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FINAL REPORT:

Gellibrand River estuary low flow investigation

November 2017

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Summary

Alluvium Consulting Australia Pty Ltd (Alluvium) has been engaged by Corangamite CMA to undertake an investigation into low flows and estuary opening status in the Gellibrand River Estuary. The Gellibrand River estuary has experienced water quality conditions that pose a risk to aquatic life (particularly low dissolved oxygen (DO) concentrations) during prolonged periods of estuary closure to the ocean and also during artificial estuary opening. Prolonged periods of estuary closure and artificial openings tend to be associated with low flow conditions in the Gellibrand River.

This investigation has used available relevant scientific information and a detailed analysis of water quality monitoring information and recorded fish deaths, to identify the main factors that influence estuary DO concentrations under low flow conditions. This latter information has then been used to provide decision support matrices to assist managers in their decision-making regarding the artificial opening of the Gellibrand River estuary.

Fish deaths
The investigation has used available literature on tolerances of fish to dissolved oxygen conditions (DO) to investigate the occurrence of conditions likely to cause fish deaths in the Gellibrand River estuary. These conditions (and therefore fish deaths) are likely to occur sometime after the closure of the estuary or during the subsequent artificial opening of the estuary.

Estuary opening status
The investigation has shown that closure of the estuary is controlled by river flow rates, wave height and wave direction (with the latter two factors controlling sand build up at the mouth). Of these factors, only the river flow rates can be directly managed, although in some cases timing of artificial estuary openings can lead to more favourable wave height and wave direction conditions.

Water quality in the estuary
We found three dominant processes that influence DO during periods over which the estuary is closed. These are respiration by estuarine flora, the mixing of surface and bottom water and the input of high organic loads from the catchment.

During estuary openings (both artificial and natural), DO was found to fall, with the characteristics of this fall a product of the rate of fall in the water level, and the rate of river flow to the estuary.

A risk framework for management
A risk framework has been developed to assist with the identification of DO risks arising from artificial opening of the estuary. The risks associated with reduced DO can be managed through both artificial openings and river flow rates. Short-term increases in flow rate can be achieved through temporary cessation of water extractions by Wannon Water.

Recommendations
The results of the analysis of fish deaths, the factors that influence the status of the estuary (open or closed) and the water quality in the estuary, have been used to assist decisions on artificial openings of the Gellibrand estuary.

However, the findings outlined in this assessment are based on limited data. Both the data set and the confidence in the results would be enhanced by ongoing monitoring and evaluation of the estuary outcomes (fish deaths and DO), and the factors that influence these outcomes (inflow rates, inflow water quality, elevation of water level in the estuary, and estuary status).

We recommend further analysis into the impacts of water extraction on the frequency of estuary closures during low flow periods, and exploration of the means by which extractions can be managed to limit estuary closure and also assist with decisions regarding the (artificial) opening of the estuary.

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1 Introduction

Alluvium Consulting Australia Pty Ltd (Alluvium) has been engaged by Corangamite CMA to undertake an investigation into low flows and estuary opening status in the Gellibrand River Estuary. The Gellibrand River estuary has experienced water quality conditions that pose a risk to aquatic life (particularly low dissolved oxygen (DO) concentrations) during prolonged periods of estuary closure to the ocean and also during artificial estuary opening. Prolonged periods of estuary closure and artificial openings tend to be associated with low flow conditions in the Gellibrand River. This investigation has considered the complex factors that influence estuary water quality under low flow conditions.

The Gellibrand River flows to Bass Straight near the town of Princetown in south western Victoria. The Gellibrand River estuary is classified as an Intermittently Closed and Open Lake and Lagoon (ICOLL) estuary, a type of wave-dominated estuary. The Gellibrand River estuary closes intermittently as part of a natural process due to the formation of a sand berm at the estuary entrance. When the estuary entrance is closed, the build-up of water behind the sand berm can cause inundation of floodplain areas. The limited flushing and turnover of the water in closed estuaries can lead to a decline in water quality conditions and adverse ecological impacts.

At times when the estuary mouth is closed, there is a threat of flooding and damage to infrastructure and agricultural land. There can also be a threat to aquatic fauna due to water quality conditions. Artificial opening of the estuary is undertaken at times to alleviate these adverse outcomes. However, artificial estuary openings can also contribute to the water quality outcomes, depending on the tidal exchange, inflows from the catchment and draining of water from the floodplain.

The **purpose** of this study is to provide information and recommendations relating to flow in the Gellibrand River that will be used to inform the decision-making process when considering whether the estuary should be artificially opened during low flow conditions. This investigation uses a data-driven approach to understand the complex processes that are occurring in the Gellibrand River estuary during estuary closure periods and openings.

The **outcome** of this project is the provision of the best available data and available science for the management of the estuary and for this information and approach to management to be in a form that can be communicated to stakeholders.

This report documents the approach to and outcomes from the investigations, including:

- Analysis of water quality and related data during periods when the estuary was closed and during times when the estuary was opened
- Supporting information regarding sustained estuary openings (i.e. openings when the mouth remains open for an extended period following its opening) and the occurrence of fish deaths
- A series of risk matrices and recommendations for actions to support estuary management.

A project steering committee comprising a member from each of the Corangamite CMA, Wannon Water and Parks Victoria has overseen this project. The project steering committee comprised:

- Tom Scarborough (Corangamite CMA)
- Peter Wilson (Wannon Water)
- Rhianna Burns (Parks Victoria).

1.1 Terminology

Throughout this report, the following terms describing the status of the estuary mouth are used:

- Estuary opening: The process and period of time over which an estuary transitions from a closed to an open status (typically occurs over a 48-hour period)
- Open estuary: The status of the estuary when it is connected to the sea
- Estuary closure: The process and short period over which an estuary transitions from an open to closed status
- Closed estuary: The status of the estuary when it is not hydraulically connected to the sea

2 Background

2.1 Site overview

The Gellibrand River rises in the Otway Ranges and flows south, exiting to the sea (Bass Straight) at Point Ronald near the township of Princetown (Figure 1, Figure 2). The catchment of 23 km^2 encompasses the Otway ranges, a mix of native and plantation forests, cleared agricultural land and small townships.



Figure 1. *Gellibrand River estuary - Looking south-west at Point Ronald [top] and looking south at the estuary mouth [bottom]*

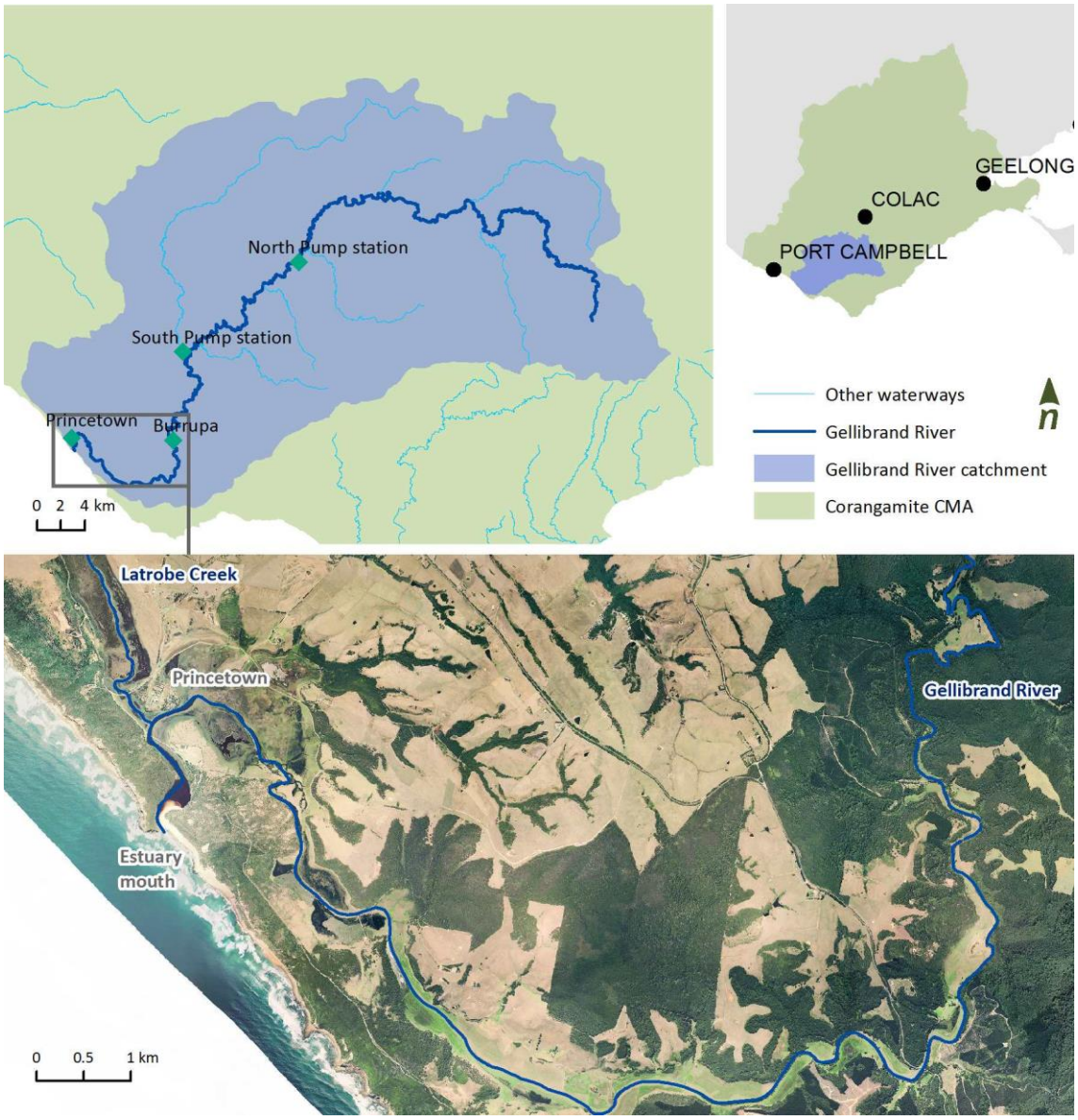

Figure 2. *Gellibrand River catchment [top] and estuary [bottom]*

The Gellibrand River estuary is a wave dominated barrier estuary (Ozcoasts 2016), (an intermittently closed and open lake or lagoon (ICOLL)) with a floodplain over 1km wide (McSweeny et al. 2016). The estuary opens to the sea across a wide sandbar with a relatively narrow channel. Saltwater and tidal influence extend up to 13.5 km upstream from the estuary mouth (Lloyd et al. 2008). Inundation extents throughout the closed estuary under low flow conditions are provided in Figure 3.

The estuary has a significant tributary, the Latrobe Creek, joining the Gellibrand River from the west, approximately 1.25 km upstream of the mouth (Figure 2). Extensive wetlands are situated across the Latrobe Creek and Gellibrand River estuary floodplains (Figure 3). The Estuarine Wetland EVC 'occurs on anaerobic/waterlogged clays and silts on the edges of estuarine water bodies' (Australian Ecosystems 2010) and may contribute to water quality outcomes in the estuary.

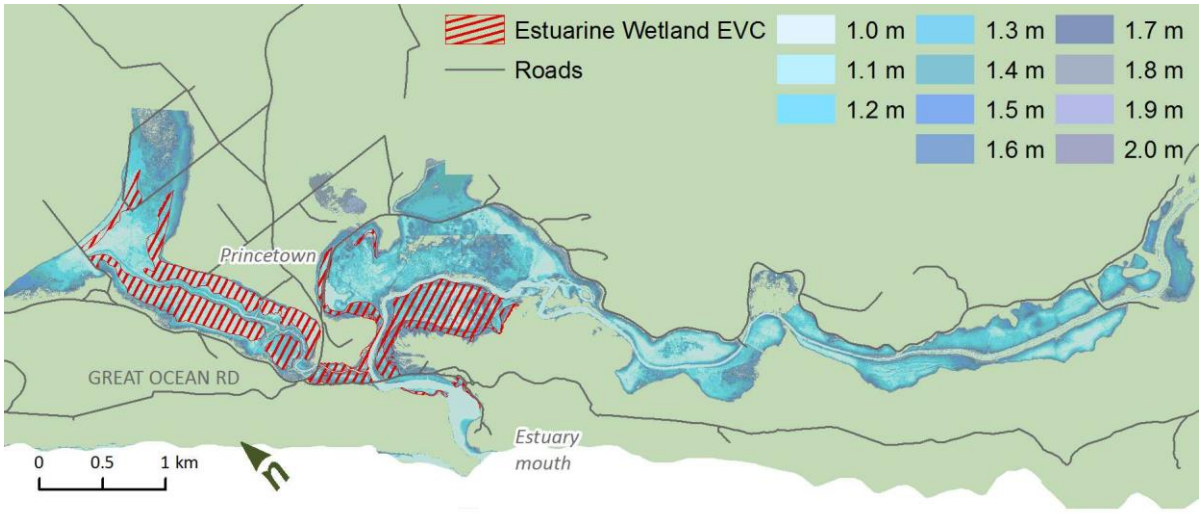

Figure 3. *Inundation extent contours – shown in 0.1 m AHD layers for Gellibrand Estuary with Estuarine wetland EVC [Data source: Corangamite CMA, Australian Ecosystems]*

The Gellibrand River estuary is widely valued for its aesthetic coastal landscape, diverse ecosystem values associated with the estuary, floodplain and wetland network, and cultural and economic values associated with indigenous significance, recreational use of the area, productivity of the floodplains and ecosystem services supported by the river and estuary. Significant values identified and managed for in the estuary are summarised in Attachment A (Table 7).

2.2 Management actions

There are two primary short-term management actions available for managing water quality and floodplain inundation objectives in the Gellibrand estuary:

- Artificial opening of the estuary
- Managing (reducing) water extractions from the upper Gellibrand River to increase streamflow.

Gellibrand River artificial estuary openings are currently implemented by Parks Victoria. This involves use of a mechanical excavator to create a breach in the estuary mouth. The Corangamite CMA generate an Estuary Entrance Management Support System (EEMSS) report to help inform the decision on whether to undertake an artificial estuary opening. Parks Victoria also undertake water quality monitoring before artificial estuary openings.

Wannon Water currently have two major water extraction points from the Gellibrand River at:

- South Otway pipeline
- North Otway pipeline (Figure 2).

These pipelines transfer water to treatment plants in Warrnambool and the surrounding area. Extractions from the Gellibrand River can be reduced for short periods to improve the flow in the river to support water quality outcomes.

Longer term management actions to address water quality and other risks in the Gellibrand River estuary are documented in the Corangamite Regional Catchment Strategy (CCMA 2013) and the Gellibrand River Estuary Management Plan (RMCG 2016). These actions include on-ground works to restore the floodplain and riparian vegetation, pursuing refined productive land management practises, investigating impacts of domestic effluent and continuing work to refine the risk based approach to estuary mouth opening.

2.3 Estuary issues and observations for investigation

The management of floodplain inundation and water quality in an estuary such as the Gellibrand is complex. We have attempted to illustrate the processes in the Gellibrand River in Figure 4. This diagram shows that a number of drivers and actions can influence the estuary conditions (closed / open, water level, flow), which in turn influence water quality and floodplain inundation outcomes. Drivers can include tides, Bass Strait swell, and catchment runoff, while short-term management actions or 'levers' available to managers are limited to artificial estuary openings and managing water extraction from the river.

Based on a review of the background information and consultation with the steering committee, we noted the following observations that have guided the investigations:

- Currently the estuary is only artificially opened to protect human assets; under current arrangements the estuary would not be artificially opened if human assets were not impacted by the estuary water level or quality
- While artificially openings are only triggered based on threats to human assets, any potential artificial opening involves careful management to minimise the potential impact on the environment, with a particular emphasis on minimising decline in water quality
- Estuary water quality generally declines through periods when the estuary is closed
- A successful estuary opening would achieve a reduction in floodplain inundation without adversely impacting water quality conditions, meeting production (economic), amenity (social) and environmental objectives
- A successful estuary opening requires both high enough water level and a significant flow event to both maintain the opening and achieve a mixing of water
- If the estuary is opened at times of low flow and the estuary is stratified prior to that opening, the oxygenated surface water layer can be released from the estuary leaving a stagnant layer of low DO water which can be a risk to aquatic fauna
- If the floodplain is inundated, when the estuary is opened, anoxic water can enter the estuary from the floodplain causing low DO conditions and pose a risk to aquatic fauna, in what is known as a 'blackwater' event.

This project focuses on low flow periods (typically summer / autumn) where there are potential trade-offs between floodplain inundation and water quality outcomes. This project has investigated the conditions and timing for successful estuary opening and improved (or not adversely impacted) water quality outcomes.

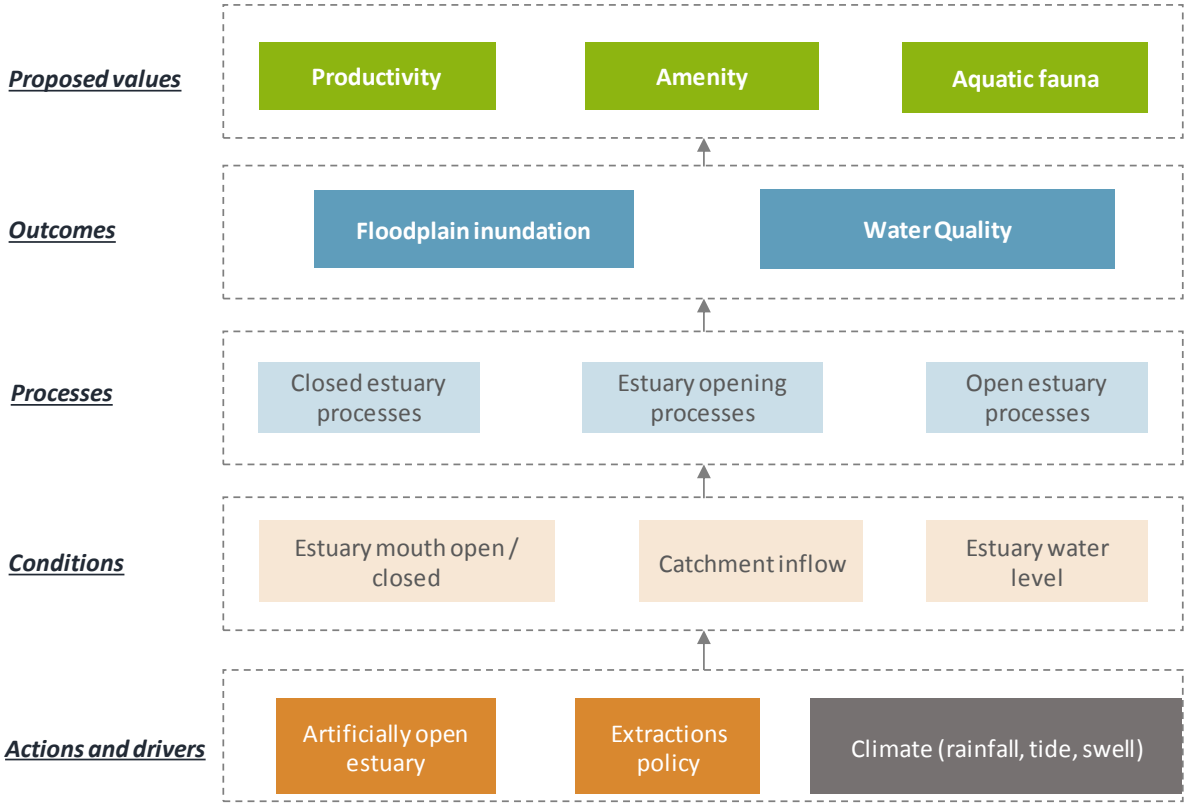

Figure 4. *Logic diagram of water management issues in Gellibrand estuary*

3 Fish deaths and water quality

Estuary fish populations are highly dependent on the water quality conditions. Apart from pollution events, the Environment Protection Authority Victoria (EPA) has assessed that low dissolved oxygen is the highest likely cause of fish deaths in Victoria (EPA 2007).

3.1 Fish deaths in the Gellibrand estuary

Up until 2012, EPA Victoria kept a record of fish deaths, some of which is detailed in the report *Fish Deaths Reported to EPA Victoria*, 1998–2007 (EPA Victoria 2007). We have been informed by EPA Victoria that this record is no longer being updated. There is one entry in this record for the Gellibrand estuary: on the 28 March 2006, it was recorded that 14 'unidentified fish and shrimp' were found dead after the estuary had been opened. The likely cause was listed as estuarine salinity, however as shrimp were found dead, which are generally salt tolerant, salinity was unlikely to be the cause.

Fish deaths are also recorded through the EstuaryWatch program. Fish deaths were recorded at the Gellibrand estuary on the following dates.

- 11 April 2014
- 29 April 2009
- 23 March 2009
- 21 March 2009
- 12 March 2009
- 8 March 2008

Given the limited data of both fish deaths and water quality in the Gellibrand estuary, we have completed a review of available literature on fish deaths (see Attachment B). Fish deaths resulting from DO decline are influenced by the magnitude of DO (i.e. how low DO falls to) and the period over which low DO conditions persist (i.e. how long a DO fall lasts for):

- fish are unable to tolerate very low dissolved oxygen levels (near 0 mg/L) in the surface waters for any length of time
- increasing levels of DO in the top of the water column enable fish survival for longer periods of time.

These factors are expressed in the matrix below.

3.2 Low DO conditions

Low risk DO trigger values have been determined by EPA Victoria for riverine estuaries; greater than 70% saturation (about 7mg/L) in surface waters and 15% saturation (around 1.5 mg/L) in bottom waters are considered to be low risk (EPA 2010). Less than these values and DO becomes a potential risk to aquatic organisms and conclusions drawn suggest that DO levels of 5 mg/L or less will be a high risk to aquatic fauna (e.g. Corangamite CMA 2012, ANZECC & ARMCANZ 2000 and US EPA 1986).

Therefore, we reviewed the available water quality data (2008 – 2016) for events where the DO fell 5 mg/L or less. While there were around 50 relatively contiguous events, many of these events were only of short duration; far fewer events saw top DO remain at high risk levels for an extended period. Table 8 in Attachment C lists all 18 events over this period when top DO fell below 5 mg/L for more than one day (full time series are provided in Attachment D).

The majority of periods when DO fell into high risk levels coincided with the opening of the estuary mouth or when the estuary mouth was closed (Figure 5). Therefore, this project has focused on:

- the conditions that contribute to an open estuary (section 4 and Attachment E)
- water quality processes occurring while the estuary is closed (section 5 and Attachment C)
- water quality processes while the estuary is in the course of opening.

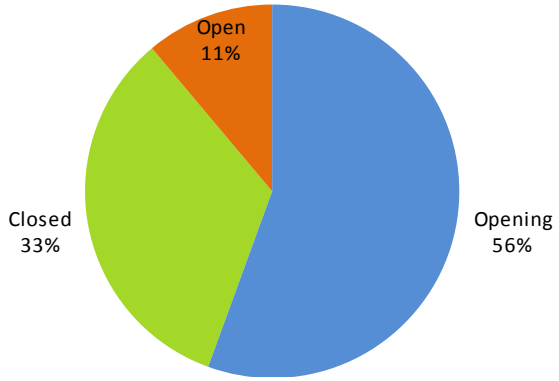

Figure 5. *Percentage of low DO events that the estuary mouth was closed, open or opening (left)*

3.3 Fish death matrix

We have developed a matrix that represents the current understanding of expected fish death response for given DO conditions (Table 1).

The following consequence categories have been developed for fish deaths in the Gellibrand River estuary. These consequence categories are preliminary only and have been developed to guide the investigations and analysis:

- Major (> 75% deaths)
- Moderate (25% - 75% deaths)
- Minor (10% - 25% deaths)
- Insignificant (< 10% death)

Table 1. Fish death matrix

Expected fish death response for given DO conditions		***Duration of dissolved oxygen conditions***		
		< 2 days	*2 – 5 days*	*> 5 days*
Dissolved oxygen (mg/L) in top of water column*	*0 – 1 mg / L*	Moderate	Major	Major
	1 – 3 mg / L	Minor	Minor	Moderate
	3 – 5 mg / L	Insignificant	Insignificant	Minor
	> 5 mg / L	Insignificant	Insignificant	Insignificant

*Note, when considering DO in the top of water column, this is defined as at least 200 mm below the water surface of the water column. Where the top layer of oxygenated water is less 200 mm deep then there will be higher risk of predation and the dissolved oxygen below this top layer should be considered.

4 Estuary entrance dynamics

The Gellibrand River estuary is classified as an Intermittently Closed and Open Lake and Lagoon (ICOLL) estuary, a type of wave-dominated estuary. The Gellibrand River estuary closes intermittently as part of a natural process.

4.1 Entrance closure mechanisms

In general, entrance closure typically occurs during periods of low fluvial discharge when waves dominate over fluvial and tidal processes (see Figure 6). There are two mechanisms of entrance closure in ICOLLs (Ranasinghe and Pattiaratchi, 1999; 2003; McSweeney, 2015):

1. Longshore drift deposition whereby under a weakened ebb-tidal current, longshore drift deposits sediment into the mouth to form a spit across the entrance channel during low river flows (Battalio et al., 2004);
2. Cross-shore transport whereby near shore normal waves gradually transport sediment onshore by cross-shore processes under a weakened ebb-tidal current.

