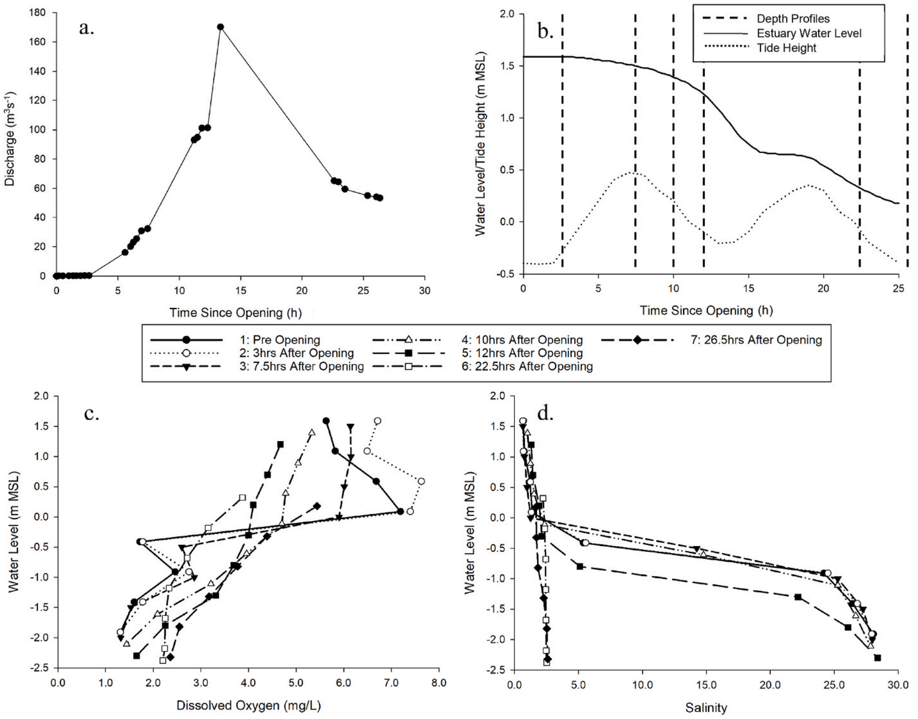

**Fig. 4.** Discharge from the mouth (a), water level, offshore tidal height and timing of depth profiles (b), DO depth profiles (c) and salinity depth profiles (d) during an artificial opening at Gellibrand River. Depth profiles in this figure are from the Low measuring site. The estuary was opened on March 18, 2021/8:30.