Regardless of the dominant transport process, sediment transport into the estuary entrance occurs at a higher rate during large swells and low river flows (Morris and Turner, 2010; Hanes et al., 2011).

At the Gellibrand River, the dominant process of entrance closure is deposition by longshore drift under a weakened ebb-tidal current. This is evident in year-round oblique direction of approach (dominant wave direction is from SSW – SW), which is indicative of longshore drift as a primary mode of onshore sediment delivery. The rate of deposition increases under large wave heights.

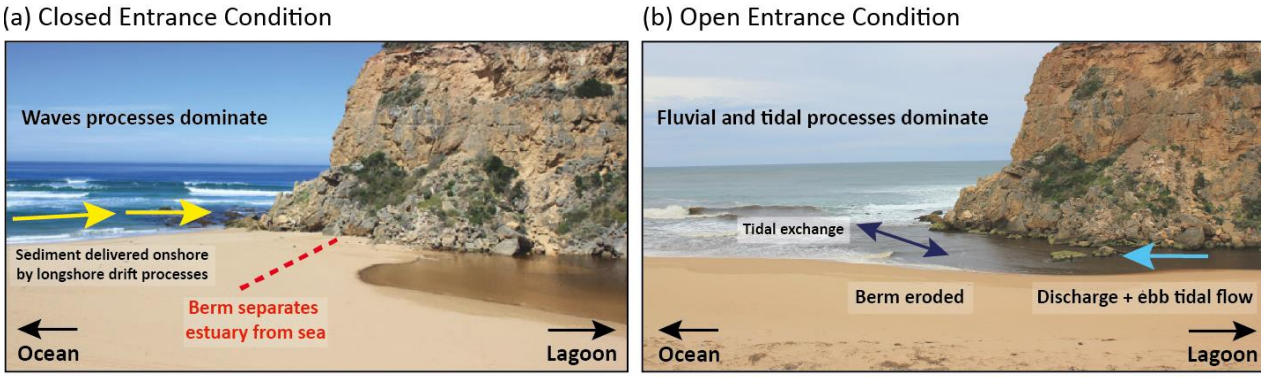

Figure 6. *Conceptual diagram of (a) closed and (b) open entrance states. Photos from EstuaryWatch Victoria (2017).*

Estuary closure generally occurs in the Gellibrand River estuary under three scenarios:

- Seasonal low flow, rapid closure following an opening (typically < 100 ML/day[1], opening duration of days - weeks, occurs during low flow months)
- Seasonal low flow following a long opening duration (typically < 150 ML/day, moderate – low wave heights, opening duration of weeks to months)
- High swells under low-moderate river flow (typically <150 – 300 ML/day, high wave heights, mostly occurs in Autumn)

[1] Note: flows provided based on Burrupa gauge.

4.2 Entrance opening mechanisms

The natural opening threshold refers to the point where the beach berm is overtopped by the water within the estuary basin and a channel is formed which connects the lagoon to the ocean. This is driven by the difference in hydraulic head between the water elevation within the estuarine basin and the height of the berm.

Multivariable linear regression was used to produce an equation capable of predicting the entrance opening duration at the Gellibrand River (see Attachment E). Mean daily discharge (LogMeanDailyDischarge), Wave height (LogSignificantWaveHeight) and Wave direction (WaveDirection) were found to be the strongest predictors of opening duration considering all historic data of marine and fluvial conditions and observed entrance opening durations. The model has an R^2 value of 0.674 meaning it can account for 67.40 % of the variability in entrance opening duration by including these three parameters. The observed vs predicted values of the regression model show good accuracy for entrance openings lasting < 200 days, which constitute the majority of openings occurring at the Gellibrand River Estuary.

4.3 Conditions for prolonged estuary openings

From the data analysed (see Attachment E), conditions which tend to favour a **prolonged open entrance** (i.e. greater than 1 month) include:

- **Daily river discharge:** > 150 ML/day[2] occurring within a week of entrance opening. Sustained high flow following entrance opening will provide energy to maintain erosion of channel sediments deposited by waves.
- **Wave height:** In general, lower waves (< 1.5 m) would reduce the amount of sediment delivered onshore by longshore drift.
- **Wave direction:** < 210 °N or > 225 °N, waves from these directions would reduce the efficiency and rate of longshore drift deposition and berm building at the mouth.

Although the **estuary water depth** is important for the timing of natural openings and for reducing flood impacts within the catchment, it does not dictate the opening duration. The effect of entrance opening is to remove the hydraulic head between the lagoon and the ocean which typically occurs within 48 hours following opening. The fluvial and marine conditions that occur after the lagoon has drained are therefore the critical control on the entrance opening duration.

In contrast, conditions that tend to **close the Gellibrand River Estuary rapidly** ($\leq$ 1 week) include:

- **Low daily river discharge:** <100 ML/day typically occurring between low flow months (December - April).
- **Large wave height:** Higher waves (> 1.5 m) would increase the longshore drift rate and berm building more rapidly provided river flow remains low. Note though, if fluvial discharge is high deposition from large swells is likely to be counteracted by the increased ebb-tidal prism i.e. there is a greater volume of water flowing from the estuary to sea on the transition from high to low tide.
- **Wave direction:** 210 – 225 °N (SSW – SW). This wave direction will increase the rate of deposition from longshore drift.

[2] Note: flows provided based on Burrupa gauge.

Table 2. Estuary Entrance Dynamics

	Expected estuary opening period after artificial opening	
Conditions during opening	*< 1 week*	*> 1 month*
River discharge (Burrupa gauge)	*< 100 ML/day*	*> 150 ML/day*
Wave height	*> 1.5 m*	*< 1.5 m*
Wave direction	*210 – 225* °N (SSW – SW)	< 210 °N or > 225 °N (SW – W or SSW – SE)

5 Water quality investigation

Water quality investigations were undertaken for two scenarios:

- During periods when the estuary was closed
- During estuary openings (natural or artificial)

The investigations focused on (top) dissolved oxygen (DO) as it is considered the most important water quality parameter in terms of healthy estuarine ecosystems and fish deaths. The investigation sought to identify the estuary conditions that led to low DO levels and potential fish deaths.

The main explanatory variables considered were: catchment inflows, estuary water level, water temperature and maximum daily air temperature. These factors were selected based on a multivariate analysis of factors that can predict DO levels in the estuary (see Attachment C).

Full details of the water quality investigation are provided in Attachment C.

5.1 Analysis of DO decline during closed periods

The Gellibrand River estuary closes as a result of a combination of low catchment flows and wave action that results in berm accumulation.

When estuary entrances are closed, the build-up of water behind the sand berm can cause inundation of low-lying floodplain areas. The limited flushing and turnover of the water in closed estuaries under low flow conditions, can lead to a decline in water quality conditions and pose a risk to aquatic ecosystems.

The water quality investigation examined 16 closed estuary events from the 2008 – 2016 period where DO fell below 5 mg/L i.e. the top water DO condition considered to represent the onset of water quality risks. The purpose of the investigation was to identify the processes driving the decline in top DO during estuary closure. This investigation identified three key processes that appear to largely explain the decline in the top[3] (i.e. surface waters) DO concentration during estuary closure, these being:

- Estuarine flora respiration and photosynthesis (Process A)
- Catchment inflow resulting in mixing of the water column (Process B)
- Catchment inflows delivering high organic load (Process C).

These three processes can occur independently of each other, or in some circumstances will occur simultaneously producing a complex response in top DO. The three processes are summarised below and described in more detail in Attachment C.

Process A – Estuarine flora respiration and photosynthesis
Like all plants, estuarine flora (including planktonic algae, epiphytic algae and rooted macrophytes) in the Gellibrand estuary produces carbon dioxide through respiration at all times, but during the day (when there is light) will use carbon dioxide to produce oxygen (O_2) through photosynthesis. When present in significant amounts estuarine flora will reduce the DO content during dark periods (due to respiration) but increase DO during light periods (when photosynthesis offsets their respiration).

The presence of flora in the Gellibrand estuary can be readily identified by examining the diurnal variation in top DO. Estuarine flora will be alive and present in significant quantities (that is, biomass) when DO levels vary from day to night; conversely an absence of diurnal variation indicates an absence of significant quantities of living estuarine flora. The amplitude of the diurnal variation in DO (i.e. the degree of variation) is a product of the amount of photosynthesis occurring, which is driven largely by the quantity of estuarine flora and duration of bright sunlight.

[3] These processes are identified for DO declines in the top of the water column only, not the bottom of the water columns, which can undergo different processes.

A fall in top DO due to this process is typically associated with a recovery to the pre-fall DO levels following a return to sunnier conditions. Although variable, such falls were found to involve a drop and subsequent recovery of approximately 4 mg/L in the Gellibrand River estuary and a subsequent return to pre-fall DO levels. This process therefore tends not to result in prolonged high levels of risk to instream fauna, unless occurring when DO levels are already approaching low levels. However, repeated cycles of cloudy conditions do tend to produce a gradual lowering of DO levels over a timescale of weeks.

Declines in DO arising from this process are most pronounced when estuarine flora is in high quantities (i.e. there is a large amount of respiration occurring), and weather conditions change sharply from sunny to cloudy conditions (i.e. very little photosynthesis occurs).

Process B – Catchment inflow resulting in mixing of the water column

A spike in inflows from the catchment to a closed estuary can result in mixing (partial or complete) of the water column. This mixing includes between the vertical layers in the channel itself and lateral mixing between the channel and the floodplain. If the estuary is highly stratified prior to inflows, it is likely that the top DO levels will be substantially higher than bottom DO levels. In this case, mixing of the top and bottom water will result in a decline of the top DO levels. Alternatively, the floodplain waters are often likely to be lower in DO due decomposition of organic matter. In this case, lateral mixing between the channel and floodplain will result in a decline in the DO levels throughout the channel.

A fall in top DO due to this process is typically associated with a recovery to the pre-fall DO levels following the peak in catchment inflows. Although variable, such falls in top DO tend to involve a drop and recovery of approximately 3 mg/l. This process therefore tends not to result in prolonged high levels of risk to instream fauna, unless occurring when top DO levels are already approaching critically low levels.

Such mixing was found to occur when inflows were increased by more than 20ML/d over a period of hours. This typical increase in flow was identified from monitoring data available from 2008 - 2016 (see drop events number 1 and 12 shown in Attachment D).

Once the estuary develops stratified conditions there is a common trajectory of declining bottom DO levels, which results in an increasing likelihood that top DO levels could be adversely impacted by a mixing event.

Process C – Catchment inflows delivering high organic load

A spike in inflows from the catchment to a closed estuary is often expected to deliver freshwater with a higher DO level than the estuary, and produce an increase in DO. While there is evidence of this occurring within the Gellibrand estuary, there is also evidence of events where DO has declined in association with very high inflows. The decline in these situations is expected to arise from the catchment inflows having a high organic load, which results in increased bacterial activity in the estuary waters, leading to deoxygenation of the water. The severity of such events is determined by the amount, age and type of organic material imported into the estuary, and whether it has been previously submerged in water.

Process C can be differentiated from process B in the timing of the events. Process C will occur with a high flow event after a long drought period. This timing is consistent with findings regarding blackwater events in other systems (see CEWO 2016).

A fall in top DO due to this process has not been associated with an immediate recovery in DO levels. In both examples on record, the DO levels fell by 5-7 mg/l during this event and did not recover. This process therefore has a high likelihood of resulting in high levels of risk to instream fauna, particularly when DO levels are not at the maximum point of saturation.

The amount of organic load delivered into the estuary (and therefore the DO decline) will be higher when high flows occur after prolonged dry periods and there has been an extensive build-up of organic material such as leaf litter in the catchment. The level of bacterial response (and therefore the DO decline) to the increased organic load will be accentuated when air and water temperatures are high.

Summary of closed estuary processes
A risk matrix has been developed that considers the three processes that have been identified to drive top DO in a closed estuary. The risk matrix is set out in Table 3.

A decision diagram has also been developed, refer Attachment C (Figure 16).

This simplified matrix is based on the premise that one of the three processes is likely to be most influencing DO at any point in time, although in reality, it is possible that such processes will be interacting and producing a complex response.

The risk matrix provides the antecedent conditions to identify which process could be occurring and also the risk factor associated with each process, which will potentially cause a drop in DO. Likely drops in DO and duration of low DO is provided in the matrix to identify the risk during estuary closure periods, based on DO conditions on any given day.

Of these three processes, DO declines have most commonly been associated with estuarine flora respiration and photosynthesis, but these tend not to produce high risk outcomes. Although occurring least often, the DO declines resulting from high organic load delivery from the catchment have caused the greatest reduction in DO levels during estuary closure periods.

While top DO does tend to decline over an extended period of estuary closure, top DO rarely falls to levels that pose a high risk to instream fauna when the estuary is closed, and when they do, recovery generally occurs within 48 hours. We do acknowledge that the data set has been influenced by artificial openings and that such openings may have prevented low DO conditions that can occur with extended estuary closure periods. While it is not possible to have a dataset free from intervention as the estuary is currently managed for multiple outcomes, the available dataset still provides a useful indication of typical drops in DO associated with processes occurring in a closed Gellibrand River estuary.

Table 3. Closed estuary water quality processes

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

5.2 Analysis of DO decline associated with opening

After an estuary is opened, the main driver for the resultant DO is the degree of mixing with other water sources. The following water sources can cause either an improvement or decline in DO conditions:

- **Tidal interchange** brings in sea water that is high in DO. The amount of tidal interchange is dependent on an opening event with good scour through the mouth

- The water from the **estuary floodplain** is generally low in DO and is a risk to DO levels where the floodplain drains quickly into the estuary without mixing from an additional water source.

- **Catchment inflows** are generally a source of well-oxygenated water while occasionally there is low DO conditions from the catchment (i.e. a blackwater event, see CEWO 2016). Higher catchment inflows generally increase mixing, and reduce floodplain draining effects.

The water quality investigation examined the characteristics of 24 events in the 2008-2016 period where a fall in DO was associated with an estuary opening event (see Attachment C and Attachment D). The purpose of the investigation was to identify the conditions that led to decline in top DO.

The analysis identified that the potential for DO to fall to critical levels during an estuary opening event is influenced by two key factors:

- DO levels prior to opening, in both the top and bottom of the water column

- Degree of mixing of the water column resulting from the opening, which is a product of inflows from the catchment and/or the development of tidal interchange.

In addition to these two key driving factors, a number of additional parameters appear to interact to provide a secondary influence on DO response after openings. These secondary parameters include:

- Whether the opening occurred naturally or artificially, where natural openings tend to provide better DO outcomes

- Whether the opening coincided with cooler air and water temperatures (which is largely driven by the time of year of the opening) - cooler conditions tend to provide better DO outcomes

- Whether water levels in the estuary fell rapidly or slowly following opening (which appears to be largely driven by the height of the estuary prior to opening) – rapidly (1 m drop in ~24 hours) or slowly (1 m drop in ~72 hours) draining conditions tend to provide lower DO outcomes than medium draining conditions (1 m drop in ~48 hours)

- Whether the opening coincided with high catchment inflows, where high inflows tend to provide better DO outcomes than low inflows.

The key factors for the drop in DO associated with an estuary opening are provided in the matrix below (Table 4). The matrix represents the expected change in DO associated with an estuary opening for the catchment inflow and water level conditions. It is important that this matrix be used in conjunction with a starting DO value (which can be identified using monitoring data or predicted using Table 3).

Catchment inflows and water level in the estuary were selected for the matrix to represent the mixing and different water sources as described above. The different water sources are represented in the following ways:

- **Tidal interchange** is represented by the water level in the estuary (higher water level will lead to greater scour and therefore greater tidal interchange).

- The amount water from the **estuary floodplain** that drains into the main channel is represented by the water level in the estuary and catchment inflows.

- **Catchment inflows** generally increase mixing, and reduce floodplain draining effects

Table 4. Expected water quality declines during an estuary opening

Expected reduction in DO during an artificial opening (mg/L)		***Catchment inflows*** (measured at South Otway Pump Station)		
		> 150 ML/d	*100 – 150 ML/d*	*< 100 ML/d*
Water level elevation in estuary (measured at Princetown gauge)	*> 1.55 m*	*4 -5 [2]*	4 – 8 [3]	3 [1]
	1.4 – 1.5 m	*3 – 5 [3]*	3 – 6 [4]	3 – 4 [3]
	< 1.4 m	*2 – 3 [4]*	3 [1]	4 – 7 [2]

*Range of DO drop for 2008 – 2016 events shown, with sample size provided in brackets

6 Proposed framework and management options

6.1 A framework for estuary openings

Based on the result of this investigation a framework has been developed to guide estuary openings. The framework applies the results of the investigations undertaken for this project.

The objective of this framework is to minimise the potential impact on the environment arising from water quality declines. This framework recognises that the estuary is only artificially opened to protect human assets. The framework does not attempt to guide decisions on whether human assets are unacceptably impacted by estuary water level or quality; rather it guides decisions on the environmental consequences of a potential opening. This framework is therefore intended to be applied alongside implementation of the EEMSS.

Figure 7 steps through the decision process for managing water quality issues during both estuary closure periods and artificial estuary openings. Alongside the decision process, supporting management actions are provided in the purple boxes.

There are three main considerations outlined in the framework:

- What is the DO risk if the estuary remains closed?
- What is the DO risk if the estuary is artificially opened (and is this risk greater or less than the risk if it remains closed)?
- If an artificial estuary opening is proposed, will the estuary remain open and for how long?

The matrices arising from the investigation set out in this report have been incorporated into the estuary opening framework. They are presented in Figure 8 below.

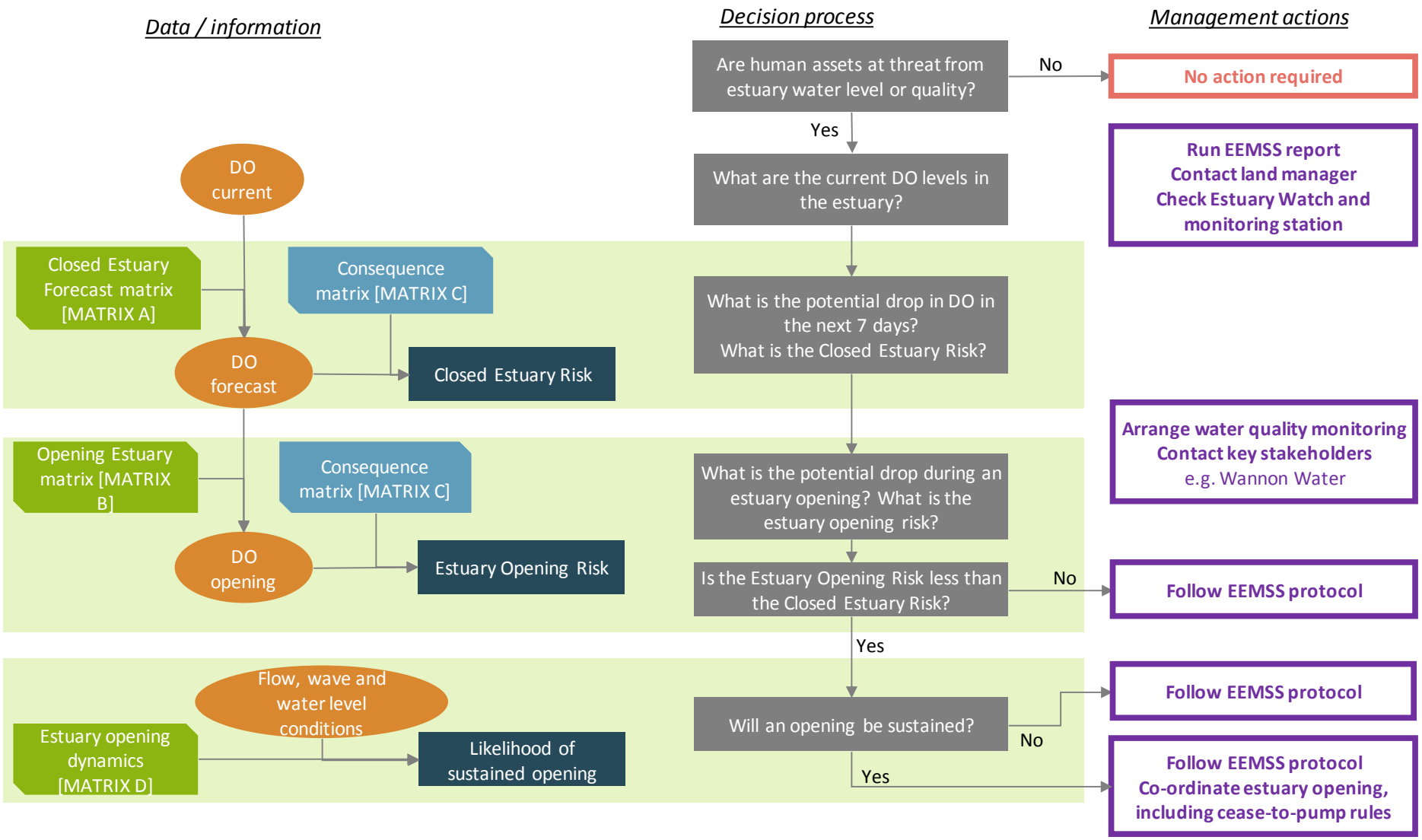

Figure 7. *Decision framework for using available data to inform estuary management*

Matrix A – Closed Estuary Forecast Matrix

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

Matrix B – Opening Estuary Matrix

Expected reduction in DO during an artificial opening (mg/L)		*Catchment inflows* (measured at South Otway Pump Station)		
		> 150 ML/d	*100 – 150 ML/d*	*< 100 ML/d*
Water level elevation in estuary (measured at Princetown gauge)	*> 1.55 m*	4 -5	4 – 8	3
	1.4 – 1.55 m	3 – 5	3 – 6	3 – 4
	< 1.4 m	2 – 3	3	4 – 7

Matrix C – Consequence matrix

Expected fish death response for given DO conditions		*Duration of dissolved oxygen conditions*		
		< 2 days	*2 – 5 days*	*> 5 days*
Dissolved oxygen (mg/L) in top of water column	*0 – 1 mg / L*	Moderate	Major	Major
	1 – 3 mg / L	Minor	Moderate	Moderate
	3 – 5 mg / L	Insignificant	Insignificant	Minor
	> 5 mg / L	Insignificant	Insignificant	Insignificant

Matrix D – Estuary opening dynamics

Conditions during opening	*Expected estuary opening period after artificial opening*	
	< 1 week	*> 1 month*
*River discharge *Burrupa gauge*	*< 100 ML/day*	*> 150 ML/day*
Wave height	*> 1.5 m*	*< 1.5 m*
Wave direction	*210 – 225* °N (SSW – SW)	< 210 °N or > 225 °N (SW – W or SSW – SE)

Figure 8. *Decision support matrices to inform estuary management*

6.2 Flow management to assist estuary openings

Catchment inflow is an important factor in the success or otherwise of estuary openings, increasing the duration of an opening and water quality outcomes from an opening.

Wannon Water currently manages extractions from the Gellibrand River at two locations: South Otway pump station and North Otway pump station. There are currently extractions of up to 19 ML/day at the South Otway pump station and up to 17 ML/day at the North Otway pump station.

As presented in section 2.2, one of the short-term management actions available for the Gellibrand River estuary is to reduce the extractions for short periods of time, e.g. 2 days. The South Otway pump station extractions may be halted (19 ML/day to 0 ML/day), while the North Otway pump station may be reduced to 6 ML/day (from 17 ML/day). Combined, the reduced extractions can increase the flow rate by up to 30 ML/day (or a volume of 60 ML for two days), depending on the timing between the two pump stations.

Temporary cessation of extractions can be used to support estuary management by increasing the flow during estuary openings.

Optimal timing of increased flow

There are opportunities and risks associated with the timing of a peak flow delivery to the estuary mouth around an estuary opening event. We have identified four risks / opportunities to be considered:

- Risk of mixing a stratified estuary, which causes top DO levels to drop (Process B for closed estuaries)
- Risk of interfering with machinery used for artificial estuary opening
- Opportunity to support sustained estuary opening (scour out channel)
- Opportunity to provide source of oxygenated water into estuary and reduce impact of floodplain water

These risks and opportunities have different impacts during the three different time periods for delivery (before, during and after opening), the assessment of these risks and opportunities is presented in Table 5. Therefore, the delivery of flows timed to arrive within 12 hours after an estuary opening is recommended.

Table 5. Timing of flow management to assist estuary openings

	Expected timing of increased flow at estuary		
Opportunities and risks of increased flow	*Within 24 hours before opening*	*At time of opening*	*Within 24 hours after estuary opening*
Risk of mixing a stratified estuary, which causes top DO levels to drop (Process B for closed estuaries)	✗	-[1]	N/a
Safety risk to machinery operator during artificial estuary opening	-[1]	✗	-[1]
Opportunity to support sustained estuary opening (sour out channel)	N/a	✓	✓
Opportunity to provide source of oxygenated water into estuary and reduce impact of floodplain water	N/a	-[2]	✓

*✗ = risk factor, ✓ = opportunity, - = Limited impact

Note 1: Only a risk where the timing of the flows is different than planned.