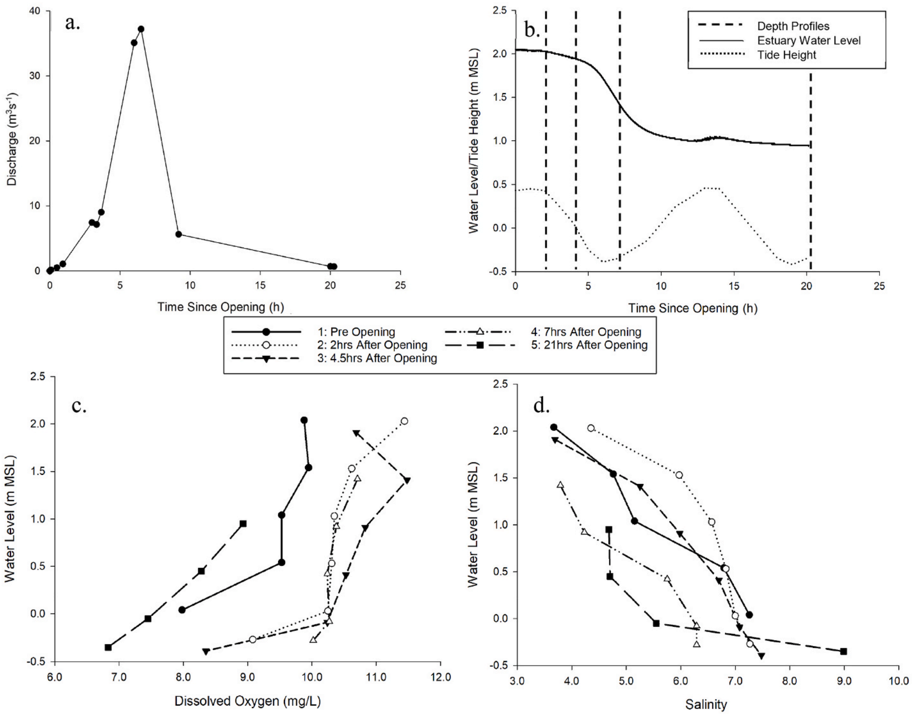

**Fig. 5.** Discharge from the mouth (a), water level, offshore tidal height and timing of depth profiles (b), DO depth profiles (c) and salinity depth profiles (d) during an artificial opening at Painkalac Creek. The depth profiles in this figure were taken from the Low measuring site. The estuary was opened on October 02, 2020/11:20.

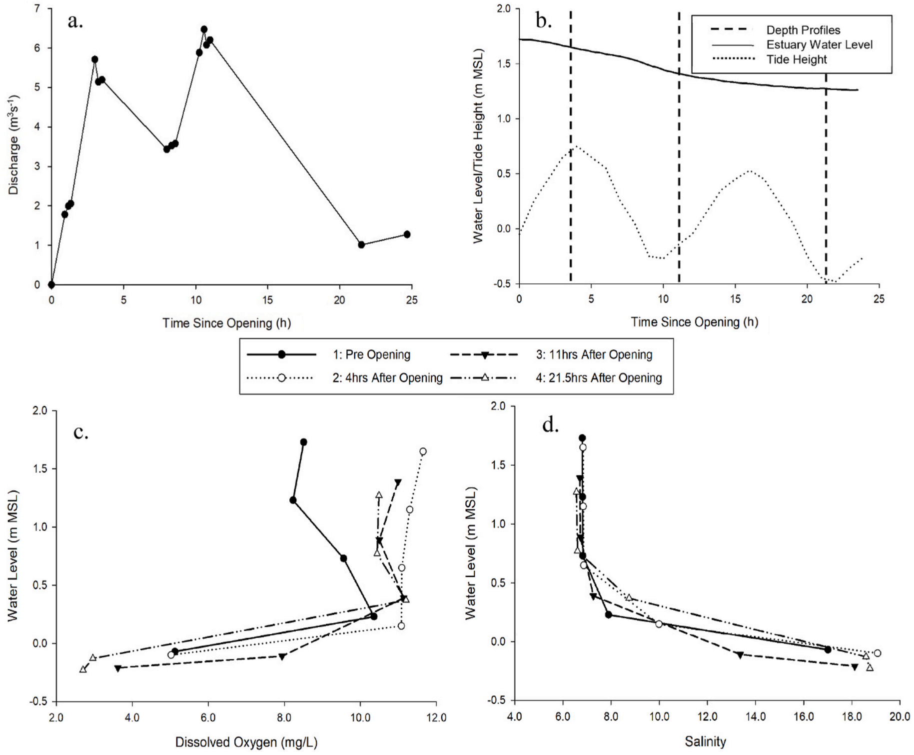

**Fig. 6.** Discharge from the mouth (a), water level, offshore tidal heights and timing of depth profiles (b), DO depth profiles (c) and salinity depth profiles (d) during an artificial opening at Anglesea River. The depth profiles in this figure were taken from the Middle measuring site. The estuary was opened on July 15, 2021/11:30.

became less uniform by the end of the measuring period (Fig. 6c and d). The upper physicochemical measuring site was similarly stratified before the opening and remained stratified (Figs. S9a–b). Bottom DO at the upper site was higher than the surface, averaging 12.62 mg/L during the measuring period compared to 10.93 mg/L at the surface, most likely due to the presence of aquatic vegetation or algae (Fig. S9a). The lower measuring site had uniform DO and salinity before the opening and remained uniform throughout the draining period (Figs. S9c–d).