Note 2: During the estuary opening, estuary water level is not yet decreasing and draining effect is not relevant.

Note than when considering timing for flow releases and artificial estuary openings, where there are diurnal fluctuations in the dissolved oxygen levels related to the abundance of estuarine flora ('Process A'), it is best to

schedule the estuary opening in the afternoon where the DO levels would be the highest for that 24-hour period.

Travel time from pumping stations
We have used two approaches to consider the travel time between the extraction points (North and South Otway pump stations) and the estuary mouth:

- estimating typical velocities
- analysing the offset between different gauges for peak flow events.

As reducing flow extractions will generally be used when the estuary is closed, the travel time between Burrupa (upstream extent of the estuary) and the estuary mouth is not considered here.

The travel times are presented in Table 6. While they provide relatively similar results, we recommend using the estimates based on the flow gauge analysis as they are based on empirical observations specifically from the Gellibrand River. Note that the flow gauge analysis is based on natural events where there is likely to be inflows from tributaries which would increase attenuation and potentially increase the travel time of the peak. As the proposed management option is not a natural event, the travel times may be slightly quicker. See Attachment F for the full analysis.

Table 6. Indicative travel times from north and south pump stations

Reach	Distance	Typical velocity	Estimated travel time (velocity of 0.5 m/s)	Estimated travel time (flow gauge analysis)
South Otway pump station to Burrupa gauge	16,858 m	0.5 m/s	9 hours	12 hours
North Otway pump station to South Otway pump station	23,761 m	0.5 m/s	13 hours	20 hours

In light of an approximate 12-hour travel time, and in recognition of the recommendation above that higher flows be timed to arrive within 12 hours after an estuary opening, it is recommended that artificial openings should coincide with ceasing extraction at South Otway pump station.

6.3 A trial estuary opening

A trial estuary opening was undertaken using the preliminary results of this investigation.

Conditions prior to the release are set out below. The estuary had been closed for 2.5 weeks and there was evidence of closed estuary 'Process A - estuarine flora respiration and photosynthesis' occurring (see Figure 10).

Parameter	Result prior to opening (8th March 2017, 9am)
Top DO	6.6 mg/L
Water level (Princetown)	1.394 m
Flow rate (South Otway pump station)	56 ML/d
Estuary condition	Closed
Expected DO and risk level (no opening)	2mg/L, <1 day (if cloudy conditions) Minor risk level
Expected DO and risk level following opening without increased flow	0 – 1 mg/L, <2 days Moderate risk level

For the purpose of the trial, extractions from the North and South Otway pump stations were reduced for two days. Extractions were reduced from 7:30am on 8th March 2017 resulting in an increase of 19 ML/d inflow to the estuary over a 2-day period.

In this case, the additional inflow would not change the expected DO and risk level (according to Table 4 and Table 1); however, the increased flow does push the scenario towards the higher flow categories (in Table 4, from the bottom right box towards the bottom centre box), which would be expected to have a lower drop in DO.

At 4 pm on 8th March 2017, the berm at the estuary was observed to be opening with minimal flow (Figure 9 – top) and two days later on 10th March, the mouth was scoured out and the estuary water level started to decrease (Figure 9 – bottom). The recorded DO and water levels for this event are shown in Figure 10. The two-day difference between the opening of the mouth and the decrease in water levels represents the time taken for the mouth to scour out and full exchange between the estuary and the ocean to develop. This is the transition from a 'closed estuary' to an 'open estuary'.



Figure 9. *Estuary mouth during trial period – 9th March looking upstream (top) and 10th march looking downstream (bottom) [Source: EstuaryWatch / Judy Spafford]*

Details of the flow release and estuary outcomes are set out below:

Parameter	Result after / during opening
Minimum top DO	0.5 mg/L (11/03/17)
DO risk category	Moderate (< 1mg/L for 1 day) to Minor (1-3 mg/L for <2 days)
Duration of opening	2 weeks (closed ~ 21/03/17)

In this case, it appears that the combination of water level, low berm height, wave and wind conditions lead to the beginning of the estuary opening (8/03/2017) without the need for mechanical intervention.

The increase in flow can be seen in the Burrupa water level around 12 hours after the extractions ceased (see Figure 10 – purple circle). This increase in water level was 0.03 m and lasted approximately 48 hours. This increase is in the same order of magnitude of the expected rise of 0.01 – 0.02 m for the additional volume on top of the existing inundation extent and inflows.

It is likely that the increase in flow delivered to the estuary on the 9-10th March may have assisted in the scouring of the estuary mouth and reduction in estuary water level to around 0.6 m by the 13th March.

There was a drop in DO associated with the opening of around 5 mg/L (from 5.5 mg/L to 0.5 mg/L). Based on the estuary opening matrix (see Table 4 or Figure 8), this event would fall under the lowest water level category (< 1.4 m) and the lowest flow category (< 100 ML/day), which estimates a typical drop of 4 – 7 mg/L. This event is consistent with the predicted drop in DO.

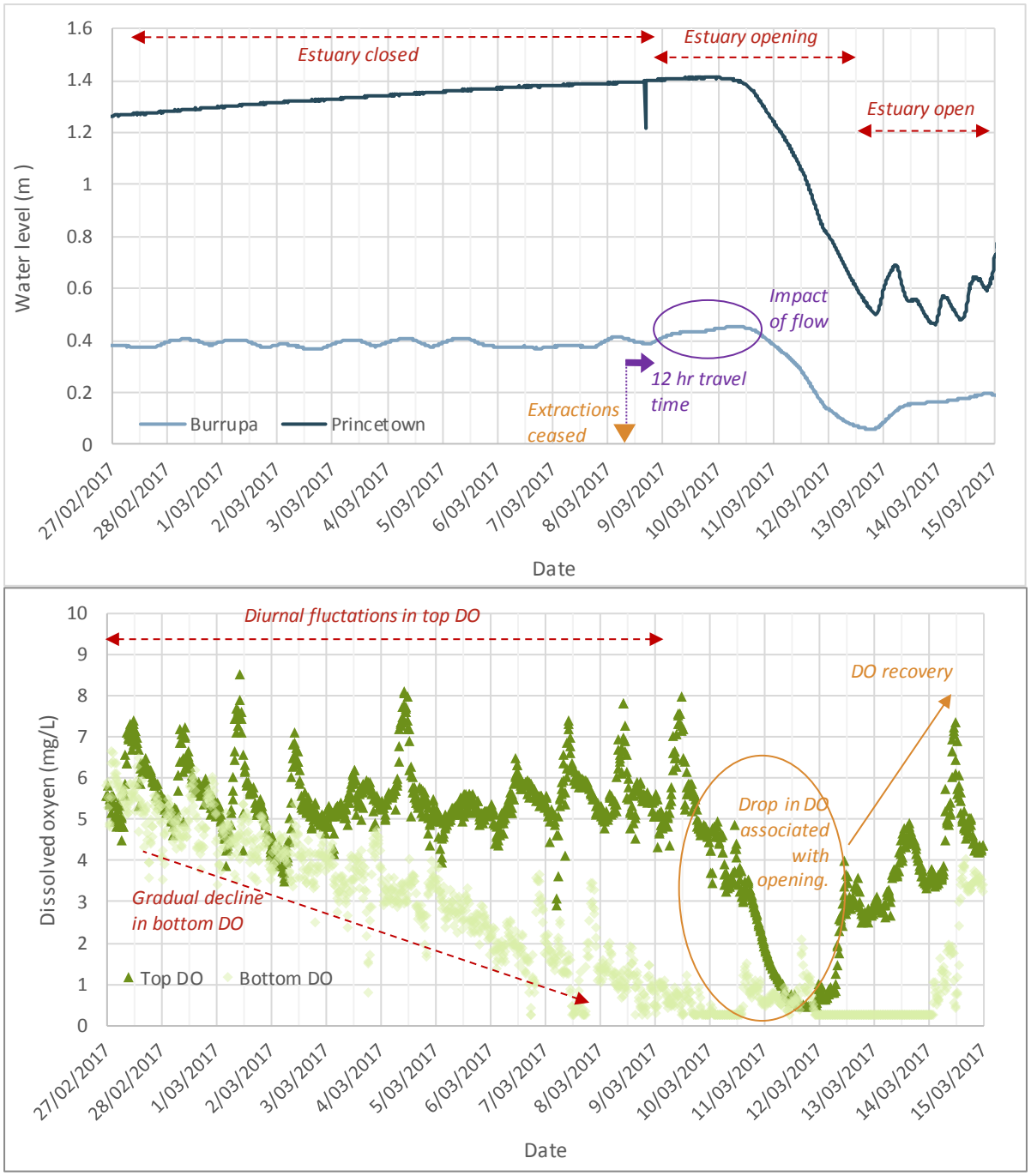

Figure 10. *Water level [top] and DO [bottom] during trial period*

6.4 Recommendations

Application of framework
The results of the analysis including fish death, and the factors that influence the status of the estuary (open or closed) and the water quality in the estuary can be used to assist decisions on artificial openings of the Gellibrand River estuary. The framework developed in this project is intended to help minimise the potential impact on the environment arising from water quality declines. The framework is intended to be applied alongside implementation of the EEMSS.

Monitoring and evaluation
The results outlined in this assessment are based on a limited data set. The data set and the confidence in the results would be enhanced by ongoing monitoring and evaluation of the estuary outcomes (fish deaths and DO) and the factors that influence these outcomes including, inflow rates, inflow water quality, elevation of water in the estuary, and estuary mouth status.

The 15-minute water quality and water level data available at the Princetown gauge was the main dataset used in this investigation. This gauge should continue to be used and additional low DO events and estuary opening events can be used to further improve the decision support matrices (Figure 8). It is important that this data is recorded at regular sub-hourly intervals to ensure that rapid drops in DO levels are identified. In addition to the Princetown gauge, the EstuaryWatch monitoring data is a valuable resource for understanding the processes in the Gellibrand River estuary in particular, understanding the spatial variability of water quality throughout the estuary and the water quality throughout the whole water column. While the EstuaryWatch data is not collected on a high resolution timestep, it should be continued to support the use of the gauge data.

An additional water quality gauge could be considered in a floodplain location to assist in understanding the contribution of low DO water from the floodplain and whether this changes under different conditions. This gauge should be recorded on a sub-hourly timestep (preferably 15-minte intervals) and include the same parameters as the Princetown gauge (water level, dissolved oxygen, salinity and water temperature). The gauge should be placed within an area likely to be contributing to low DO conditions (e.g. within the Estuarine Wetland EVC area, see Figure 3).

As with the water quality datasets, the information on when and under what conditions fish deaths occur can continue to be developed. As there is not a formal database through EPA maintained with this information, we recommend that EstuaryWatch is utilised where possible to record the incidence of fish deaths, and where possible the magnitude the event.

For the estuary entrance dynamics, undertaking regular field measurements of berm elevation would add data to develop a predictive threshold for natural openings. This would involve establishing reference survey markers (ideally relative to m AHD) and using a staff to measure the berm height during each field visit.

River discharge is an important variable in the estuary water quality and the estuary entrance dynamics; however, there are limitations with the discharge information available. Discharge measurements at the Burrupa gauge can be influenced by the estuary water levels, while the rating table for the South Otway Pump Station gauge does not exceed 130 ML/day. The South Otway Pump Station rating table could be improved for larger flow events. The travel time estimates provided in this investigation could also be refined. This could be done by installing water level gauges between the South Otway pump station and the Burrupa gauge.

Long-term extraction management
Given that river discharge is a significant factor in the occurrence of estuary closures (see section 4 and Attachment E), flow management in the Gellibrand River is an important component of the ongoing estuary management. During low flow periods extractions in the catchment make up a significant proportion of the potential inflow to the Gellibrand River estuary. Therefore, we recommend analysis into the impacts of catchment extractions on the frequency of estuary closures during low flow periods and exploration of the means by which extractions can be managed to limit estuary closure and assist the opening of the estuary.

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Attachment A
Gellibrand estuary values

The landscape characteristics, environmental values, threats to values and ongoing management challenges in the Gellibrand River Estuary have been documented in recent reports (and supporting research) including:

- Environmental water requirements of the Gellibrand Estuary: final estuary FLOWS report. (Lloyd et al . 2008)
- Gellibrand River Estuary. An interpreted summary of data. Extract from the Gellibrand River Data Analysis 2007 – 2012. (CCMA 2015)
- Gellibrand River Estuary. Draft Estuary Management Plan. (RMCG 2016).

A snapshot of key background information is provided in the following sections drawn from these reports and additional relevant sources as context to this current investigation. For further information on landscape features and values please refer to Lloyd et al. (2008) and RMCG (2016).

Table 7. Summary of estuary values (from existing sources)

Type	Value	Summary	Management
Environmental	Geomorphic landforms	The natural landforms of the region are widely valued from an aesthetic perspective as well as for ecosystems they support. These include the coastal cliffs, sandy estuary and coastline, extensive floodplains and wetlands backed by the Otway ranges.	Landscape aesthetics recognised as a key value of the landscape in planning
	Vegetation	The endangered Coastal Saltmarsh (EVC 009) vegetation community occurs at the estuary, as well as stands of sea grass meadows and riparian native vegetation providing important habitat for aquatic and semi aquatic fauna. Significant patches of the vulnerable Swamp Greenhood Orchid (Pterostylis tenuissima) occur at the Princetown Wetlands. (RMCG 2016)	Flow requirements for vegetation communities have been identified (Lloyd et al. 2008)
	Fish and aquatic fauna	The Gellibrand River is among Victoria's more important rivers for the conservation of native fish and carries the largest population of Blackfish (Gadopsis marmoratus), and the vulnerable Australian Grayling (Prototroctes maraena) is also present in the Gellibrand River and estuary. RMCG (2016).	Fish are recognised as a key value in planning. Flow requirements for these fish species and other selected species have been identified (Lloyd et al. 2008)
	Wetland fauna	The estuary and the associated Princetown Wetlands provide an important refuge for migratory and non-migratory waterbirds, including the endangered Australian Bittern (Botaurus poiciloptillus). RMCG (2016).	Estuary and Wetlands Management Plan developed in 2001. Wetlands management plan updated in 2005.
Cultural and economic	Indigenous community significance	Indigenous communities have a long association with the Gellibrand River estuary (CCMA 2015). The abundant resources of the lower Gellibrand River were important to two Indigenous communities who occupied the area – the Girari Wurrung tribe to the west and the Kaubanuut tribe to the east. RMCG (2016)	Recognition and collaboration with indigenous communities
	Amenity and recreation	Amongst the local community, the Gellibrand estuary remains highly valued for its opportunities for recreation, relaxation and learning. RMCG (2016) Bird watching, fishing, kayaking, walking and camping are popular pursuits, valued by locals and tourists. The 62ha Princetown (Serpentine Creek) State Game Reserve is a popular duck hunting destination. RMCG (2016).	Amenity is recognised as a key value in planning, including recreation values

Type	Value	Summary	Management
	Agriculture	In the early 1800's when European's settled the area, the fertile alluvial floodplains were sought out for farming and cultivated to grow crops. RMCG (2016) Today, agriculture, is predominately dairy and beef grazing.	Productivity of the landscape recognised as a key value recognised in planning
	Other	The river also provides drinking water to major population centres of Warrnambool, Cobden, Terang and Camperdown (CCMA 2015). The estuary currently supports a commercial eel fishery.	

Attachment B
Fish deaths and water quality

This section provides initial inputs on the influence of dissolved oxygen and water quality parameters on fish deaths in estuaries for the Gellibrand Estuary Low Flow Investigation Project. Fish deaths are notoriously hard to diagnose and can be caused by a range of factors although low dissolved oxygen and other water quality parameters are often high in the list potential causes (EPA 2007).

The aim of this review is to consider how DO (and other water quality parameters) influence fish populations in estuaries and what conditions will lead to fish kills. Other questions relate to whether there are thresholds and if spatial variability of the DO throughout the estuary might influence the occurrence of fish deaths.

Background

This work is to support the development of a model for establishing relationship will be flow and dissolved oxygen. The model will help define under what conditions fish deaths may occur, and under what conditions artificial estuary openings are likely to be successful.

There is a range of water quality data available including information of readings at the top and bottom layers such as dissolved oxygen, conductivity, temperature, turbidity, and pH. While nutrient data might also be helpful in being one of the drivers of high production and therefore potentially leading to situations of low dissolved oxygen but the data is not often available and the relationships are complicated and difficult to model.

Low DO events often occur at the Gellibrand estuary (and other locations) occur when water levels drop quickly after an opening associated with a long closure with water levels are high and extend into the surrounding estuarine wetlands which sometimes have very low DO or develop it late in the season. Following the opening event, the water from the surrounding wetland brings a large quantity of low DO into the estuary. This water sits on the surface (being fresh water) and blocks access to the normally well-oxygenated surface layer. Therefore, oxygen levels in both layers is important for fish health but low dissolved oxygen in surface layers will often drive fish kills. This situation occurs more often in estuaries than freshwaters because saline waters are heavy and freshwater sits on top of the saline wedge. While dissolved oxygen is the critical factor but temperature and salinity can also result in stratified water columns which also leads to low dissolved oxygen. Stratified water columns can lead to dissolved oxygen problems can build up in bottom layer and when "turn-over" events and the whole water column become de-oxygenated and this results in fish kills.

Turbidity and pH are less important in fish kills but can cause issues in extreme situations. Turbidity indicates levels of suspended sediments which can smother eggs and gills and high or low levels of pH may result in release of toxicants which are stored in sediments but these are likely to be rare events.

Role of Dissolved Oxygen in Fish Biology in Estuaries

Apart from pollution events (which in itself is a multiple processes) the EPA has assessed that low dissolved oxygen is the highest likely cause of fish deaths in Victoria (EPA 2007).

The EPA review showed that most fish kills occurred in summer but as they investigation and records show this was during the millennium drought, so this has exacerbated the role of dissolved oxygen and temperature. Significantly, the review showed that marine and estuarine fish made up about 45% of the fish deaths (with bream and flathead being the majority of these). The series of eel deaths in Victorian waterbodies 2005 were from decreasing water quality conditions beyond the tolerances of eels in the millennium drought, not dissolved oxygen alone (EPA 2007).

Native freshwater fish seem to have higher tolerances than introduced freshwater fish (with carp being the most common fish observed dying) and higher than estuarine fish which can be sensitive to low oxygen levels. That said, many native fish are able to survive in very low levels of dissolved oxygen (such as ~1mg/L in the case of one species but often 2 mg/L) as long as the fish have access to the surface layer of water which is often supersaturated with oxygen (McNeill and Closs 2007; Raadik and Hindell 2008).

Other causes of low dissolved oxygenation are illustrated by figure 1 and show multiple factors, some of which interact, are important in the processes concerned.

The key factors which affect dissolved oxygen (O2) levels in bottom waters of estuaries are:

- Photosynthesis – the major physical factor influencing areas of estuaries where photosynthesis is possible is light penetration. Net photosynthetic production often results in daytime peaks of dissolved oxygen.
    - Oxygen Demand – regulated by a combination of features including respiration by bacterial, plant and animal communities (both benthic and pelagic),
- Chemical oxidation of metals which diffuse from anoxic sediments.
- Exchange of oxygenated surface waters and or marine waters due to wind, tidal and river-generated turbulence.

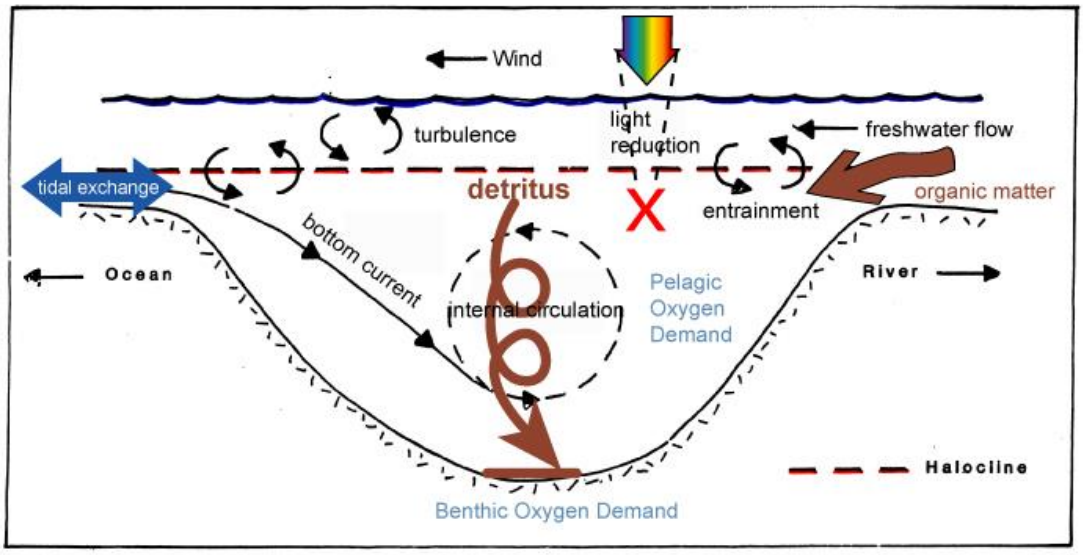

Figure 11. *Schematic diagram of factors influencing oxygen demand in bottom waters (Sherwood and Pope 2008)*

Temperature and nutrient levels along with stratification are also important factors as these led to high growth of plants or algae (Arundel et al. 2009; Sherwood and Pope 2008; Coleman et al. 2011). Low flow can also result in low DO mediated release of nutrients, sulphides or ammonia or other toxicants which affect fish and can cause fish kills (Arundel et al. 2009; Pope, 2006).

In the Yarra River, there was a strong relationship observed between low flow and low dissolved oxygen (Coleman et al. 2011) resulting from both observations and detailed modelling. Coleman et al. (2011) showed that long spells of de-oxygenated water can occur over summer, stretching into early autumn with shorter spells at other times.

Low dissolved oxygen events also affect fish behaviour as fish tend to congregate around shallow areas of relatively high dissolved oxygen when deeper waters had low oxygen levels (Coleman et al. 2011).

Other conditions which cause low dissolved oxygen levels can occur with limited tidal input in wave-dominated estuaries, making them more prone to hypoxic events (Arundel et al. 2009).

Dissolved oxygen is very variable along and across estuaries (Sherwood et al. 2005) and is driven by the residence time of water within an estuary (Figure 2).

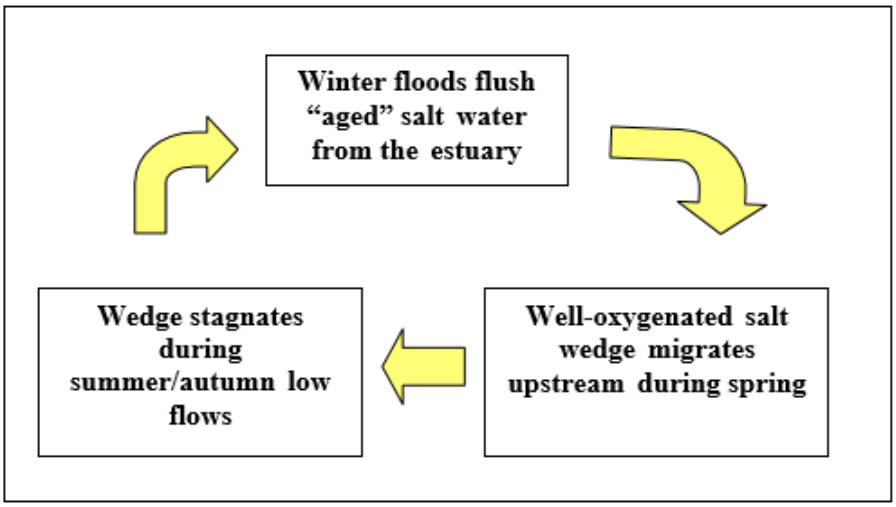

Figure 12. *Processes leading to low DO levels in estuaries (Sherwood et al. 2005)*

Flushing flows (high flow freshes) are very important in removing areas of low oxygenated water (Sherwood et al. 2005, Lloyd et al 2008).

These factors have been assembled into a comprehensive driver-stressor model to explain the factors leading to fish kills in the Gellibrand estuary (Figure 3).