## 5. Discussion

Our findings indicate that over the long-term (weeks-years), fluvial inflow, mouth state and air temperature have the strongest relationships with the degree of stratification in IOCE but that IOCE type, as defined earlier (Table 2), did not fully capture these differences, as we explain further below. Second, field observations of change during the draining phase have enabled the creation of conceptual models of hydrodynamic, physicochemical and morphological changes during the draining period. These conceptual models will be discussed with regard to how they vary for IOCE with different morphologies with the practical implications examined.

### 5.1. *The relationships between environmental variables and stratification*

Rather than stratification in IOCE having uniform relationships to environmental variables as predicted, we found a continuum of different relationships. These differences are most likely attributed to variability in IOCE size, catchment inflows and basin morphology. However, these differences are not quite reflected in the IOCE categories defined in Table 2. The first type of relationships was found in an IOCE with a larger catchment and largely infilled central basin, large catchment inflows, and with maximum depths of over 4m (Gellibrand River). The correlations in this IOCE suggest that during winter and spring when fluvial inflows into the estuary are high enough to keep IOCE open, there is enough freshwater inflow to regularly flush out brackish water from the basin, thus leaving the water column uniformly fresh and oxygenated. Then, when fluvial inflows decrease so that the mouth closes and temperatures increase over summer and autumn, there is only enough freshwater inflow to overtop the saline, deoxygenated layer, resulting in high values of stratification.

The second type of relationship was observed in IOCE with much smaller catchments, with maximum depths of less than 2.5m and with low catchment inflows (Anglesea River and Painkalac Creek). The relationships in these IOCE suggest that during open periods in winter and spring there is only enough freshwater inflow to overtop the brackish to saline water layer, leading to stronger stratification. Fluvial inflows over the measuring period at Anglesea River and Painkalac Creek averaged 0.07 $m^3s^{-1}$ and 0.10 $m^3s^{-1}$ over winter and spring respectively compared to Gellibrand River which averaged 12.29 $m^3s^{-1}$ (Department of Environment, Land, Water and Planning, 2022). Then, over summer, when these IOCE tend to be closed and air temperatures are higher, the freshwater layer completely evaporates away, leaving the water column uniformly saline and with uniform DO and water temperature. Our results suggest that these IOCE are influenced less by fluvial inflows and more by evaporation rates (i.e. maximum air temperature) and mouth state over summer. There may be times where these IOCE are flushed with freshwater, but this was not picked up in our monitoring dataset.

Finally, the third type of relationship is somewhere in between the first two responses and occurred in an IOCE with a moderate catchment and highly variable catchment inflow with maximum depths greater than 4 m (Powlett River). The relationships in this IOCE suggest that over winter and spring when the mouth is open there are occasions where there is enough fluvial inflows to flush out brackish to saline water similar to the first response, above. Then, over summer and autumn, the freshwater layer evaporates away, leaving a uniformly saline water column similar to the second response.

These different types of relationships do not quite align with the geomorphic types outlined in Table 2. For example, Powlett, Curdies and Gellibrand Rivers were all classified as the same type but had very different relationships between environmental variables and stratification. Potentially there are differences in each of these IOCE not picked up in the classification system that have caused these differences.

Hoeksema et al. (2018) similarly found that larger catchment IOCE with higher fluvial inflows in Western Australia were less prone to becoming uniformly hypersaline. The processes of estuary flushing, stratification and evaporation of the freshwater layer have been described in IOCE across South Africa (Snow and Taljaard, 2007; Whitfield et al., 2012) and California (U.S.A.), (Clark and O'Connor, 2019). However, this is the first time that IOCE have been categorised by the relation between stratification and environmental variables through rigorous statistical analysis. These processes suggested by our statistical analysis are common in IOCE globally and therefore these results can be applicable for IOCE internationally with similar climate and morphologies. A good example is the seasonally stratified IOCE of the east coast of South Africa that are located in temperate climates, and which occupy a continuum of morphologies, sizes, and infill states (Cooper, 2001). However, our results also showed that mouth state, while statistically significant, explained little variation in Gellibrand River, Powlett River, Curdies River and Anglesea River. Similarly, maximum air temperature explained little variation in Painkalac Creek, Gellibrand River and Curdies River. These tests were statistically significant because large sample sizes delivered high power to detect effects against background variation, but the results suggest that these variables were not as important as other variables in affecting stratification for these estuaries.