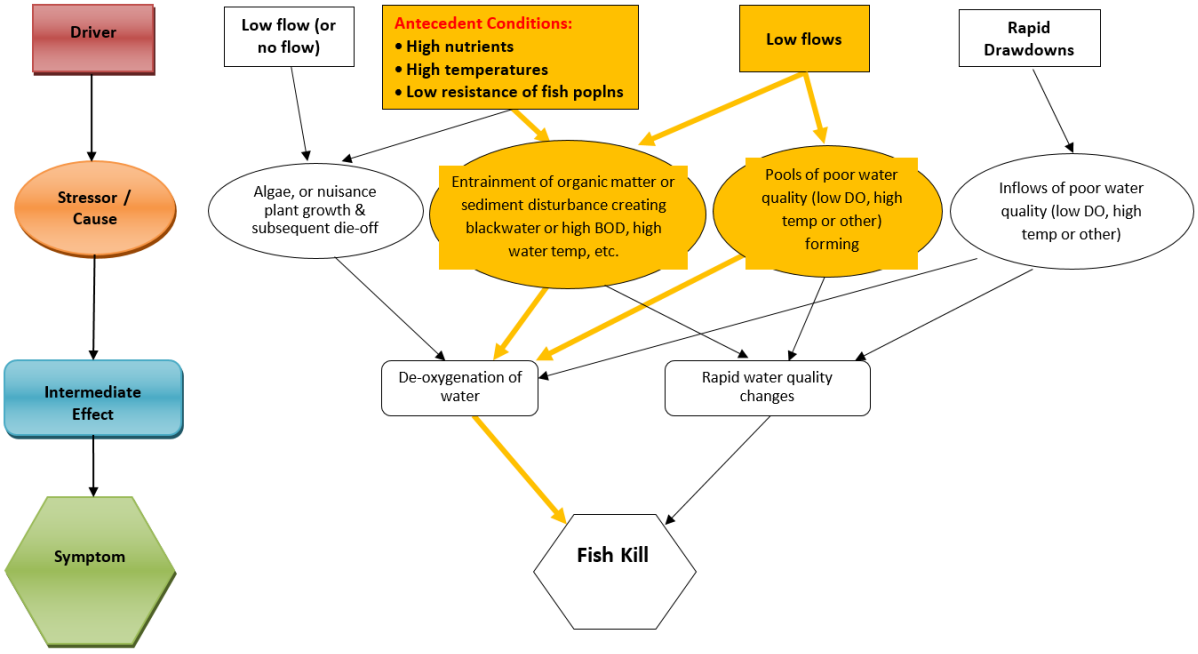

Figure 13. *Driver-Stressor Model of low dissolved oxygen levels causing fish kills*

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Attachment C
Water quality investigation

Scope of the investigation

This section investigates the processes influencing dissolved oxygen (DO) levels in the Gellibrand estuary, with a specific focus on understanding the conditions that lead to declines in DO to levels that pose a high risk to instream fauna. The investigation has not sought to understand or describe the conditions that give rise to average or high DO levels, as this is not an area of management concern at this stage.

The investigation is focused on the drivers of DO decline under two scenarios:

- When the estuary mouth is closed
- When the estuary mouth has recently opened

The processes driving DO decline when the estuary mouth has been open for some time was beyond the scope of this work.

Furthermore, the investigation has largely focused on the DO response in the top of the water column in recognition that bottom levels are more variable primarily due to the presence of a halocline that effectively cuts of the bottom waters from re-oxygenation from the air and at times will also be cut off from marine water interchange when the mouth is closed. This makes it harder to predict DO levels for the bottom waters. While bottom DO values have been plotted and examined, they have been largely considered as an explanatory variable that influences top DO, rather than a response variable in their own right.

The investigation of DO levels primarily drew upon temporal analysis of data from the Princetown gauge since late 2008 through to late 2016. Over this period this gauge has sampled dissolved oxygen, water temperature, salinity and water level at 15 minute intervals. These variables have been sampled at two points in the water column and thereby provide data on conditions in the 'top' and 'bottom' of the water column.

Overview of temporal patterns in DO

Dissolved oxygen levels in the Gellibrand estuary tend to follow a relatively consistent pattern throughout the year, with levels rising during the winter/spring period and declining during summer/autumn (Figure 14). Over the sampled period almost all instances when DO fell into a range that presents a high risk to instream fauna occurred during the summer/autumn period, and specifically, the six months from December through to May inclusive. In light of this, the investigation focused on DO levels from December to May for each year from 2008/09 to 2015/16 – all the 15 minute DO readings for this period are plotted in Attachment D.

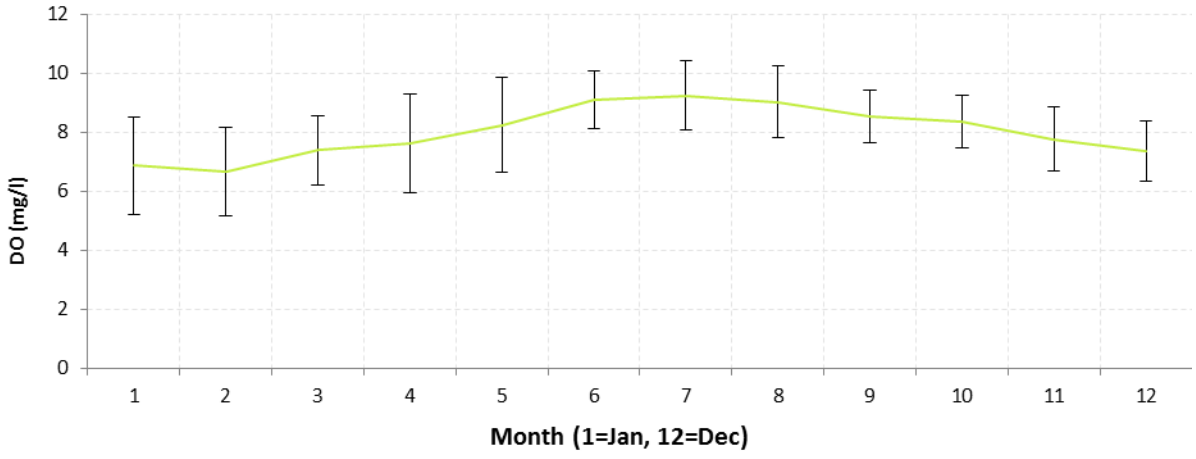


Figure 14. *Mean top DO in each month with bars showing ± one standard deviation*

An initial review of Attachment D identifies that from 2008/09 to 2015/16 there were many instances when top DO levels fell to values posing a high risk to instream fauna (approximately 50 relatively contiguous events). Fortunately, many of these events were only of short duration; far fewer events saw top DO remain at high risk levels for an extended period. Table 8 lists all 18 events over this period when top DO fell below 5 mg/l for more than one day.

A stand-out finding from Table 8 is that the majority of periods when DO fell into high risk levels coincided with the opening of the estuary mouth (Figure 15). Furthermore, the vast majority of the openings that coincided with a fall in DO to high risk levels were created artificially. These findings suggest that artificial opening of the estuary mouth is likely to produce a higher risk to instream fauna than would have occurred without an opening. To further explore this issue, the gauged DO data was further examined to focus on:

- DO decline during periods when the estuary mouth was closed
- DO decline associated with opening of the estuary mouth

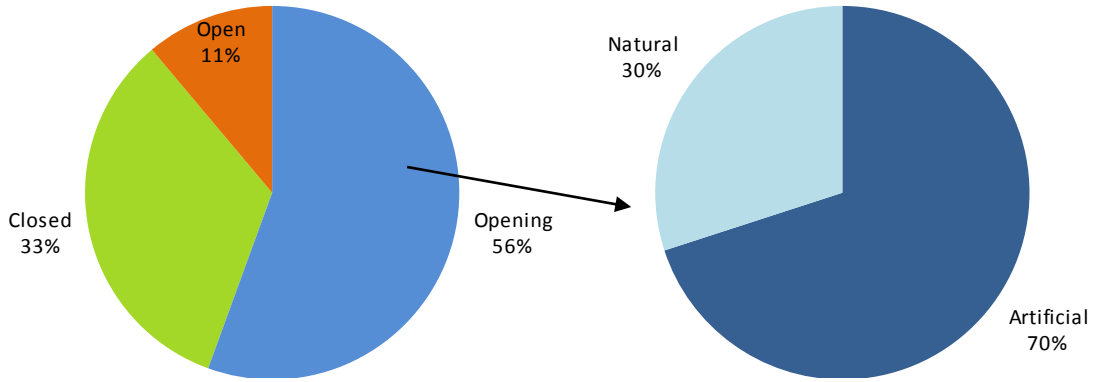


Figure 15. *Percentage of low DO events (in Table 8) that the estuary mouth was closed, open or opening (left) and for the low DO events associated with an opening, percentage of events that the estuary was opened artificially or naturally (right)*

Table 8. Periods from 2008/09 to 2015/16 when top DO fell below 5 mg/L for more than one day

Starting date	Approximate duration with top DO below 5 mg/l	Mouth status	Opening type
18 Mar 2009	3 days	Immediately following opening	Artificial
19 May 2009	4 days	Immediately following opening	Natural
08 Dec 2010	2 days	Open (mouth opened ~ 6 months prior)	n/a
14 Jan 2011	10 days	Open (mouth opened ~ 7 months prior)	n/a
17 Jan 2012	3 days	Immediately following opening	Natural
16 Feb 2012	2 days	Immediately following opening	Natural
15 Apr 2012	3 days	Immediately following opening	Artificial
16 Feb 2013	6 days	Closed (mouth closed ~40 days prior)	n/a
22 Feb 2013	5 days	Immediately following opening	Artificial
13 Apr 2013	5 days	Prior to and immediately following opening	Artificial
11 Apr 2014	2 days	Immediately following opening	Artificial
12 Jan 2015	6 days	Immediately following opening	Artificial
25 Jan 2015	7 days	Closed (mouth closed ~2 days prior)	n/a
07 Mar 2015	2 days	Closed (mouth closed ~3 days prior)	n/a
02 Dec 2015 – 22 Dec 2015	8 days	Closed (mouth closed ~ 10 days prior)	n/a
28 Jan 2016	6 days	Closed (mouth closed ~10 days prior)	n/a
12 Mar 2016	2 days	Immediately following opening	Artificial
08 May 2016	3 days	Closed (mouth closed ~35 days prior)	n/a

Spatial variability of water quality data

Spatial analysis of DO levels has identified that when the top DO level at Princetown is 6 mg/l or less, the DO levels in the top of the water column elsewhere in the estuary are expected to be higher than that at Princetown. The Princetown top DO readings are likely to provide a 'worst-case' representation of top DO levels in the estuary, and in turn, may provide a good 'early warning' system for DO declines elsewhere in the estuary. Management based on readings at the Princetown gauge therefore has a good chance of preventing high risk conditions elsewhere in the estuary. Further detail is provided below.

Investigation summary

Many factors interact together to produce a complex DO response during and estuary closure, and following an estuary opening. Through a data-driven processed-based investigation we have identified a suite of three core processes that appear to largely govern top DO response during estuary closure. Likewise, we have been able to identify a number of parameters that appear to govern top DO response following an estuary opening.

Each of these processes are accentuated by other factors and can interact together, making the DO response highly complex to model. A multi-linear regression developed to predict top DO was able to successfully identify the broad trend in average DO throughout each season, but was not able to predict when DO would fall levels posing high risk to instream fauna.

Analysis of DO decline during closed periods

Figure 15 identified that only one-third of the low DO events in Table 8 (i.e. six events) occurred when the estuary mouth was closed. In order to gain a more comprehensive picture of DO decline during estuary closure the Princetown gauge data was therefore further examined to consider additional events where DO fell to high risk levels, even if for short periods only. Attachment D plots the 15-minute DO readings for 16 different events where DO fell below 5 mg/l when the estuary was closed; for context the timing of these periods are also shaded in full low flow time series in Attachment D. For each event, the preceding and proceeding 7 days either side of the DO decline are shown for context.

The investigation sought to examine each of these 16 events individually, to identify the likely processes driving the decline in top DO, and in turn understand the processes driving decline during estuary closure since 2008/09. This investigation identified three key processes which appear to explain the majority of top[4] DO declines during estuary closure observed in the data:

- Estuarine flora respiration and photosynthesis (Process A)
- Catchment inflow resulting in mixing of the water column (Process B)
- Catchment inflows delivering high organic load (Process C)

These three processes can occur independently of each other, or in some circumstances will occur simultaneously producing a complex response in top DO. The three processes are described below.

Process A – Estuarine flora respiration and photosynthesis

Process description
Like all plants, estuarine flora (including planktonic algae, epiphytic algae and rooted macrophytes) in the Gellibrand estuary produces carbon dioxide through respiration at all times, but during the day (when there is light) will use CO_2 to produce oxygen (O_2) through photosynthesis. When present in significant amounts estuarine flora will therefore reduce the DO content during dark periods (due to respiration) but increase DO during light periods (when photosynthesis offsets their respiration).

The presence of flora in the Gellibrand estuary can be readily identified by examining the diurnal variation in top DO. Estuarine flora will be alive and present in significant quantities (that is, biomass) when DO levels vary from day to night; conversely an absence of diurnal variation indicates an absence of significant quantities of living estuarine flora.

The amplitude of the diurnal variation in DO (i.e. the degree of variation) is a product of the amount of photosynthesis occurring, which is driven largely by the quantity of estuarine flora and duration of bright sunlight. Several scenarios are possible:

- Living estuarine flora is largely absent or only in small quantities. In this case DO levels will not exhibit diurnal variation.
- Living estuarine flora is present in relatively modest quantities. In this case DO levels will experience diurnal variation with low amplitude. The occurrence of a cloudy day would prevent DO levels rising during the day time, but the low amplitude of variation means this would not result in a major impact on DO.
- Living estuarine flora is present in large quantities. In this case DO levels will experience diurnal variation with high amplitude. The occurrence of one or more cloudy day would prevent DO levels rising during the day time, and the high amplitude of variation means this would result in a major impact on DO.

[4] These processes are identified for DO declines in the top of the water column only, not the bottom of the water columns, which undergoes different processes.

Evidence of response in the Gellibrand estuary
The plots in Attachment D show many periods when living estuarine flora are obviously present and affecting DO levels in the Gellibrand estuary. The typical cycle in these periods sees DO levels falling during night and rising during the day. However, there are many times when declines in DO to high risk levels appear to be a function of estuarine flora experiencing low rates of photosynthesis (due to cloud cover). These include mid-March 2009 (event #2), early-May 2010 (event #5), mid-April 2012 (event #6) and late April 2016 (event #16) amongst others.

Typical recovery pattern
A fall in top DO due to this process is typically associated with a recovery to the pre-fall DO levels following a return to sunnier conditions. Although variable, such falls tend to involve a drop and subsequent recovery of approximately 2-4 mg/L. This process therefore tends not to result in prolonged high levels of risk to instream fauna, unless occurring when DO levels are already approaching low levels.

However, repeated cycles of cloudy conditions do tend to produce a gradual lowering of DO levels over the timescales of weeks.

Accentuating factors
Declines in DO arising from this process are most pronounced when estuarine flora is in high quantities (i.e. there is a large amount of respiration occurring), and weather conditions change sharply from sunny to cloudy conditions (i.e. very little photosynthesis occurs).

An analysis of the amplitude of DO variability indicates that the quantity of flora in the Gellibrand estuary tends to increase over long periods of estuary closure, as loads of organic matter in the water column increase. This finding is consistent with an independent analysis of the nutrient and turbidity levels of the estuary and the freshwater inflows, which compared recorded values to the SEPP (WoV) objectives and the 2010 EPA estuary guidelines (Table 9). This found that inflows do not meet nutrient objectives, suggesting there is a risk of excessive plant growth, although this should be offset somewhat by moderate levels of turbidity. Surface waters in the estuary also exceed guidelines for nutrients, reinforcing the risk of excessive plant growth in the surface waters (Table 9). While the levels are not high, they would nonetheless promote plant growth, but most likely not rapid growth. Turbidity is close to the guideline value and is unlikely to inhibit plant growth. Bottom waters in the estuary have lower phosphorous levels but higher nitrogen levels than the guidelines, and as nitrogen is usually limiting in marine waters, it is likely that the bottom waters would also promote plant growth. The bottom waters are also very clear and light would most likely not be limiting, as long as the surface is not too turbid.

Table 9. Assessment of monthly EPA data at Old Coach Road from 2000 - 2005

Statistic	Metric	TP (mg/L)	TN (mg/L)	Turbidity (NTU)
75th percentile of catchment inflows	SEPP (WoV) "Coastal Plain" segment objective	0.045	0.600	10
	Freshwater inputs recorded	0.082	1.2	18
Median at estuary surface	EPA guideline	0.05	0.5	5
	Gellibrand estuary recorded	0.061	0.67	8
Median at estuary bottom	EPA guideline	0.07	0.6	7
	Gellibrand estuary recorded	0.046	0.9	4

The pattern of DO decline arising from build-up of excessive estuarine flora is quite prominent in mid-March 2009 (event #2), mid-April 2012 (event #6), mid-February 2013 (event #7) and late April 2016 (event #16). Prolonged sunny periods would also be expected to result in increased quantities of estuarine flora. Declines in DO due to this process are therefore likely to be most significant when a prolonged period of dense cloud cover occurs following prolonged closure of the estuary and recent sunny conditions.

It is also noteworthy that the development of this process can lead to subsequent deterioration of bottom DO levels - if estuarine flora from the top waters dies off and sinks into the bottom waters, along with flora dying

off in the bottom waters, a subsequent decline in bottom DO would be expected. This process appears to have occurred in mid May 2010 (event #5).

Process B – Catchment inflow resulting in mixing of the water column

Process description
A spike in inflows from the catchment to a closed estuary will often result in mixing (partial or complete) of the water column. If the estuary is highly stratified prior to inflows, it is likely that the top DO levels will be substantially higher than bottom DO levels, and therefore mixing will result in decline of the top DO levels.

Evidence of response in the Gellibrand estuary
The plots in Attachment D show several periods when top DO levels fall during a spike in catchment inflows, and when bottom DO is significantly less than top DO. Examples include the small inflow peaks in mid-February 2009 (event #1) and possibly the peak of the mid-May 2015 spike (event #12). There was little diurnal variation in the lead up to each of these events, indicating that process B was more influential than process A at these times (i.e. living estuarine flora would have been largely absent or only in small quantities).

Typical recovery pattern
A fall in top DO due to this process is typically associated with a recovery to the pre-fall DO levels following the peak in catchment inflows. Although variable, such falls tend to involve a drop and recovery of approximately 1-3 mg/l. This process therefore tends not to result in prolonged high levels of risk to instream fauna, unless occurring when top DO levels are already approaching critically low levels.

Accentuating factors
Mixing resulting from inflows will obviously only detrimentally affect top DO levels when bottom DO levels are significantly lower than top DO levels; this occurs as a result of stratification of the estuary. Once stratification has occurred the top of the water column maintains an ability to oxygenate through exposure and interaction with the atmosphere, whereas the bottom of the water column is physically disconnected from this process, so can only oxygenate through photosynthesis of estuarine flora in the bottom water column. Following the onset of stratification, bottom DO levels tend to decline at a faster rate than top DO, resulting in a steady divergence as bottom DO approaches zero. This pattern continues until a break-down of the stratification allows reoxygenation of the bottom waters (e.g. mixing of the water column) as evidenced in early-February 2009 (event #1), early-April 2012 (event #6) and early-April 2013 (event #8). This has an important implication for top DO levels - once the estuary develops stratified conditions there is a common trajectory of declining bottom DO levels, which results in an increasing likelihood that top DO levels could be adversely impacted by a mixing event.

On the other hand, the degree of mixing (and therefore the DO decline) resulting from a given inflow from the catchment will be accentuated when the depth of the top freshwater lens is relatively thin compared to the depth of the saltwater lens below. These conditions are more likely to occur immediately following an estuary closure than after a prolonged period of closure.

Process C – Catchment inflows delivering high organic load

Process description
A spike in inflows from the catchment to a closed estuary is often expected to deliver freshwater with a higher DO level than the estuary, and produce an increase in DO. While there is evidence of this occurring within the Gellibrand estuary (e.g. early-May 2010, event #5), there is also evidence of events where DO has declined in association with very high inflows. The decline in these situations is expected to arise from the catchment inflows having a high organic load, which results in increased bacterial activity in the estuary waters, leading to deoxygenation of the water. The severity of such events is determined by the amount, age and type of organic material imported into the estuary, and whether it has been previously submerged in water.

Evidence of response in the Gellibrand estuary
The plots in Attachment D show several periods when top DO levels fall during a spike in catchment inflows, but bottom and top DO levels are similar (indicating that the top DO decline is not due to mixing). The two examples include the inflow in mid-May 2009 (event #4) and the falling limb of the early-May 2016 spike (event #16).

Typical recovery pattern
A fall in top DO due to this process has not been associated with an immediate recovery in DO levels. In both examples on record, the DO levels fell by 5-7 mg/l during this event and did not recover. This process therefore has a high likelihood of resulting in high levels of risk to instream fauna, particularly when DO levels are not at the maximum point of saturation.

Accentuating factors
The amount of organic load delivered into the estuary (and therefore the DO decline) will be higher when high flows occur after prolonged dry periods and there has been an extensive build-up of organic material such as leaf litter in the catchment. The level of bacterial response (and therefore the DO decline) to the increased organic load will be accentuated when air and water temperatures are high.

Declines in DO due to this process are therefore likely to be most significant when high inflows follow a prolonged dry period and when air and water temperatures in the estuary are high.

Summary of closed estuary processes

In light of the dominance of the three processes outlined above driving top DO levels in the Gellibrand estuary when the mouth is closed, a decision diagram is provided in Figure 16. This simplified approach is based on the premise that one of the three processes is likely to be most influencing DO at any point in time, though in reality, it is possible that such processes will be interacting and producing a complex response.

Of these three processes, declines have most commonly been associated with estuarine flora respiration and photosynthesis, but these tend not to produce high risk outcomes. Although occurring least often, the DO declines resulting from high organic load delivery from the catchment have caused the greatest reduction in DO levels during estuary closure periods.

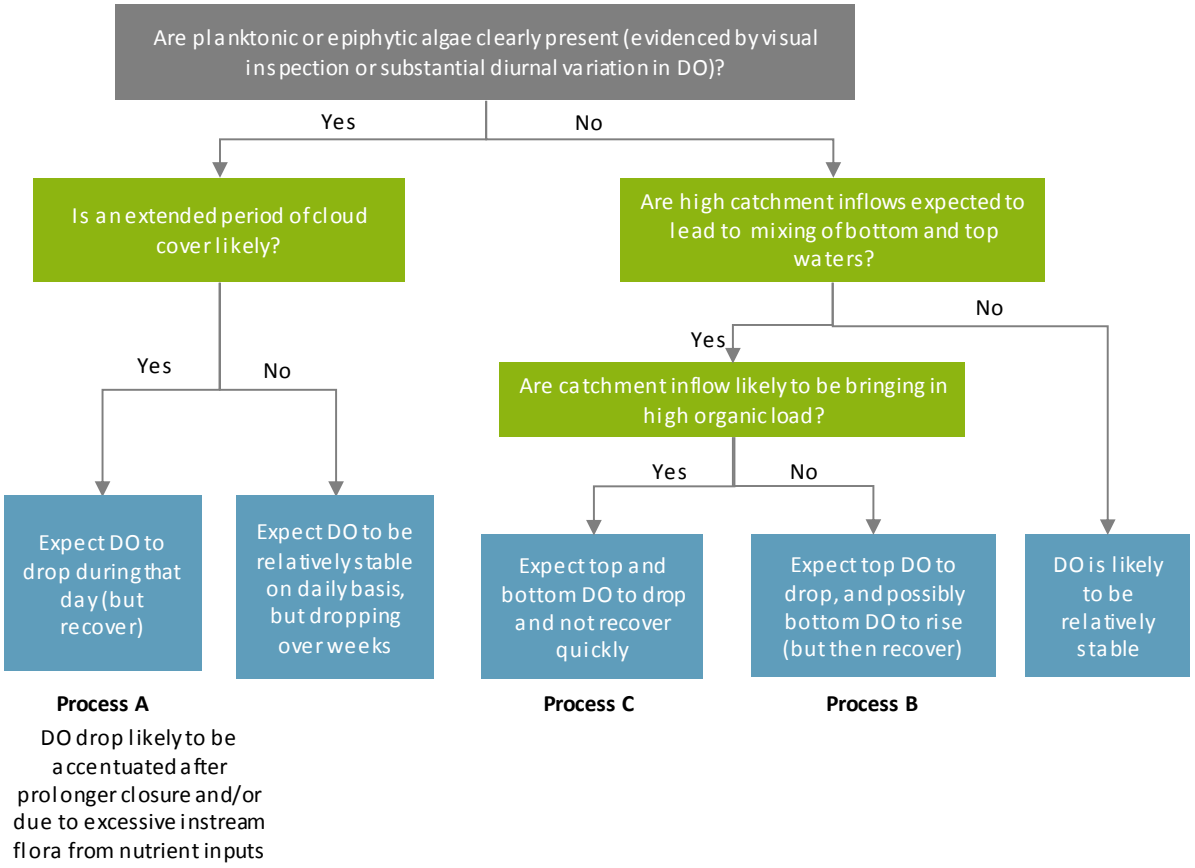


Figure 16. *Decision diagram for investigation top DO level declines when estuary is closed*

Analysis of DO decline associated with opening

Figure 15 identified that the majority of low DO events in Table 8 occurred when the estuary mouth was in the process of being opened and most of these low DO events were associated with artificial openings. In order to gain a more comprehensive picture of DO decline during estuary openings the Princetown gauge data was therefore further examined to consider all estuary opening events on record. Attachment D plots the 15-minute DO readings for the 24 estuary opening events between late 2008 and early 2016. For each event, the preceding day and proceeding 5 days of the opening are shown for context.

The investigation sought to examine the characteristics of these 24 events, to identify what conditions lead to decline in top DO. The significance of decline in DO was considered through the degree of drop in top DO (i.e. DO at opening minus minimum DO following opening), the rate of DO fall, the duration of the DO recovery period and the minimum value that DO reached.