The distLM models provided a robust explanation of stratification in IOCE for all sites except Curdies River. Curdies River has a different morphology than the other estuaries studied, which could explain the lack of variation explained by the model. Curdies River has a much larger central basin, with higher surface water area, and is less infilled and channelised compared to the other estuaries. In comparison, all other sites had highly infilled central basins, less surface water area, and more channelised estuary morphologies. IOCE that have larger basins with more open water area tend to be more well mixed and less stratified due to wind mixing (Gale et al., 2006). Other IOCE with similar morphologies in Western Australia (Chuwen et al., 2009) and New South Wales (Gale et al., 2006) also tend to be more well mixed (e.g. Wilson Inlet in Western Australia). It seems that the model does not work well on IOCE with a large, shallow central mud basin and that are well mixed.

Our models did not detect a relationship between wind mixing and stratification, which has been found to occur in other IOCE, especially over summer (Gale et al., 2006). Possibly, wind mixing and stratification are unrelated for our IOCE, but it is also possible that the variable used as a proxy for wind mixing (maximum wind gust speed) was not appropriate.

Human influences in the rivers upstream of these IOCE could have affected the relationships between environmental variables and stratification. Curdies and Gellibrand Rivers and Painkalac Creek all have hydrologies that are heavily altered by water extraction for agriculture and drinking water supply (Department of Environment, Land, Water and Planning, 2010). Powlett River and Curdies River also suffer from severe catchment clearing of >90% in each. More research is needed into how these human impacts can affect stratification in IOCE.

While this study provides the first comparison and analysis of the response of stratification to environmental variables across multiple IOCE with different geomorphic and hydrological characteristics, a limitation is that only one physicochemical measuring site was chosen for each IOCE. In reality, physicochemical characteristics and stratification vary longitudinally across the IOCE as well as temporally (Slinger et al., 2017). While outside the scope of this study, further research could investigate whether results differ across multiple sites that are distributed longitudinally in IOCE.

### 5.2. *Changes in stratification during estuary entrance openings*

Over the scale of an individual opening, our observations indicate two distinct responses to estuary artificial openings occur: (1) the basin water column mixes and becomes uniform, and (2) there is minimal change in stratification where water drains off the surface. These two different responses are likely to be a function of the magnitude (i.e. energy) of each opening - in terms of peak discharge at the mouth and fluvial inflows into the estuary during the opening.

The Gellibrand and Aire Rivers followed this first response. In both IOCE, initially there was little to no change in stratification, with a slow drop in water level. As discharge from the mouth increased, salinity in the top layer started to decrease as freshwater was drawn down from upstream. Once the discharge from the mouth reached its maximum, the water column mixed together and DO and salinity became less stratified. Water velocity at the top and bottom of the water column at the upstream measuring sites also reached its peak at this stage. Eventually the water column became almost uniform and had fully mixed together. However, in both openings there was insufficient freshwater inflow to completely flush out brackish water during the draining period, indicated by values of salinity greater than 0.5. Similar results have been found in IOCE in California where artificial openings have caused similar large drops in salinity and destratification, but with salinity levels higher than freshwater (Williams, 2014). These results support the prediction (H3) that the water column will de-stratify but it seems that there was insufficient freshwater flow to completely flush out the estuary with freshwater as predicted (H3a). This is unsurprising given that both IOCE were opened in March, typically when there is lower rainfall in Victoria. Other openings, where the estuary was flushed out with freshwater, had much higher freshwater flows - for example as observed in the Great Brak estuary in South Africa (Slinger et al., 2017) which has an estuary area of approximately 0.57 $km^2$, similar to Aire and Gellibrand estuaries (Table 1). This opening showed orders of magnitude difference in river inflow into the estuary with fluvial inflows of up to 26 $m^3s^{-1}$, compared to the Aire and Gellibrand Rivers with fluvial inflows of 0.87 $m^3s^{-1}$ and 1.85 $m^3s^{-1}$ respectively.