The analysis identified that the potential for DO to fall to critical levels is influenced by two key factors:

- DO levels prior to opening, in both the top and bottom of the water column
- Degree of mixing of the water column resulting from the opening, which is a product of inflows from the catchment and/or the development of tidal interchange.

In addition to these two key driving factors, a number of additional parameters appear to interact to provide a secondary influence on DO response after openings. These secondary parameters include:

- Whether the opening occurred naturally or artificially, where natural openings tend to provide better DO outcomes (Figure 17)
- Whether the opening coincided with cool air and water temperatures (which is largely driven by the time of year of the opening), where cool conditions tend to provide better DO outcomes (Figure 18)
- Whether water levels in the estuary fell fast or slowly following opening (which appears to be largely driven by the height of the estuary prior to opening), where fast or slow draining conditions tend to provide lower DO outcomes than medium draining conditions (Figure 19).
- Whether the opening coincided with high catchment inflows, where high inflows tend to provide better DO outcomes than low inflows (Figure 20).

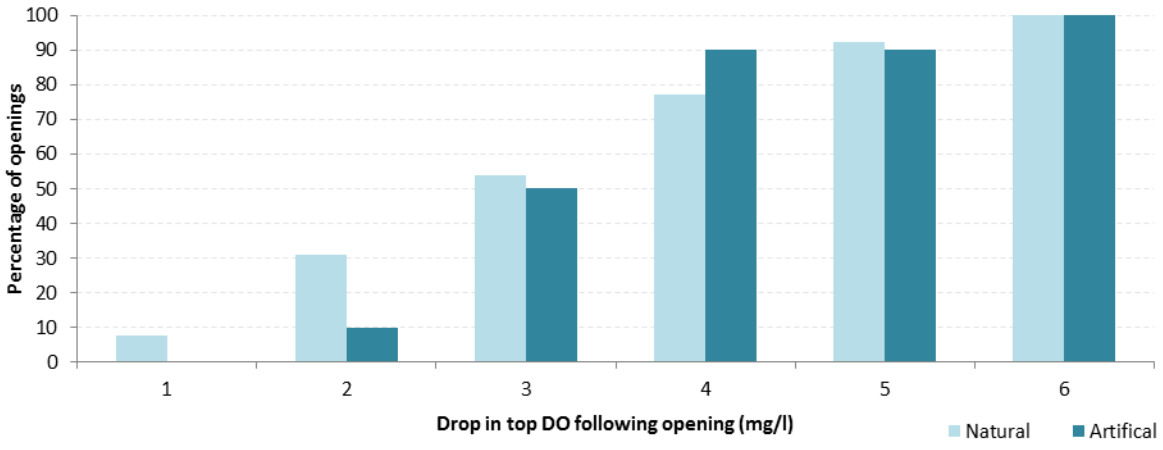


Figure 17. *Cumulative histogram of the total drops in DO following opening, separated into natural and artificial opening events*

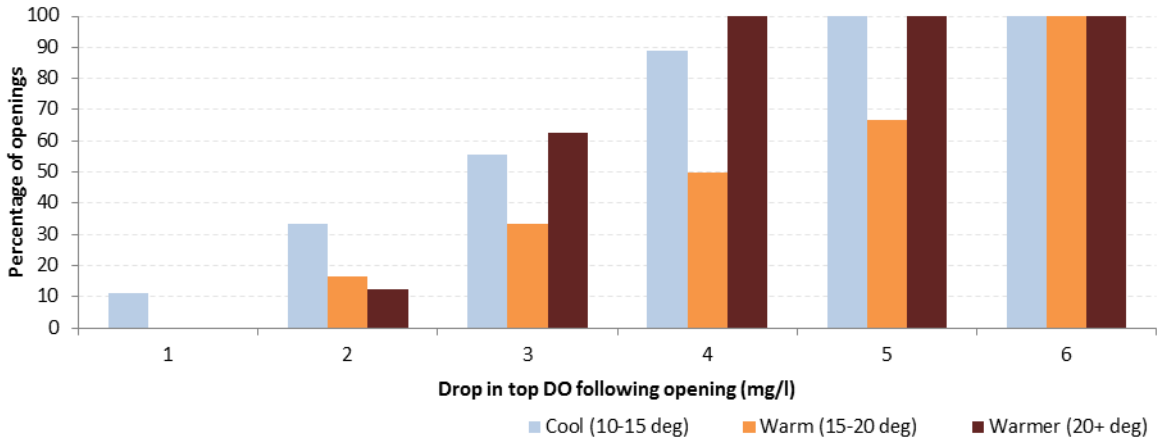


Figure 18. *Cumulative histogram of the total drops in DO following opening, separated into groups based on water temperature*

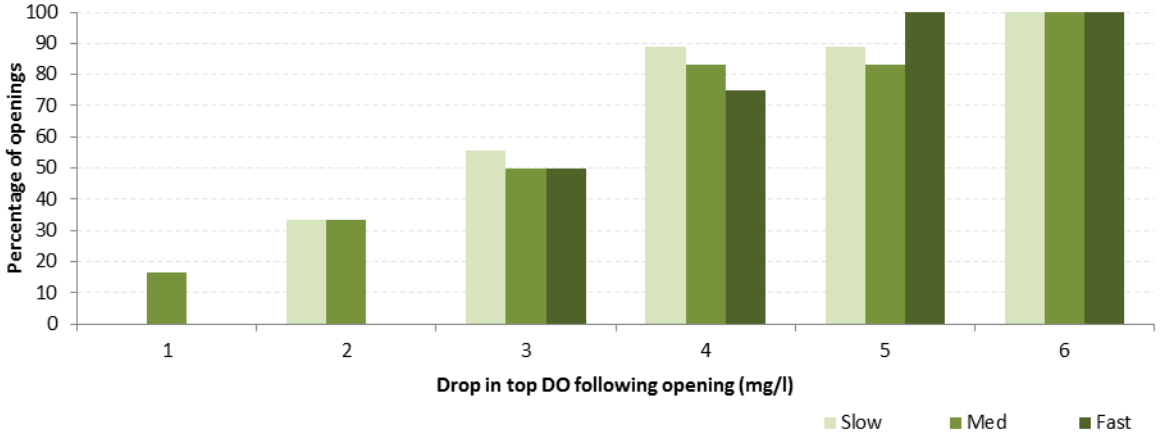


Figure 19. *Cumulative histogram of the total drops in DO following opening, separated into groups based on water temperature*

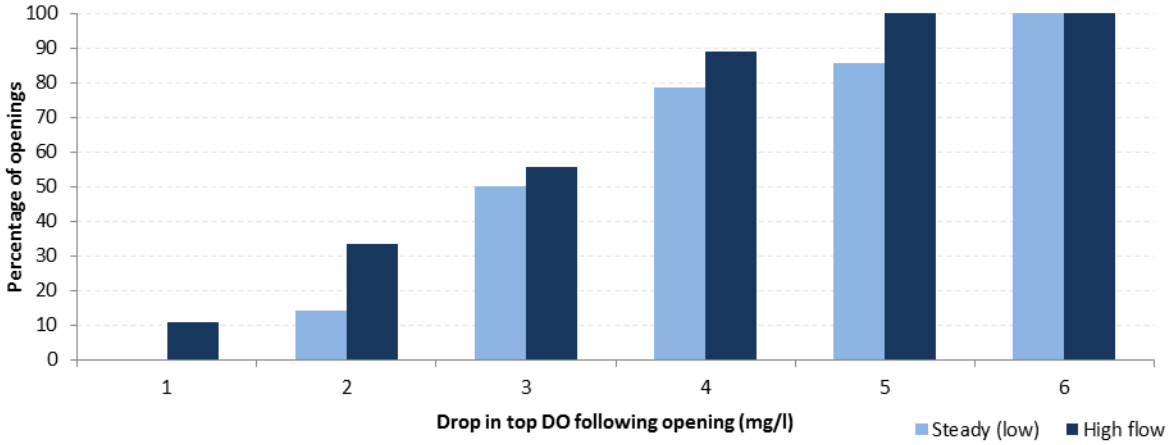


Figure 20. *Cumulative histogram of the total drops in DO following opening, separated into groups based on catchment inflows*

Estuary openings tend to result in a fall in top DO of between 2 to 5 mg/l (but occasionally 1, 6 or 7 mg/l). The top DO level at opening is therefore highly influential on the minimum DO level that occurs following an opening. For example, despite the conditions present, any opening that occurs when top DO is around 5 mg/l are much more likely to produce high risk conditions for instream fauna than openings occurring when top DO

is around 8 mg/l. Artificial openings when top DO is already at low levels should be undertaken with extreme caution.

Given that DO levels tend to decline over time as the estuary is closed, openings earlier in the closure period are likely to have a higher DO level at opening, and experience less risk of DO falling to critical levels. If artificial openings are undertaken, they would be better placed to occur earlier rather than later (from a DO perspective, but this may conflict with other objectives).

Estuary openings will tend to produce better DO outcomes when they coincide with catchment inflows, cool weather and/or water levels in the estuary below 1.5 m. Higher water levels tend to lead to faster draining, which tends to be more associated with rapid rates of decline in DO. If artificial openings are undertaken, they should seek to coincide with these conditions where possible.

Spatial variability of dissolved oxygen levels

The sections above investigated the processes that drive declines in top DO by examining the 15-minute interval data available at the Princetown gauge from 2008 onwards. While this represents the only automated water quality logger in the Gellibrand estuary, manual water quality observations from the EstuaryWatch program are available for several sites along the estuary. This section presents the results of analysis undertaken to examine the spatial variability of DO levels in the estuary, which offers insights into the ability for instream fauna to avoid a deoxygenation event occurring within a sub-section of the estuary.

Sample sites

There are seven EstuaryWatch sites for the Gellibrand Estuary. This section uses data from the four sites with most extensive water quality measurements:

- Latrobe creek
- Old Coach Road (Princetown)
- Rivernook
- Coxon's bridge

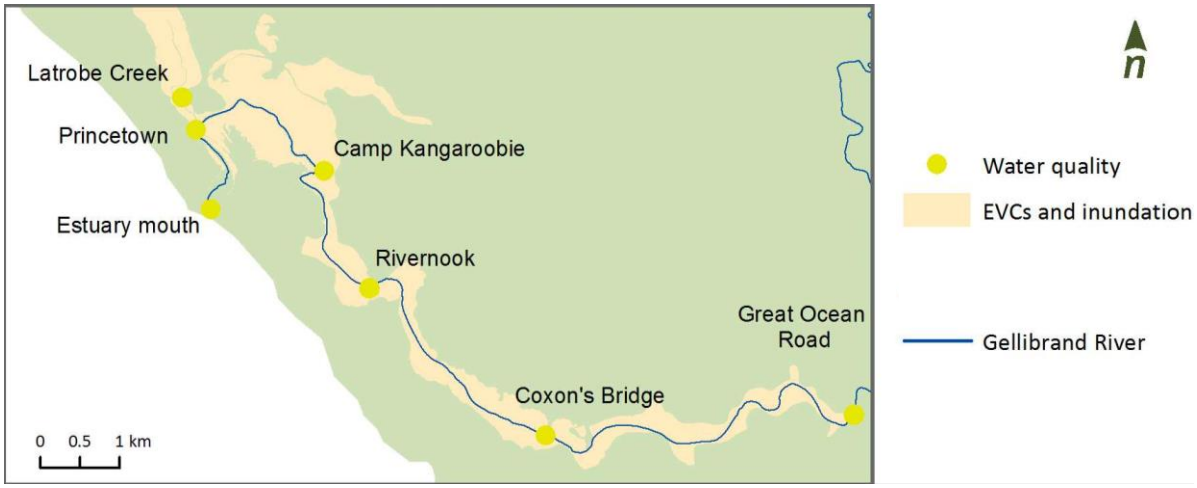


Figure 21. *Location of EstuaryWatch sites*

Analytical approach

The analysis sought to develop regression relationships between the gauged DO level at Princetown and the measured DO level at EstuaryWatch sites, to allow an interference of DO levels throughout the estuary based on Princetown readings.

EstuaryWatch water quality data is sourced from manual in-situ measurements undertaken at irregular intervals and at varying times of the day. It was initially envisaged that the time recorded on data sheets for these EstuaryWatch measurements could be used to identify the corresponding period in the Princetown gauge, with a regression then undertaken on the relevant data. However, preliminary exploration of the data indicated a low level of regression relationship between the relevant 15-minute data points. As such, the mean daily mean DO at Princetown was used for the regression relationship instead. To reduce the potential for error, days with high levels of variability in DO readings at Princetown were excluded from the regression relationship, providing confidence that the daily average was reflective of the conditions at the time of the EstuaryWatch sampling.

The relevant series of daily mean at Princetown and EstuaryWatch observations at each site were compared via linear regression. This provided a linear line of best fit for the relationship, as well as 80% prediction bands.

For any given DO value at the Princetown gauge, these relationships therefore provide the best estimate of the value occurring at each EstuaryWatch site, and also identify the range of values at the EstuaryWatch site that we are 80% confident contains the actual DO value. Regression relationships were undertaken separately for top DO and bottom DO.

Regression relationships

The regression relationships (Figure 22 - Figure 25) generally provide a relatively high degree of fit between top DO levels at Princetown and the respective EstuaryWatch site, but a poorer relationship for bottom DO levels.

These relationships indicate that when the top DO level at Princetown is 6 mg/l or less, the DO levels in the top of the water column elsewhere in the estuary are expected to be higher than that at Princetown (Figure 26). Conversely, when top DO at Princetown exceeds 6 mg/l the other sites in the estuary are predicted to have lower levels that this. This finding however is subject to considerable uncertainty, due to the low number of data points with top DO levels less than 6 mg/l at Princetown used in the regression relationships – most values fall between 6 and 10 mg/l. In any case, on the data available it does suggest that the Princetown top DO readings are likely to provide a 'worst-case' representation of top DO levels in the estuary, and in turn, may provide a good 'early warning' system for DO declines elsewhere in the estuary.

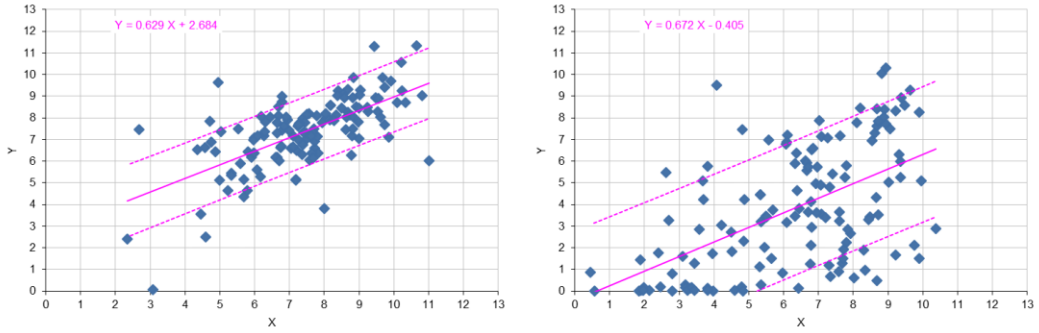


Figure 22. *Regression between Princetown DO (x-axis) and EstuaryWatch Old Coach Road Bridge data (y-axis). Relationship for top DO on left and bottom DO on right. Upper and lower lines show the 80% prediction bands.*

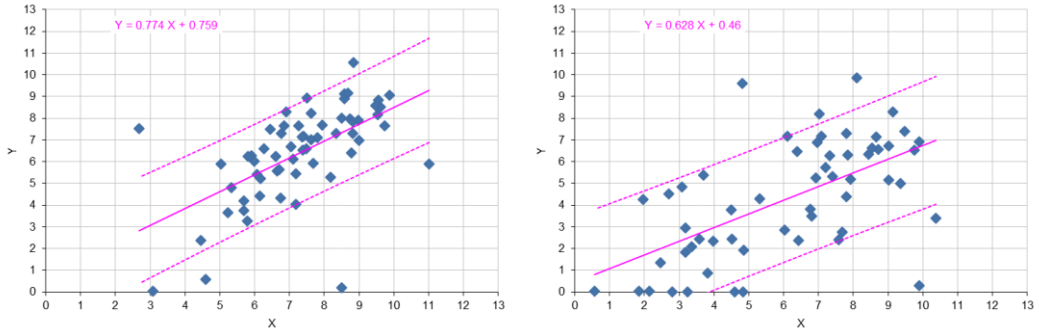


Figure 23. *Regression between Princetown DO (x-axis) and EstuaryWatch Latrobe Creek Mouth Bridge data (y-axis). Relationship for top DO on left and bottom DO on right. Upper and lower lines show the 80% prediction bands.*

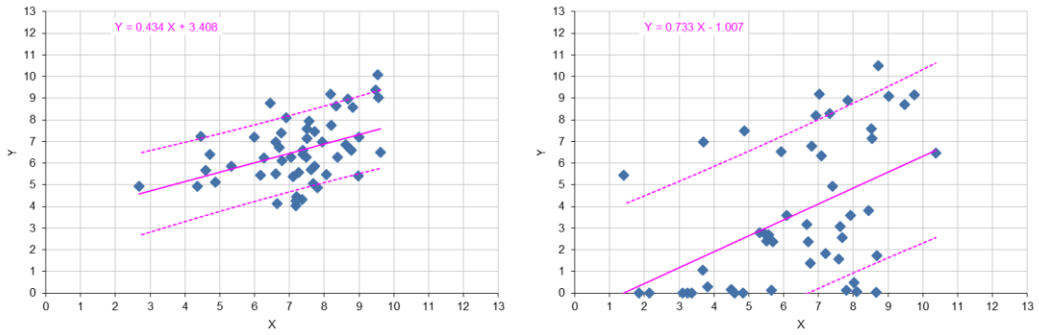


Figure 24. *Regression between Princetown DO (x-axis) and EstuaryWatch Rivernook data (y-axis). Relationship for top DO on left and bottom DO on right. Upper and lower lines show the 80% prediction bands.*

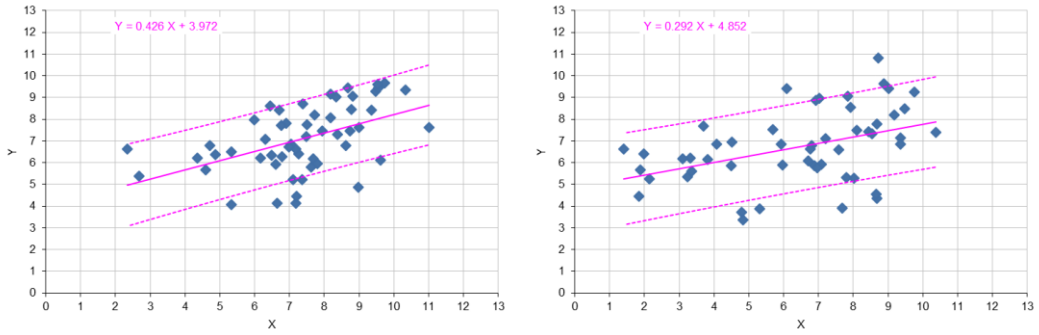


Figure 25. *Regression between Princetown DO (x-axis) and EstuaryWatch Coxon Bridge data (y-axis). Relationship for top DO on left and bottom DO on right. Upper and lower lines show the 80% prediction bands.*

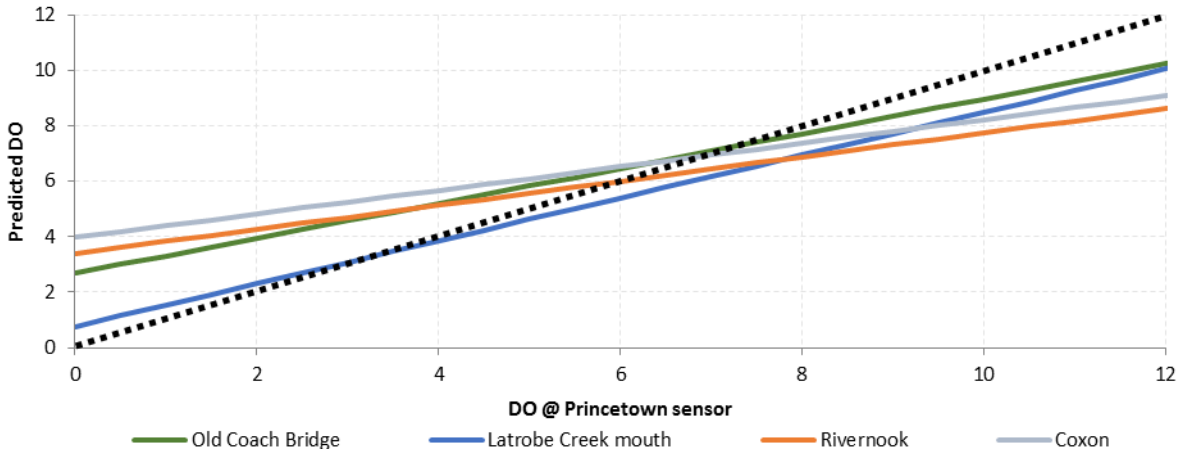


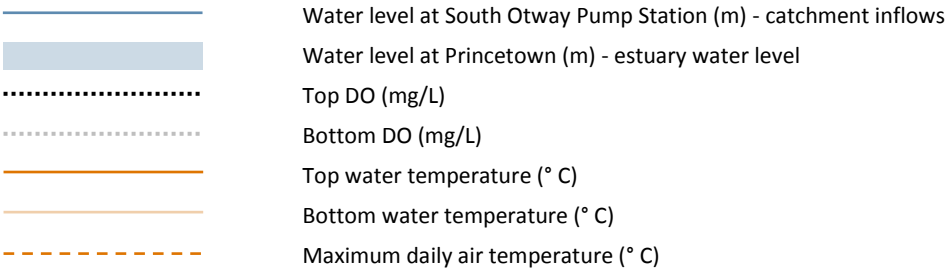
Figure 26. *Lines of best fit for regression of top DO at Princetown gauge and each EstuaryWatch site*

Attachment D
Water quality investigation – event data

This section shows three sets of data that were used in the water quality investigation:

- Full low flow time series data for 2008 – 2016
- DO drops associated with estuary closures
- Estuary opening events

The following key should be used throughout this section.