Alternatively, at Painkalac Creek and Anglesea River, discharge from the mouth was between 2 and 26 times lower than at the Gellibrand and Aire Rivers (Figs. 3a–6a). Top and bottom water velocity at the upstream measuring sites was 7–9 times greater at Aire and Gellibrand Rivers and freshwater inflow was 10–60 times higher at Aire and Gellibrand Rivers than at Painkalac Creek and Anglesea River. There were minimal changes in stratification at Painkalac Creek and Anglesea River that could be attributed to the draining period after the artificial opening (Fig. 4c and d, 5c-d) as was predicted in IOCE with low flow conditions (H3b). There were only minor changes in DO levels caused by natural diurnal changes and changes in salinity at Painkalac Creek lower measuring site due to the re-entry of ocean water towards the end of the measuring period. The changes to stratification observed during the draining period in each IOCE seemed to better reflect the geomorphic classifications in Table 2. Aire and Gellibrand Rivers (Type 2) responded similarly and Painkalac and Anglesea Rivers (Type 3) responded similarly.

Stratification seemed to be unaffected by the rate of water level decrease. In fact, Painkalac Creek drained faster than Aire River and Gellibrand River (peak rate of water level decrease = 0.25 cm/h compared to 0.15–0.20 cm/h). Our results indicate that freshwater inflow and catchment and basin size have a greater effect on stratification during the draining period than the rate of water level decrease. These results support the prediction of H3b that IOCE with low freshwater inflow will remain stratified following the draining period. Our results also suggest that tides could have influenced the timing of peak discharge at the mouth and the lagoon drainage rate. Peak discharge at the mouth for each opening occurred around 1–2 h either side of low tide. High tides during the draining period at each opening also tended to slow the rate of water level decrease by reducing hydraulic head between the ocean and the IOCE basin.

The amount of physicochemical and geomorphic data gathered during the draining period across multiple IOCE has never been done before However, there was not enough data gathered to undertake statistical analyses. Future studies should fill this data gap to then determine whether the processes observed during the draining period are statistically significant. Another limitation of the field study was a lack of bathymetric data in IOCE studied, which meant that the results could not be put in context of estuary volume. Further studies could consider how estuary volume affects the outcome of the draining period.

The IOCE that were included in the field study and the long term data analysis were grouped the same. Painkalac Creek and Anglesea River were grouped together, and Gellibrand River was grouped separately. It seems that differences in responses to long term environmental variables are also reflected on a much shorter time-scale during the draining period and vice versa.

### 5.2.1. *Conceptual model*

Observations from the two types of openings (high energy, low energy) have been summarised in two conceptual models.

*5.2.1.1. High energy opening.* Conceptually, high energy openings, as observed at the Aire and Gellibrand Rivers, consist of six stages.