Full low flow period 2008 - 2016

December 2008 – May 2009

EVENT #1

EVENT #2

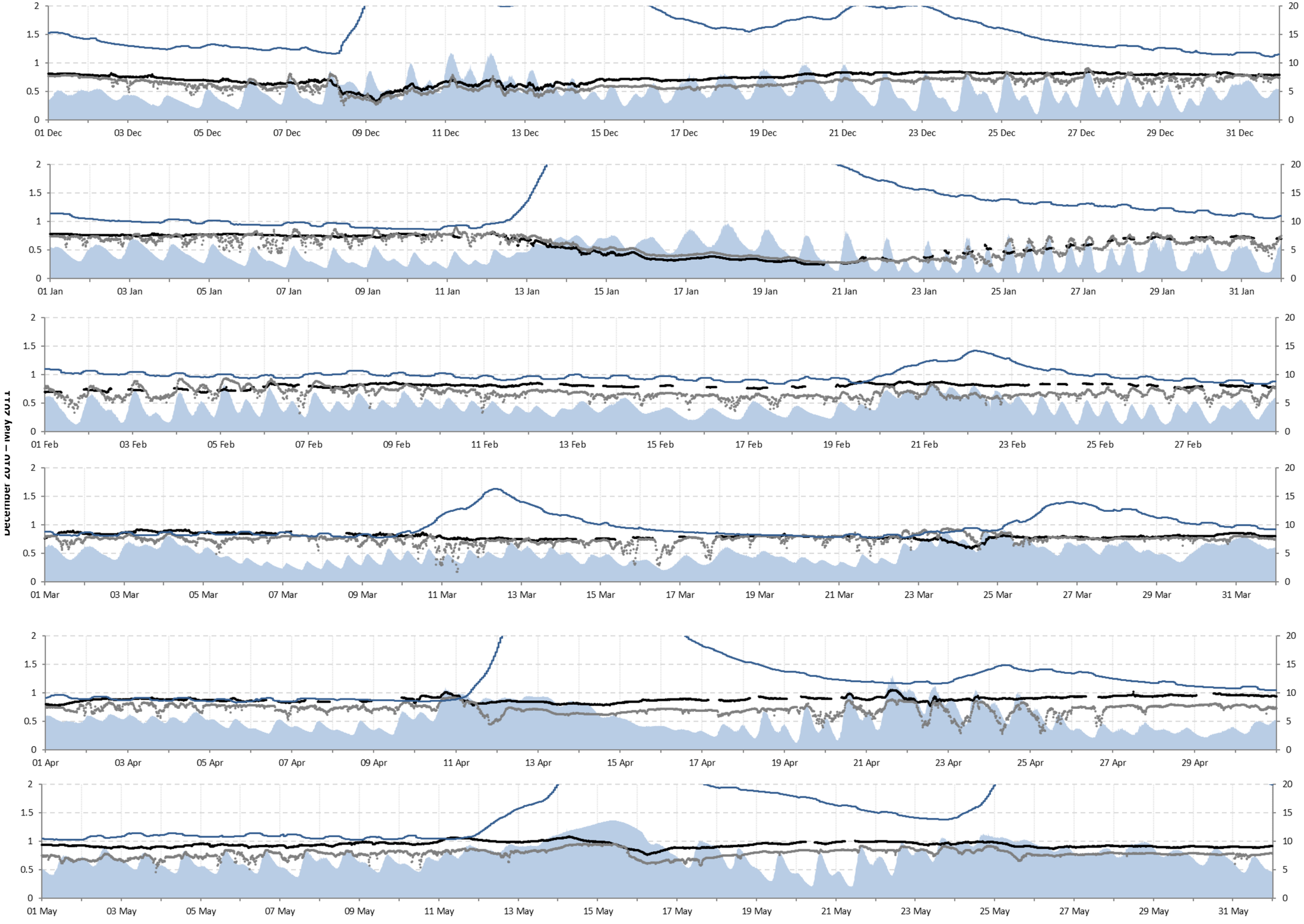
EVENT #3

EVENT #4

December 2009 – May 2010

EVENT #5

EVENT #5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03 Dec
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29 Dec
31 Dec
01 Jan
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07 Jan
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07 Feb
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01 Mar
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01 May
03 May
05 May
07 May
09 May
11 May
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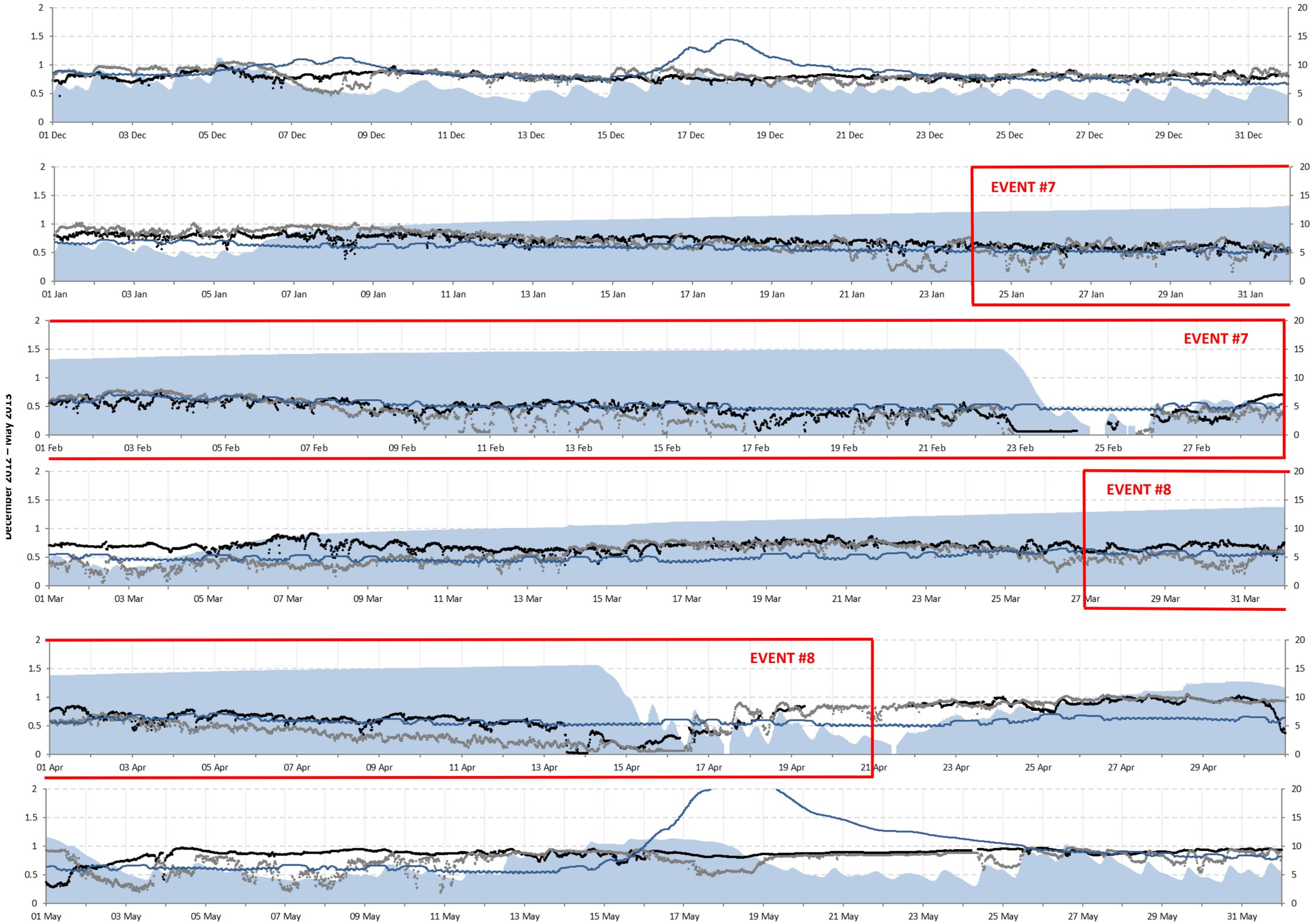
23 May
25 May
27 May
29 May
31 May

December 2017 – May 2018

EVENT #6

EVENT #6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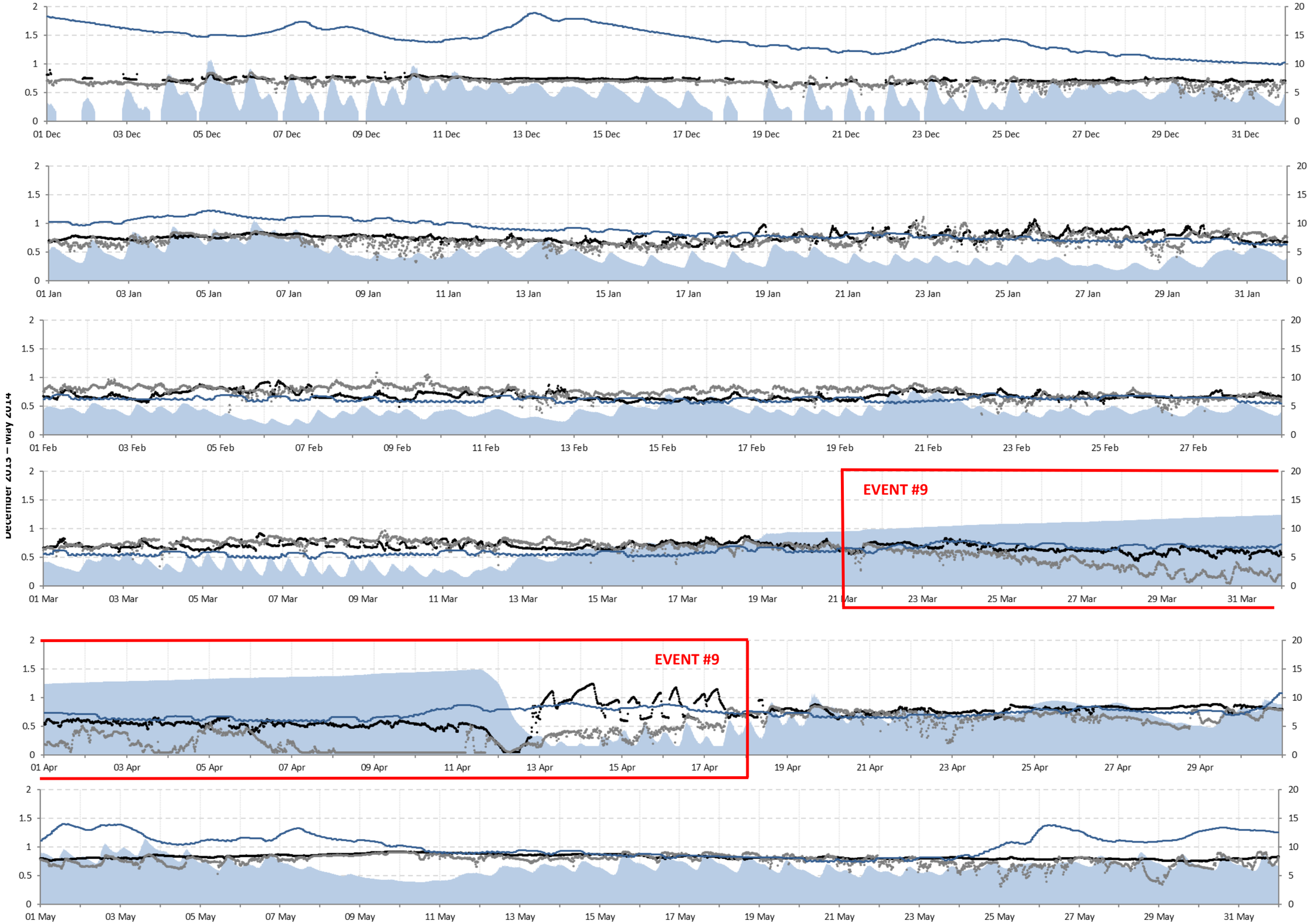
EVENT #7
EVENT #8
EVENT #8


December 2013 – May 2014
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03 Dec
05 Dec
07 Dec
09 Dec
11 Dec
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31 Dec
01 Jan
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27 Mar
29 Mar
31 Mar
EVENT #9
01 Apr
03 Apr
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07 Apr
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13 Apr
15 Apr
17 Apr
EVENT #9
19 Apr
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01 May
03 May
05 May
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15 May
17 May
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25 May
27 May
29 May
31 May

December 2014 – May 2015

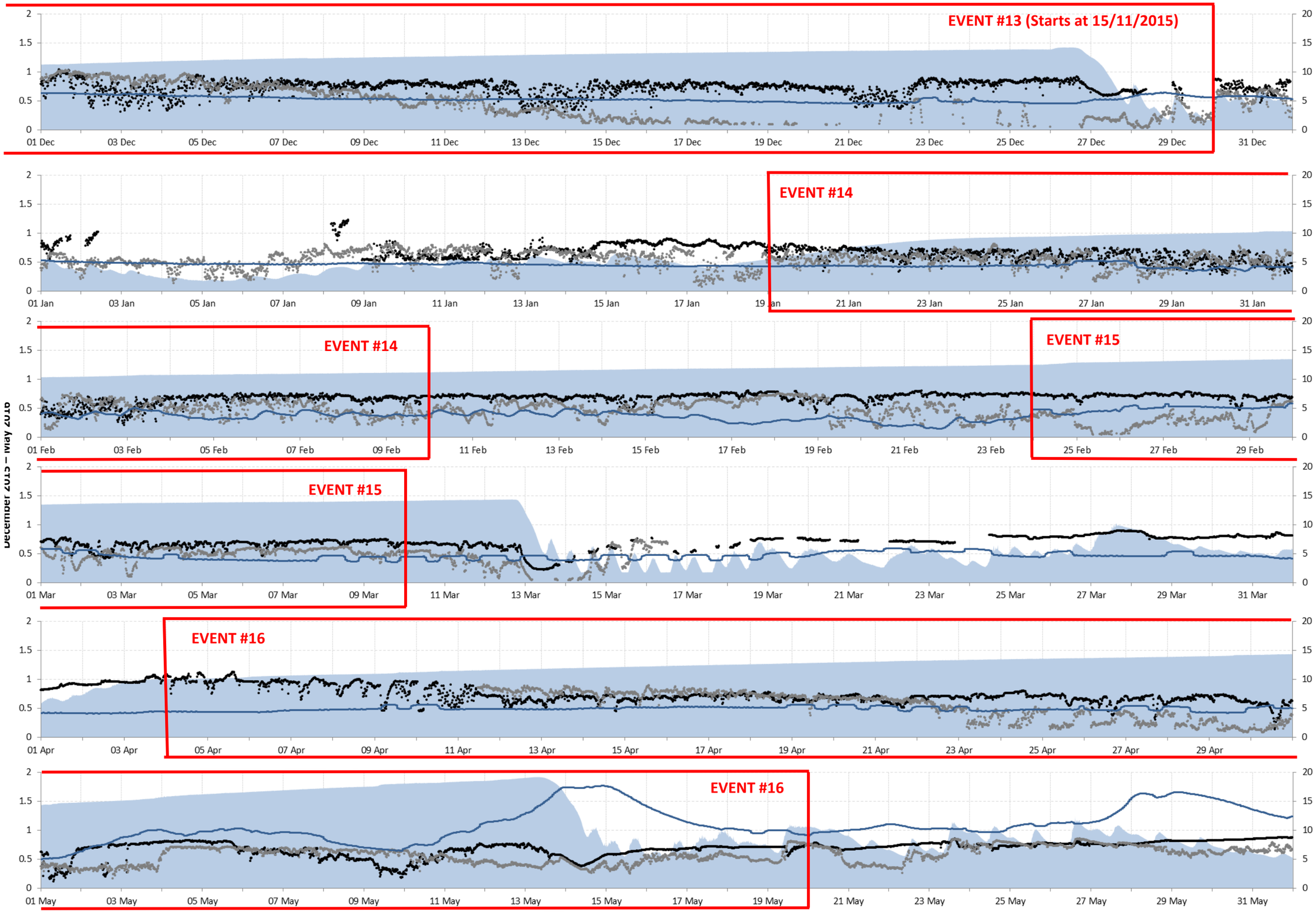
EVENT #10

EVENT #10

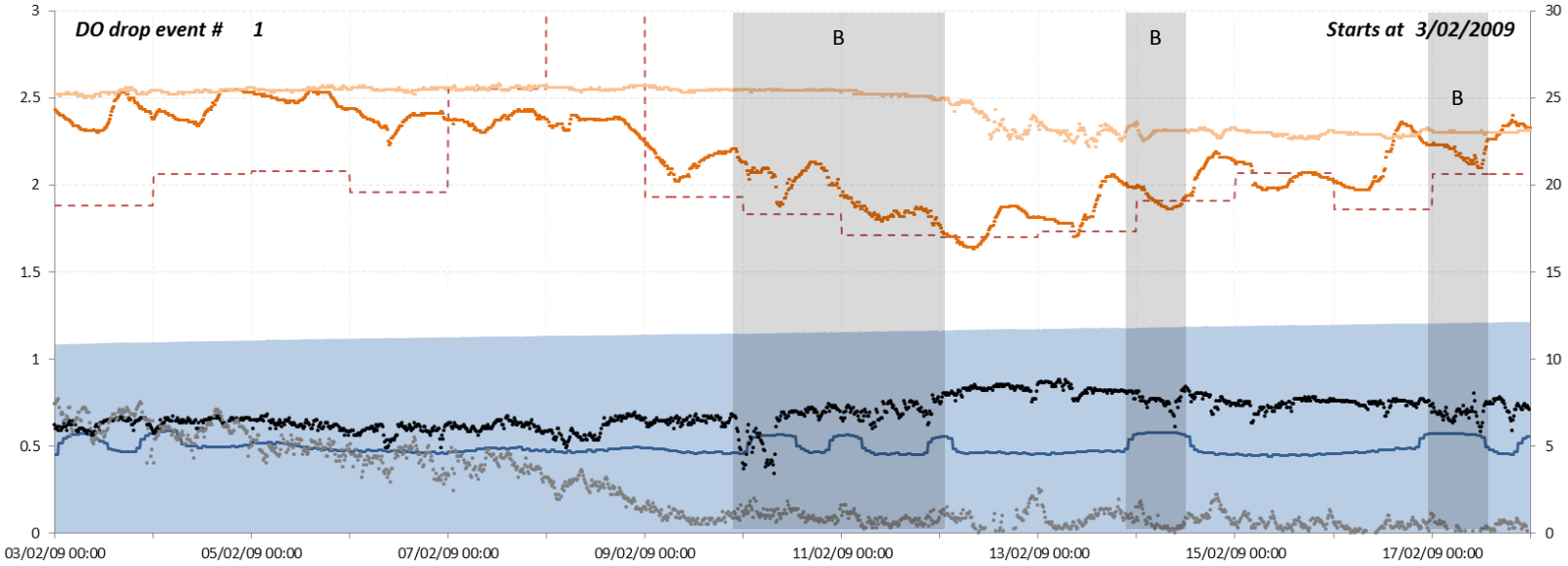
EVENT #11

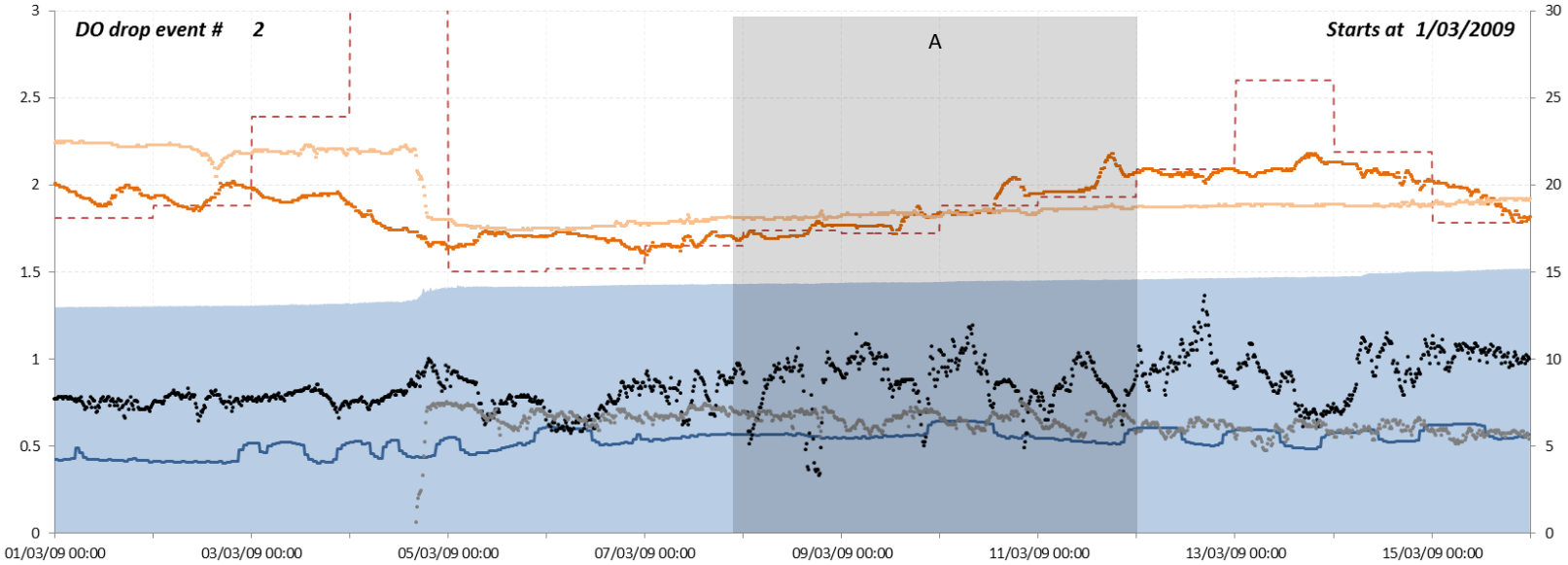
EVENT #11

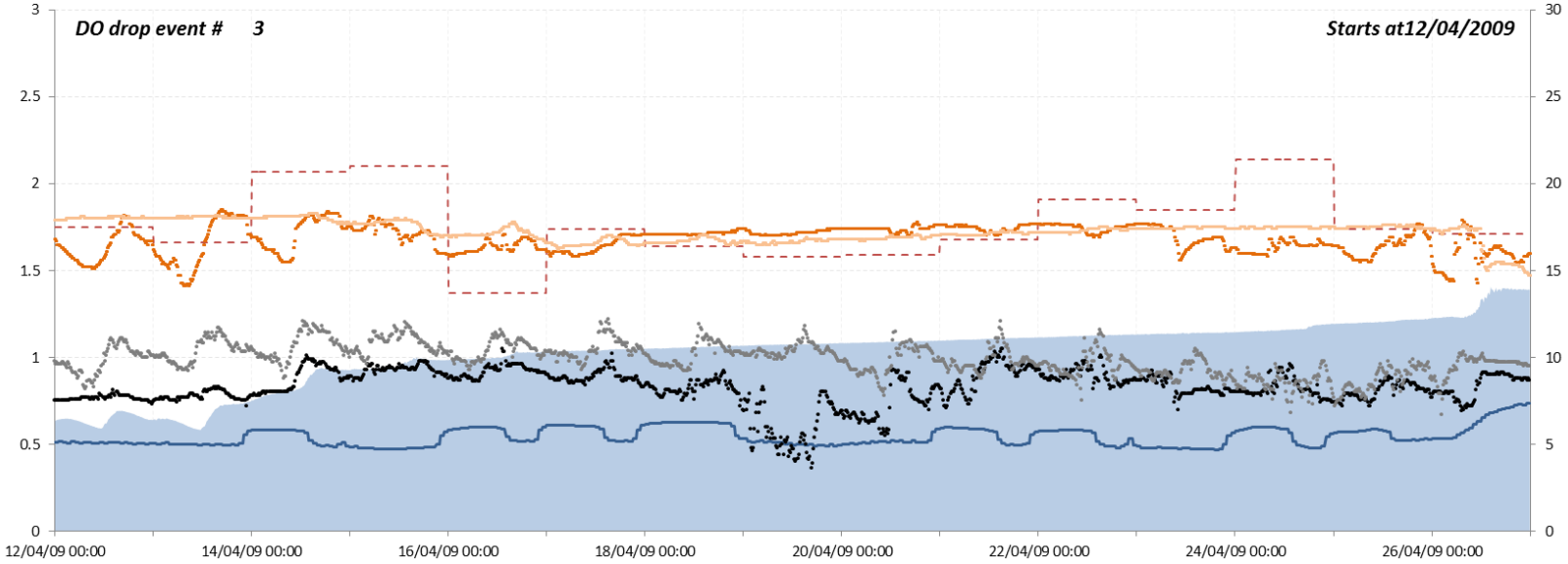
EVENT #12


EVENT #13 (Starts at 15/11/2015)
EVENT #14
EVENT #14
EVENT #15
EVENT #15
EVENT #16
EVENT #16
December 2015 – May 2016