1. **Pre-opening:** The estuary is closed, and the water column is stratified. The top layer has high DO and low salinity, and the bottom layer has lower DO and high salinity (Fig. 7a).
2. **Initial outflow:** Initially after the opening, there is low outflow from the mouth. Freshwater from the surface is flowing out of the estuary with little to no flow towards the bottom of the water column. The water level is dropping slowly (<1 mm/h), and stratification is largely unchanged (Fig. 7b). This stage may last between 5 and 10 h.
3. **Rising limb:** Outflow velocities increase and the beach berm is eroded, which initiates a rapid increase in discharge through the mouth. More water is being drawn down from further upstream, increasing the thickness of the top freshwater layer, and water level is dropping faster (1–5 cm/h). The IOCE water column is still stratified (Fig. 7c). This stage may last between 5 and 8 h and usually occurs on the falling tide.
4. **Peak outflow:** As the channel further incises and widens, maximum discharge at the mouth is reached. Upstream, surface flow has transitioned to flow throughout the entire water column. The increased flow has initiated mixing of the water column as stratification of the water column is beginning to break down. The estuary water level is rapidly decreasing (10–20 cm/h) due to higher discharge at the mouth (Fig. 7d). This stage may last 1–2 h and usually occurs around low tide when hydraulic head between the estuary and ocean is at a maximum.
5. **Falling limb:** As the basin water level falls, hydraulic head between the estuary and ocean decreases. Discharge from the mouth is decreasing, channel expansion ceases and the rate of water level decrease slows (1–5 cm/h). At this stage, the water column is uniform with consistent salinity and DO (Fig. 7e). If there is enough freshwater flows from upstream, then the estuary is flushed out with freshwater. This stage may last 3–5 h and usually occurs on a rising tide (Fig. 7f).
6. **End of Draining phase:** The estuary water level has stabilised near or at mean sea level. Outflow from the mouth is low enough for sea water to re-enter the IOCE, the water column becomes tidally influenced, and the draining phase has finished (Fig. 7f).

Similar openings have been observed in the Great Brak estuary in South Africa (Slinger et al., 2017) and in the Pescadero Estuary in U.S.A (Williams, 2014). Both openings had large amounts of freshwater river inflow into the estuary with upstream river flows of up to 26 $m^3s^{-1}$ and 10 $m^3s^{-1}$ respectively and salinity became uniform in the water column.

*5.2.1.2. Low energy opening.* Lower energy openings were observed at Painkalac Creek and Anglesea River. Here discharge at the mouth was 7–9 times lower than at the Gellibrand and Aire Rivers and fluvial inflow was insufficient to de-stratify the estuary water column. Lower energy openings can be summarised in three stages.

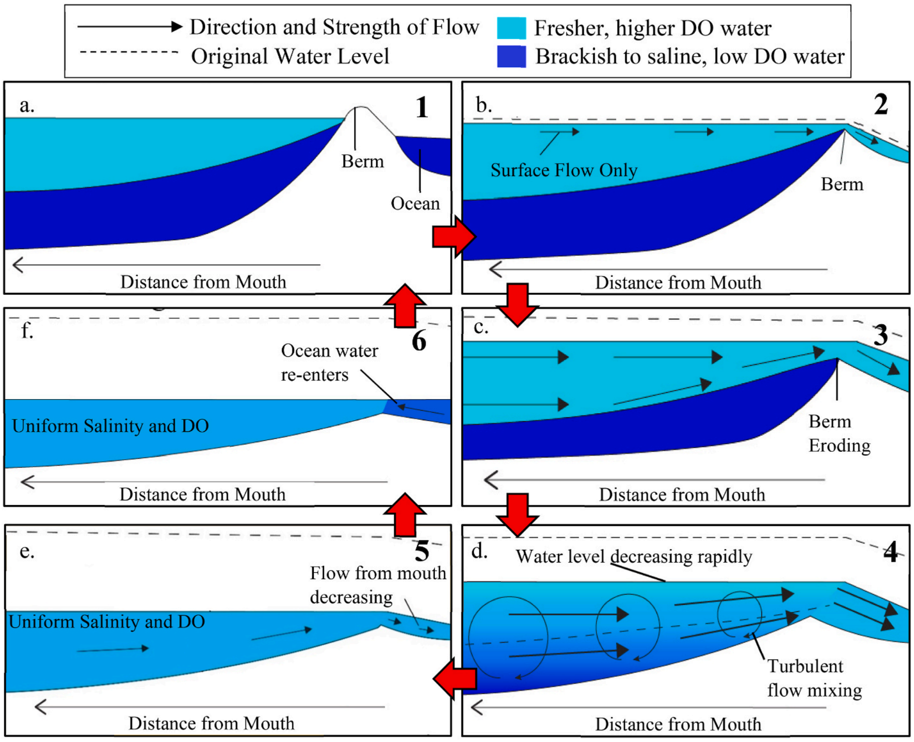

**Fig. 7.** Conceptual model of the initial conditions before the artificial opening at Gellibrand and Aire Rivers (a), the draining period (b–e) and the transition to the open period (f).