Drops in DO during estuary closure periods



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Starts at12/04/2009
3
2.5
2
1.5
1
0.5
0
30
25
20
15
10
5
0
12/04/09 00:00
14/04/09 00:00
16/04/09 00:00
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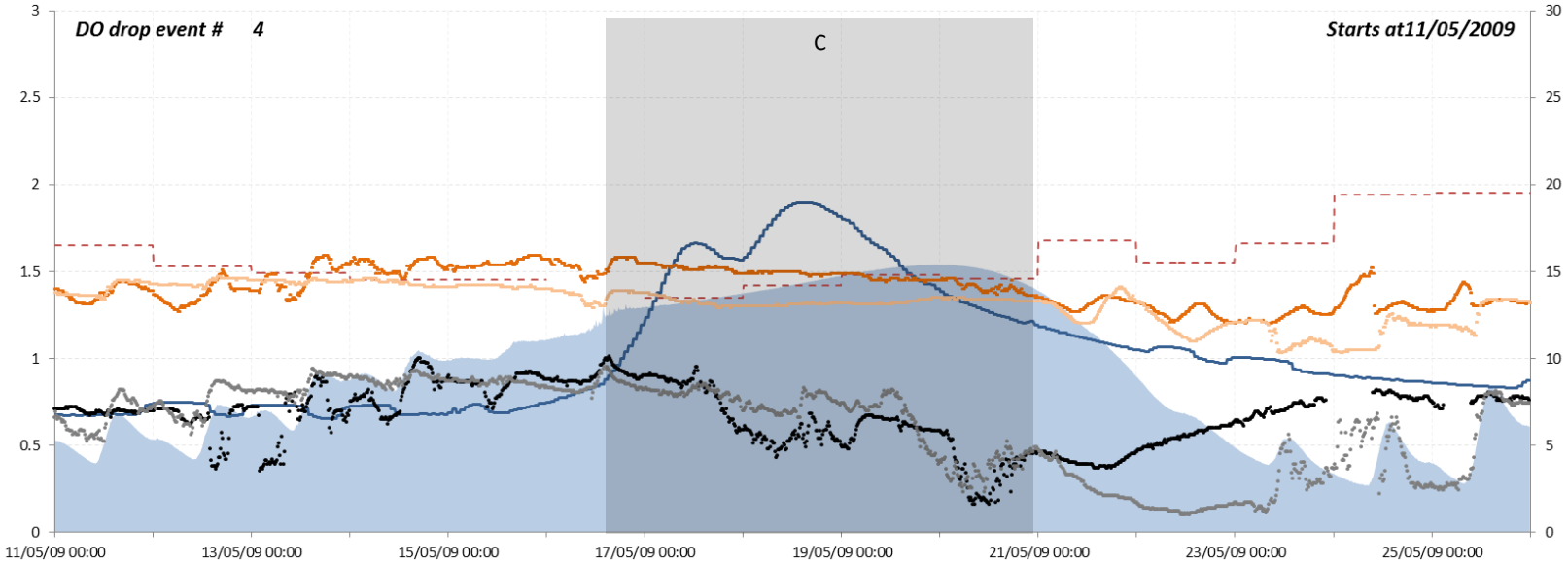
24/04/09 00:00
26/04/09 00:00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C
Starts at11/05/2009
3
2.5
2
1.5
1
0.5
0
30
25
20
15
10
5
0
11/05/09 00:00
13/05/09 00:00
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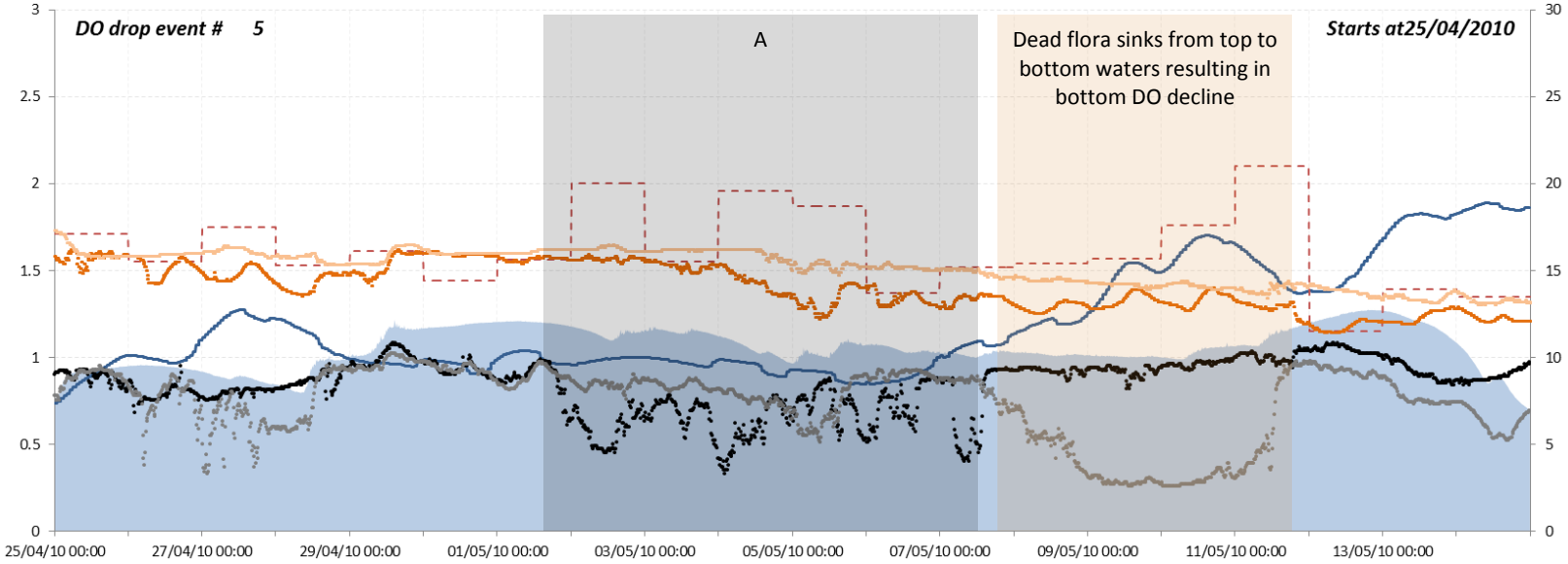
25/05/09 00:00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Dead flora sinks from top to bottom waters resulting in bottom DO decline
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1.5
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0.5
0
30
25
20
15
10
5
0
25/04/10 00:00
27/04/10 00:00
29/04/10 00:00
01/05/10 00:00
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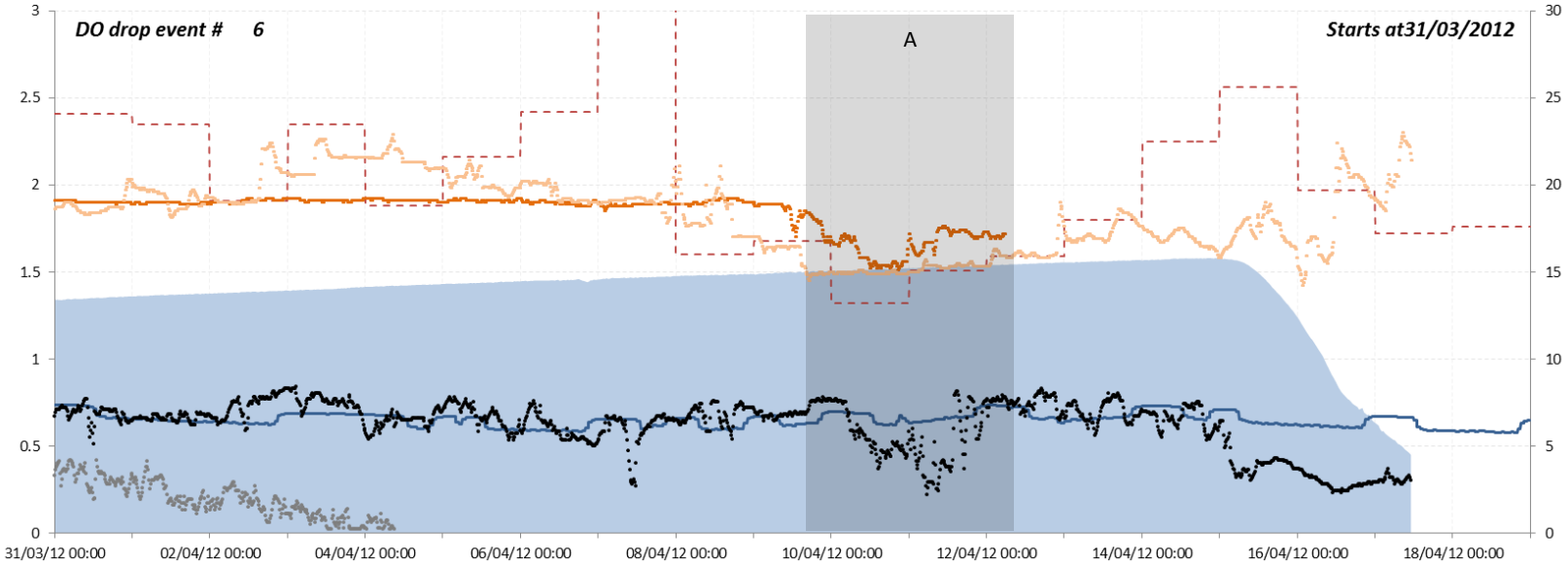
13/05/10 00:00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Starts at31/03/2012
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2.5
2
1.5
1
0.5
0
30
25
20
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02/04/12 00:00
04/04/12 00:00
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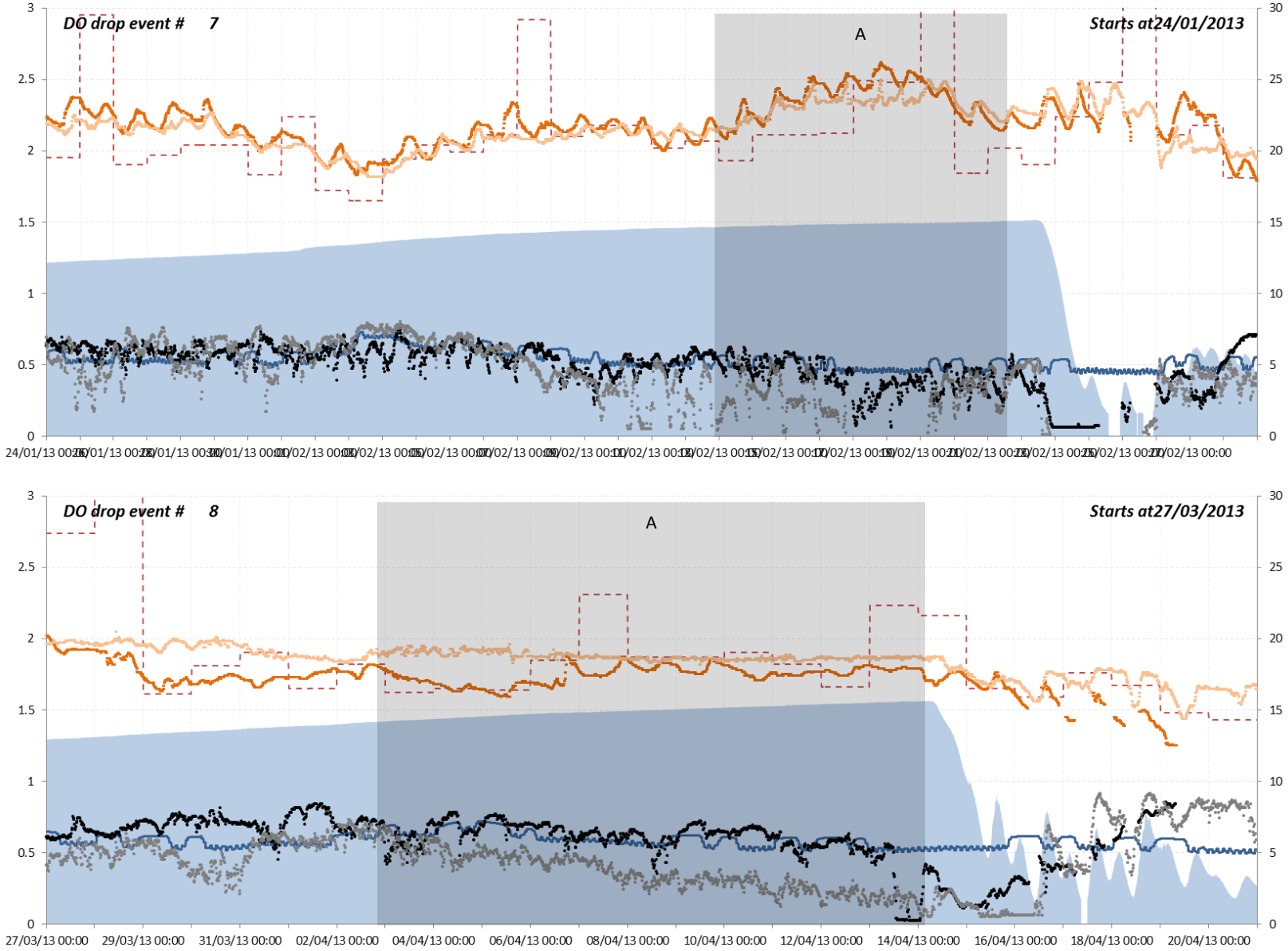
18/04/12 00:00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Starts at24/01/2013
DO drop event # 8
A
Starts at27/03/2013
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08/04/13 00:00
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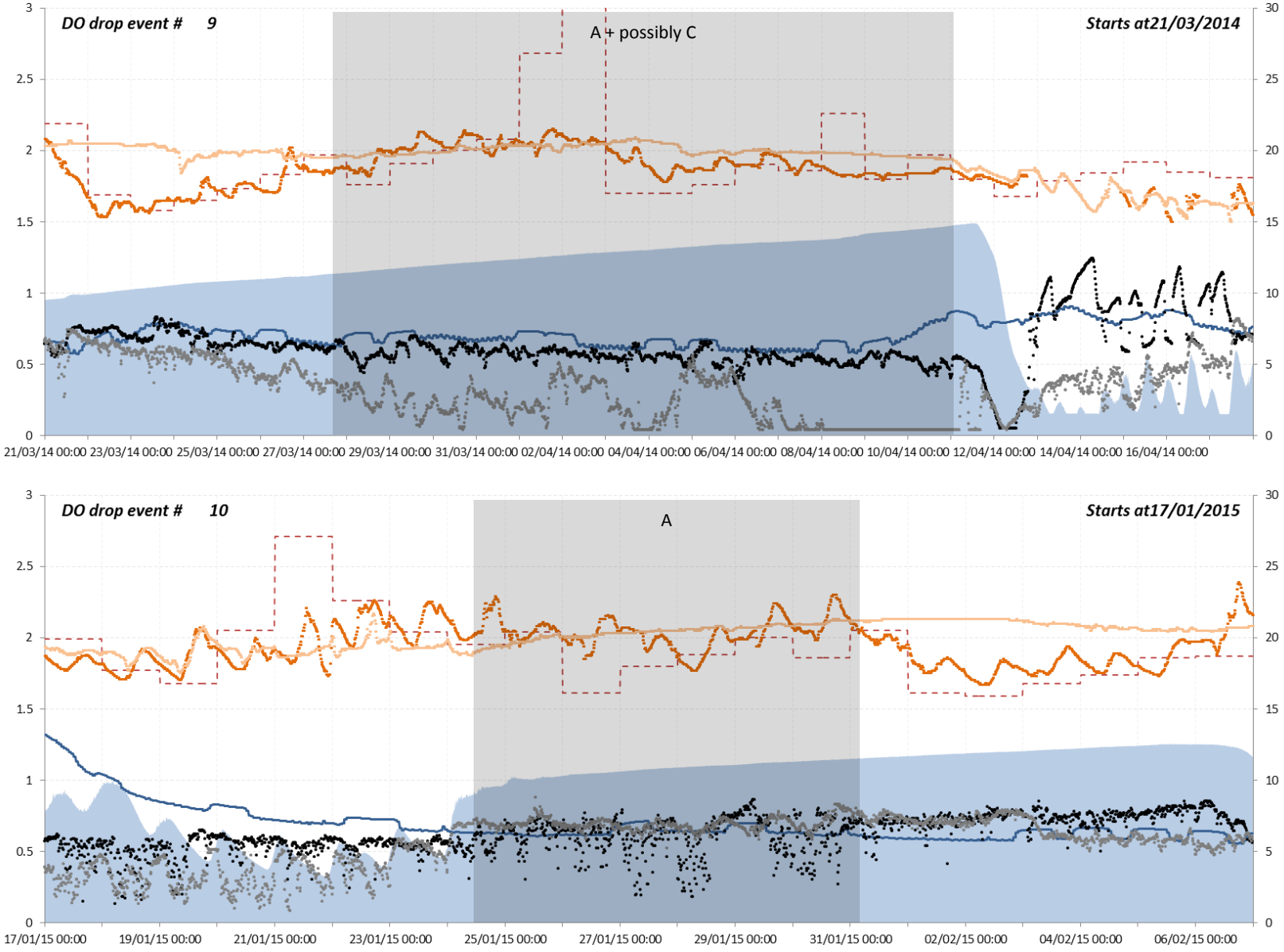
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0
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06/04/14 00:00
08/04/14 00:00
10/04/14 00:00
12/04/14 00:00
14/04/14 00:00
16/04/14 00:00
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Starts at17/01/2015
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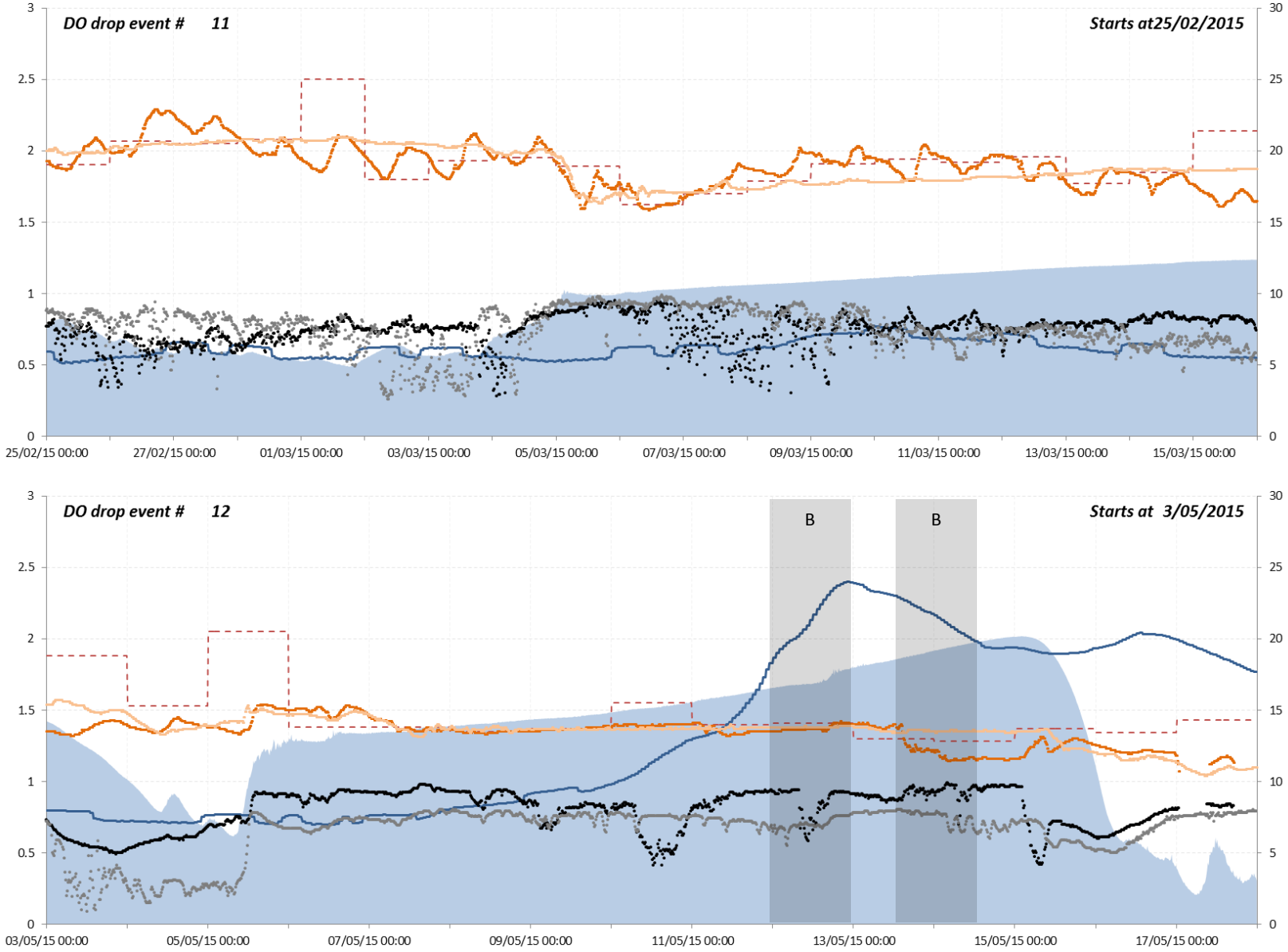
06/02/15 00:00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09/03/15 00:00
11/03/15 00:00
13/03/15 00:00
15/03/15 00:00
DO drop event # 12
Starts at 3/05/2015
B
B
03/05/15 00:00
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07/05/15 00:00
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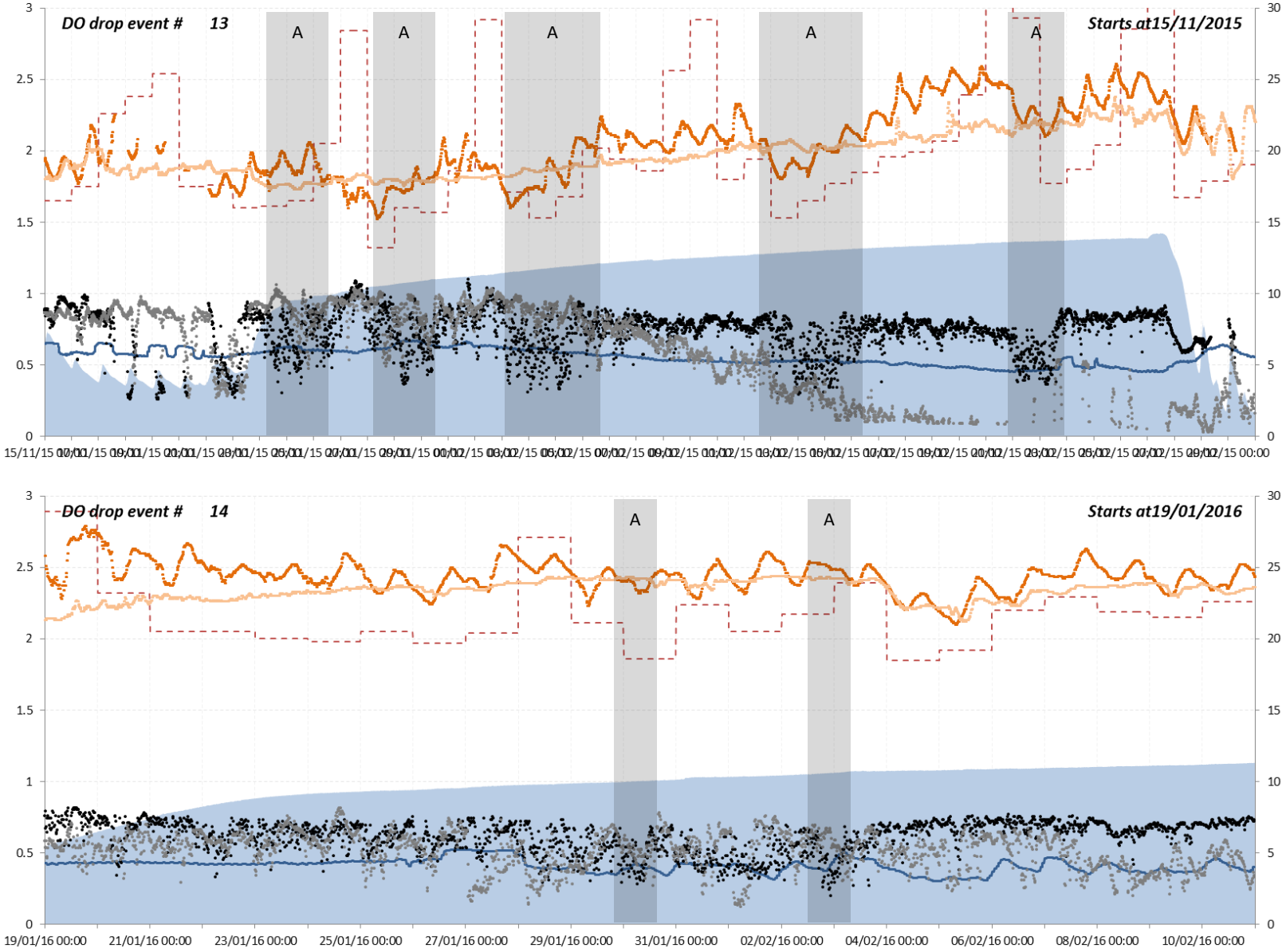
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A
A
A
A
Starts at15/11/2015
DO drop event # 14
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A
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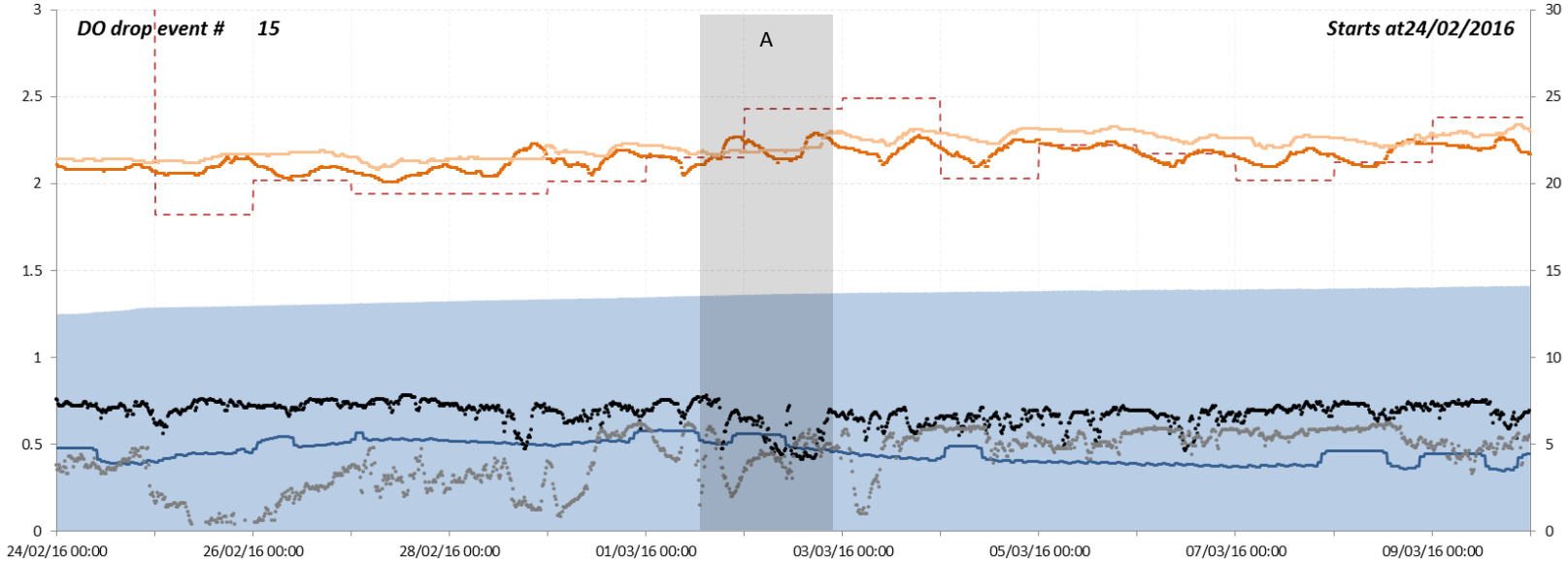
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Starts at24/02/2016
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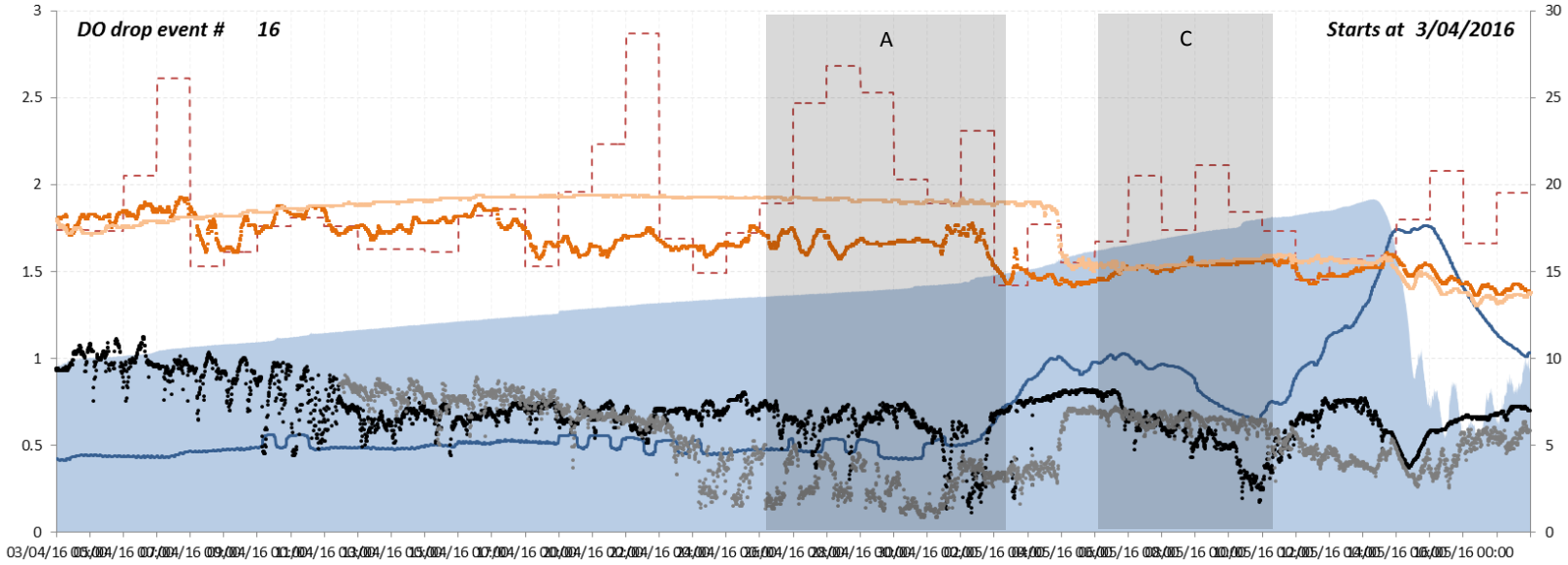
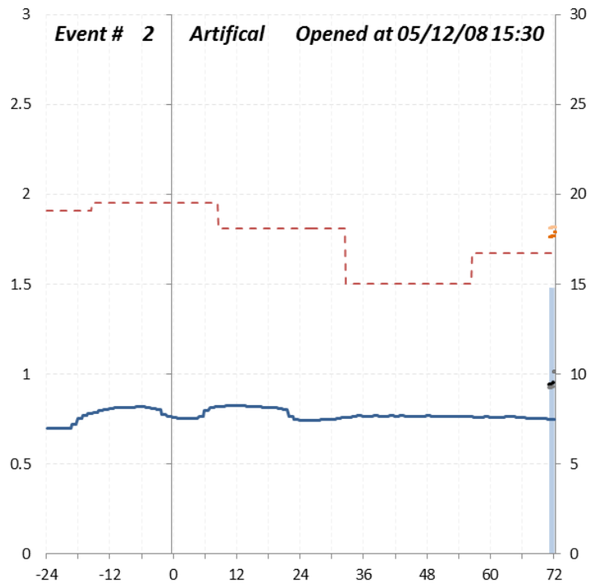
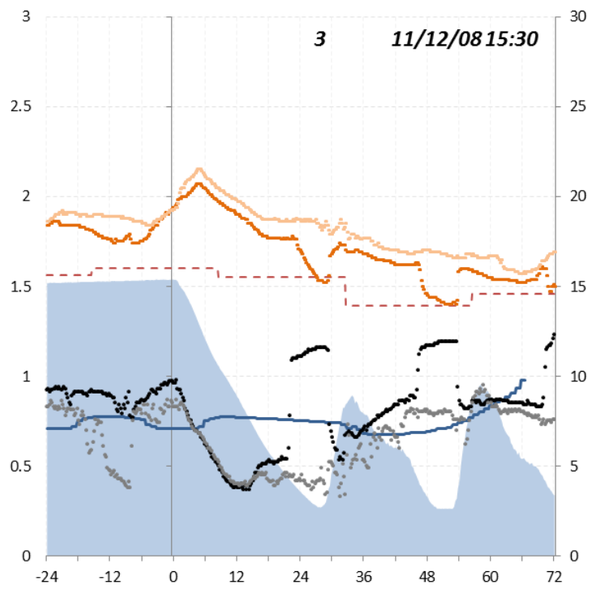
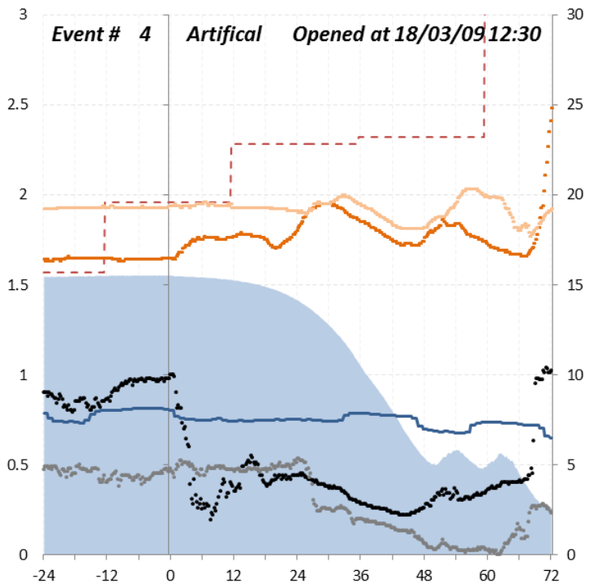
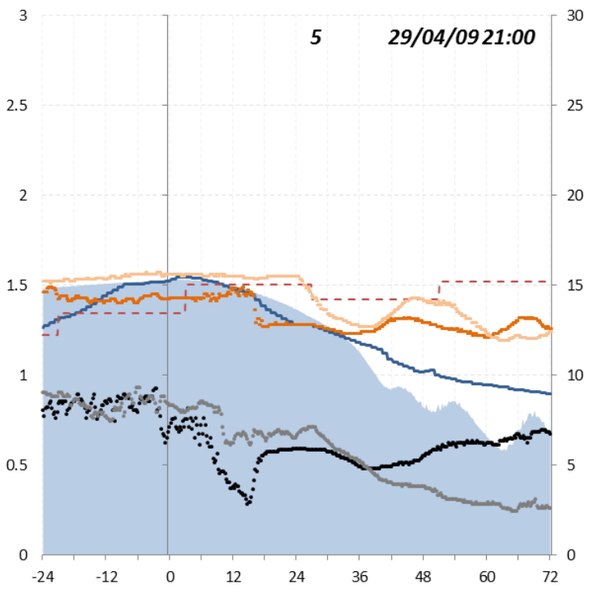
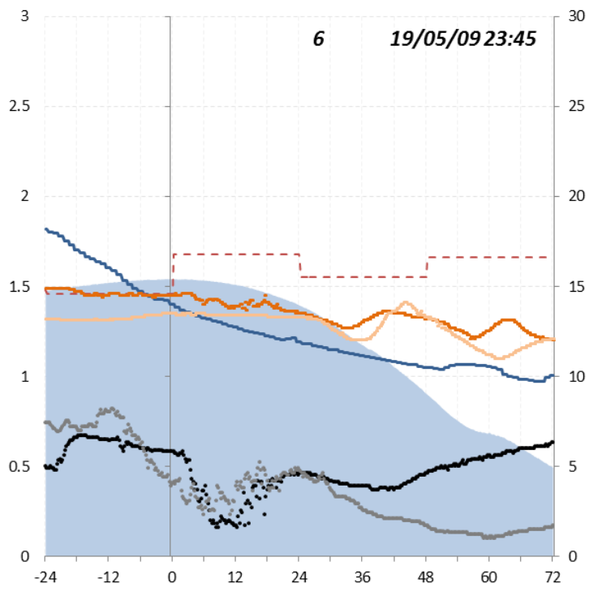
05/03/16 00:00
07/03/16 00:00
09/03/16 00:00