1. **Pre-opening:** The estuary is closed, and the water column is stratified. The top layer has high DO and low salinity, and the bottom layer has lower DO and high salinity (Fig. 8a).
2. **Outflow:** Throughout the draining period, there is low fluvial discharge at the mouth compared to the high energy opening because there is less water in the basin, less freshwater inflow from upstream and the berm is not eroded as much as the high energy opening. Water level decrease can be highly variable ranging from slow draining (peaking at 5 cm/h) to fast draining (peaking at 25 cm/h). Flow in the IOCE basin is mainly coming from the surface layer with negligible flow towards the bottom of the water column. The water column remains stratified even during peak discharge from the mouth (Fig. 8b). This phase lasts for the whole draining period which can vary between 10 and 20 h.
3. **End of draining phase:** Once discharge from the mouth decreases to the point where ocean water can re-enter the estuary, the draining period finishes. The estuary basin is still stratified but water levels have lowered and the thickness of the fresher top layer of the water column has reduced (Fig. 8c).

Similar openings have been observed in Great Brak estuary in South Africa (Slinger et al., 2017) and in Pescadero Estuary in U.S.A (Williams,

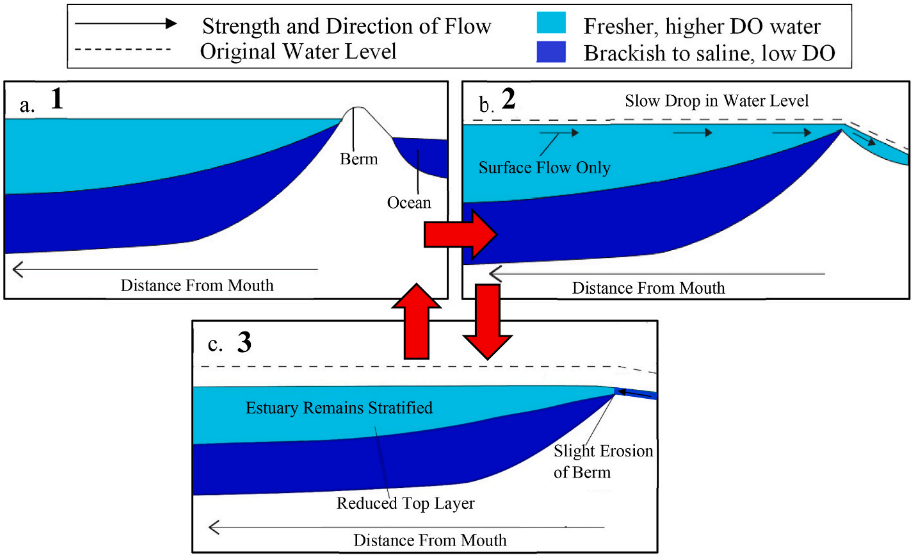

**Fig. 8.** Conceptual model of the initial conditions before the artificial estuary opening at Painkalac Creek and Anglesea River (a), during the draining period (b) and when draining has ceased (c).

2014). These openings had 3-10 times less freshwater flow than the high energy openings observed at these same IOCE.

### 5.3. Implications

Results from the analysis of long term water quality and environmental data provide an indication of how stratification in IOCE may respond to future climate change. Globally it is predicted that there will be longer dry periods but with increased storm and large rainfall events, as well as increased temperatures and extreme temperature events in the future (IPCC, 2021). IOCE entrance dynamics are very sensitive to changes and modifications in river inflow (Stein et al., 2021). Lower rainfalls in Australia have already caused IOCE in New South Wales to be closed for longer periods and have resulted in a reduction in salinity due to reduced connectivity with the ocean (Scanes et al., 2020). In contrast, IOCE in Western Australia have seen marked increases in salinity due to reduced rainfall and fluvial inflows that have also resulted in increased hypoxic conditions (Hallett et al., 2018; Hoeksema et al., 2018; Warwick et al., 2018). How climate change will affect stratification in IOCE is similarly unclear. It is predicted that sea level rise (Chilton et al., 2021) and decreased river flow (Hallett et al., 2018; Stein et al., 2021) will cause stratification to increase in estuaries. On the other hand, it is suggested that decreased river flows and increased evaporation rates in the future will cause stratification to decrease and the water column will become uniformly saline to hyper-saline (Gillanders et al., 2011). Our results also suggest that with less rainfall and higher temperatures predicted, smaller IOCE could become uniformly saline for longer periods while larger IOCE may become uniformly saline when they previously have not. On the other hand, increased storm, and high rainfall events (IPCC, 2021) could see larger IOCE flushed out with freshwater at more regular intervals. Our results will be helpful to estuary managers to help better predict how stratification in IOCE will be affected by climate change. These changes in stratification could potentially have negative implications for the biota that lives in these estuaries and that may only be able to tolerate a particular range of conditions. For example, larger salt wedges and hyper-saline conditions caused by increased temperatures and catchment clearing in Western Australian estuaries have reduced the range of freshwater fish species (Hallett et al., 2018) and have caused fish deaths (Hoeksema et al., 2006). It will be important for estuary managers to understand how stratification will change in the future and how this will affect estuary biota so that important species can be protected. More studies are needed to quantify to what degree will stratification in IOCE will change under future climates.

Our study has provided the first high-resolution analysis of changes in IOCE physicochemistry during the draining period, while linking these observations with geomorphic change at the mouth. These findings are directly important for coastal managers who need to know when to implement openings so that fish kills are avoided. Results from the field study indicate that destratification following estuary entrance openings as described by Williams (2014) does occur in other IOCE, but only in IOCE that have catchment areas and river inflows great enough to mix the water column. Otherwise, the IOCE basin will remain stratified as described by Human et al. (2016). A common theme among mass fish deaths is a lack of freshwater flow into the estuary during artificial openings (Becker et al., 2009; Stacey et al., 2017). The results from this study show that if artificial openings are needed, there are three ways of reducing the likelihood of mass fish deaths.

1. Ensuring the water column is well oxygenated before proceeding with artificial openings.
2. Undertaking artificial openings during periods of high freshwater inflow.
3. Making the artificial opening small and with low energy for IOCE with low freshwater inflows by using tides to manipulate the hydraulic head and by digging wide shallow channels with bends.

Mass fish deaths can also be caused by deoxygenated water situated in surrounding floodplains that drains into the water column when the IOCE is artificially opened (Stacey et al., 2017). Whilst this study did not focus on this mechanism for mass fish deaths, high freshwater inflows could also play a role in preventing mass fish deaths by flushing out deoxygenated water from the system, but that requires tests.

Our results demonstrate that how IOCE stratification responds to long term changes in environmental conditions is reflected in short term changes seen during artificial openings. Thus, long term hydrodynamic and water quality characteristics can be used to indicate how IOCE will respond to artificial openings, rendering detailed studies of artificial openings unnecessary if long term data are available. Additionally, our results show that smaller and larger catchment IOCE need to be managed differently in order to maintain species diversity in these ecosystems into the future.

## CRediT authorship contribution statement

**Callum Edwards:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sarah McSweeney:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Barbara J. Downes:** Writing – review & editing, Supervision, Software, Methodology, Formal analysis, Data curation.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Acknowledgements

Thank you to Corangamite Catchment Management Authority, Parks Victoria and Surf Coast Shire Council for notifying of artificial openings and allowing us to conduct our field measurements. Also thank you to all of the EstuaryWatch volunteers who collected the physicochemical and mouth condition data that we have used in this study, the Bureau of Meteorology who provided weather data, and the Victorian Department of Environment, Land, Water and Planning (DELWP) that provided fluvial inflows and water level data. This research was funded by Corangamite Catchment Management Authority and DELWP.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2023.108341.

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