DO drop event # 16
A
C
Starts at 3/04/2016
3
2.5
2
1.5
1
0.5
0
30
25
20
15
10
5
0
03/04/16 00:00

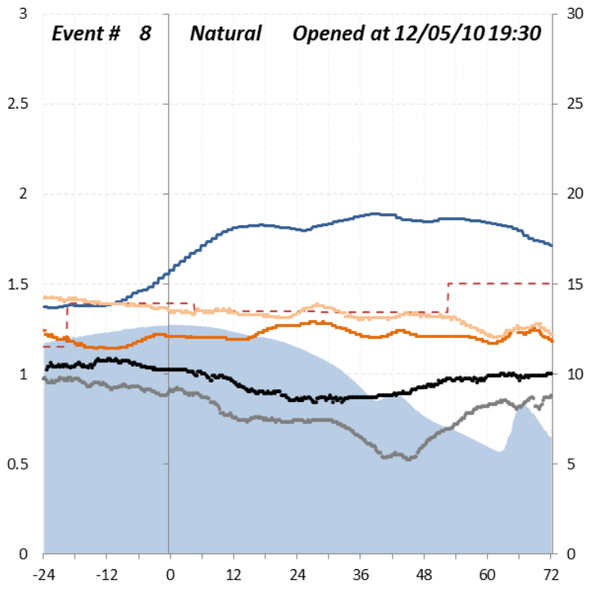
Estuary opening events

Chart	Event no.	Opening	Top DO response	Top DO values	Bottom DO values	DO summary	Catchment flow	Tidal interchange	Air temp	Water temp	Drain speed	Time to top DO>6	Stratification
	2	Artificial	No data	No data	No data	No data	Steady (low)	No data	Warm	No data	No data	No data	No data
	3	Natural	Plummets	Short dip <~5	Mostly >~5	DO falls but quick recovery	Steady (low)	Present	Cool	Warm (15-20 deg)	Fast	21.75	No data

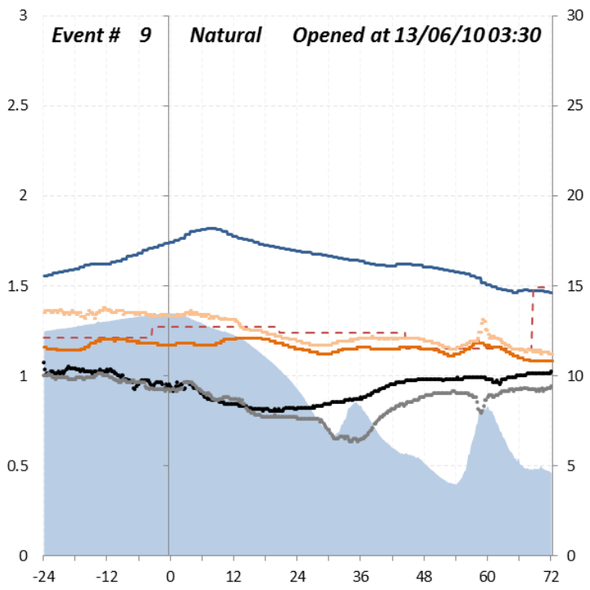
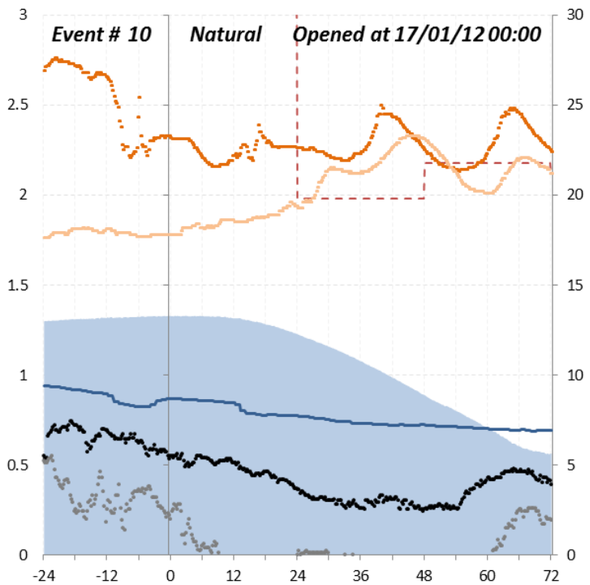
	4	Artifical	Plummets	Long dip <~5	Prolonged <~5	DO falls and slow recovery	Steady (low)	Present	Hot	Warm (15-20 deg)	Med	68.75	Fresh above
	5	Natural	Plummets	Short dip <~5	Prolonged <~5	DO falls but quick recovery	High flow	Not present	Cool	Cool (10-15 deg)	Slow	50.75	Fresh above

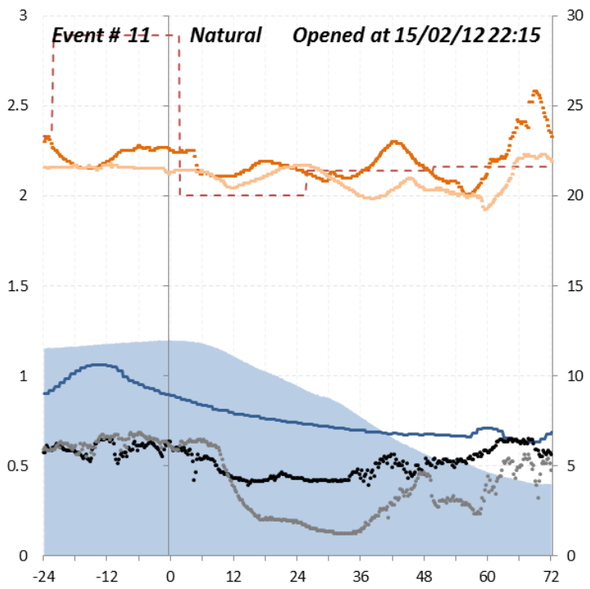
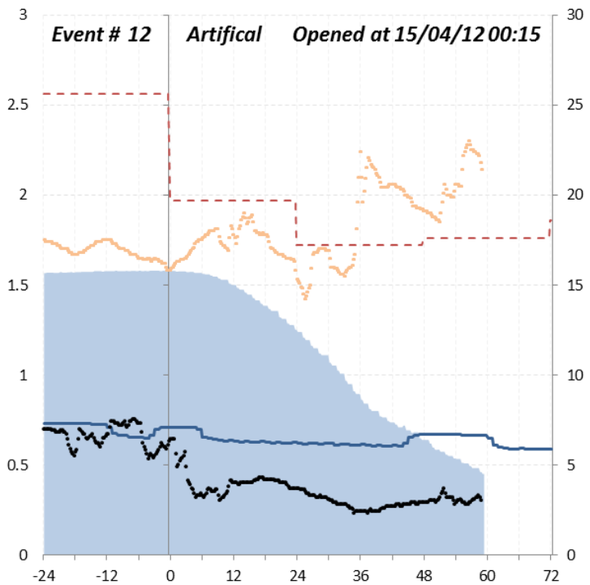


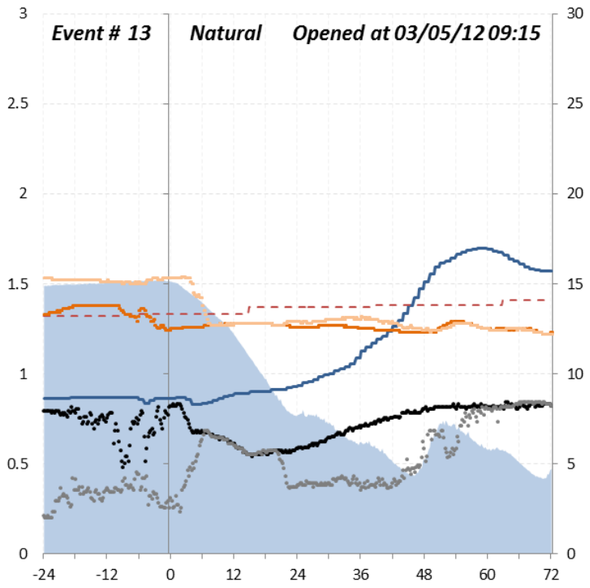
6	Natural	Plummets	Long dip <~5	Prolonged <~5	DO falls but quick recovery	High flow	Not present	Cool	Cool (10-15 deg)	Slow	65.75	Fresh above



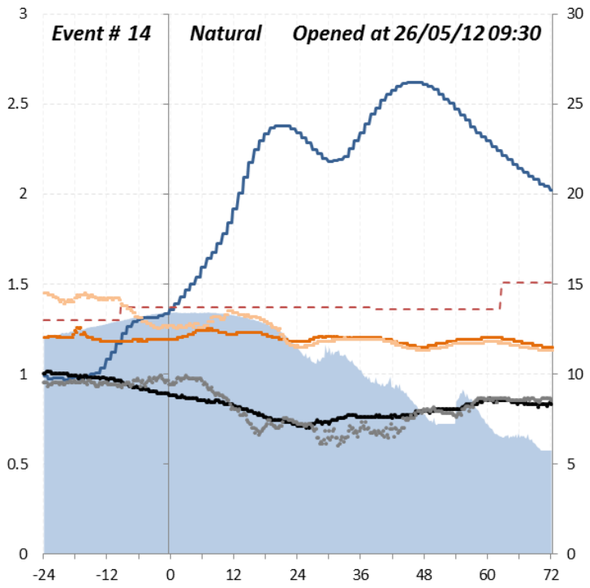
8	Natural	Gradual decline	Always >~5	Mostly >~5	DO remains highish	High flow	Not present	Cool	Cool (10-15 deg)	Slow	0	Fresh above

	9	Natural	Gradual decline	Always >~5	Mostly >~5	DO remains highish	High flow	Present	Cool	Cool (10-15 deg)	Med	0	>20% mild
	10	Natural	Gradual decline	Long dip <~5	Prolonged <~5	DO falls and slow recovery	Steady (low)	Not present	Hot	Warmer (20+ deg)	Slow	105.75	>20% mild

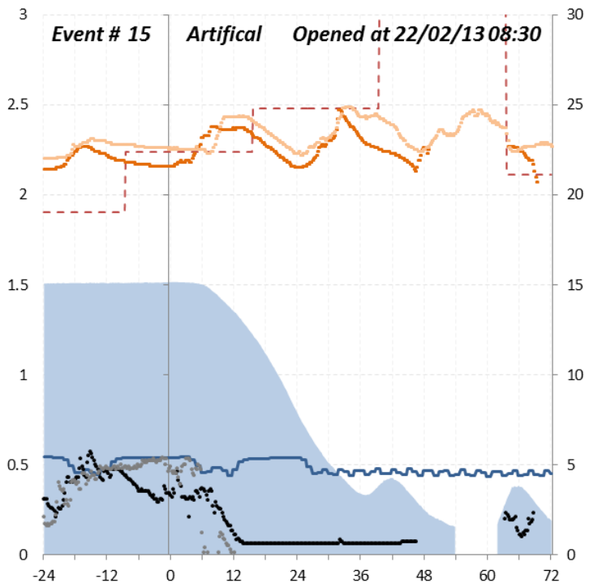
	11	Natural	Gradual decline	Long dip <~5	Prolonged <~5	DO falls and slow recovery	Steady (low)	Not present	Hot	Warmer (20+ deg)	Slow	61	Fresh above
	12	Artifical	Plummets	Long dip <~5	No data	DO falls and slow recovery	Steady (low)	Not present	Hot	Warmer (20+ deg)	Med	107.5	No data



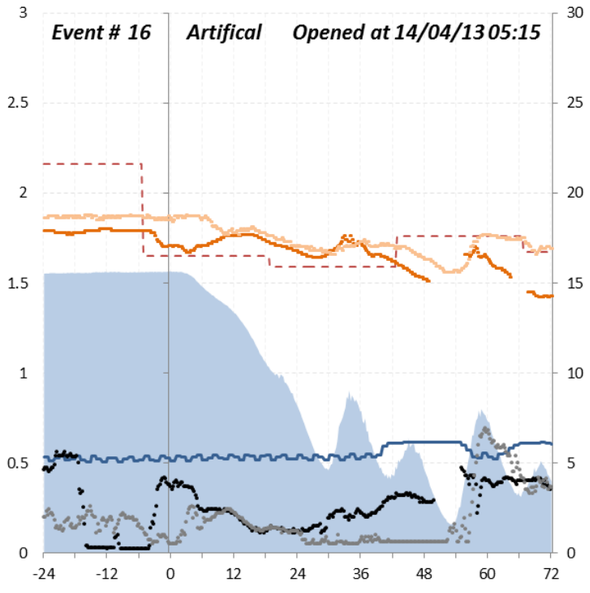
13	Natural	Plummets	Always >~5	Prolonged <~5	DO remains highish	High flow	Present	Cool	Cool (10-15 deg)	Fast	0	Fresh above



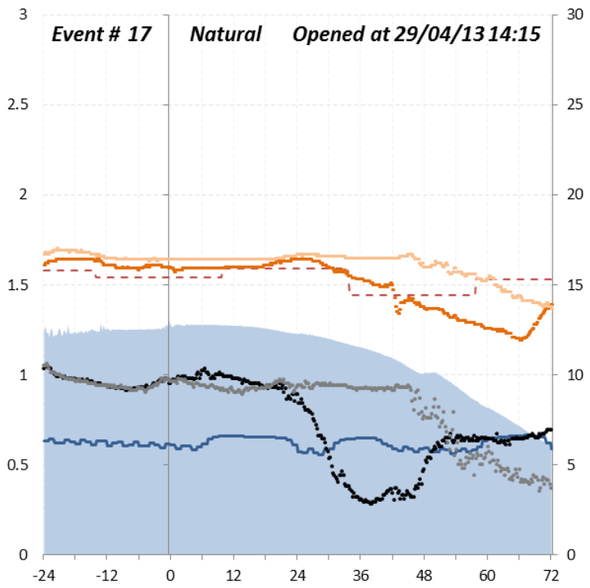
14	Natural	Gradual decline	Always >~5	Mostly >~5	DO remains highish	High flow	Present	Cool	Cool (10-15 deg)	Slow	0	>15% mod-high



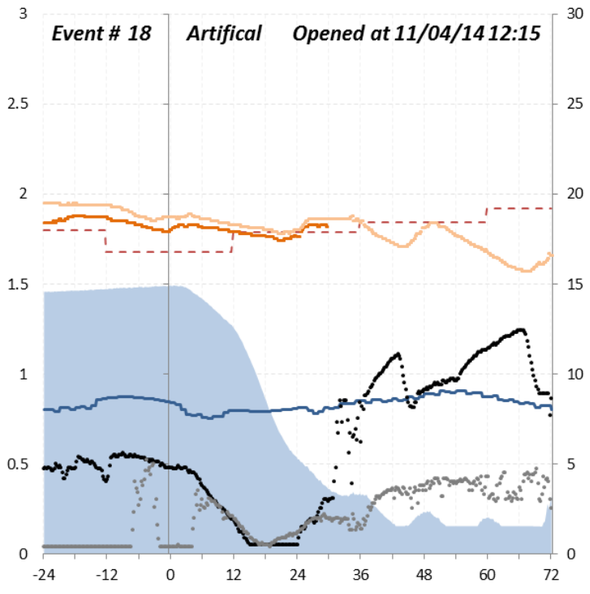
15	Artifical	Plummets	Long dip <~5	No data	DO falls and slow recovery	Steady (low)	Present	Hot	Warmer (20+ deg)	Fast	120+	Fresh above



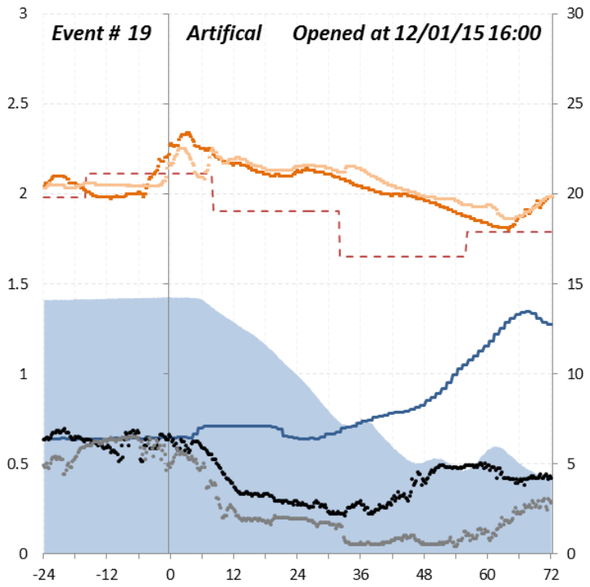
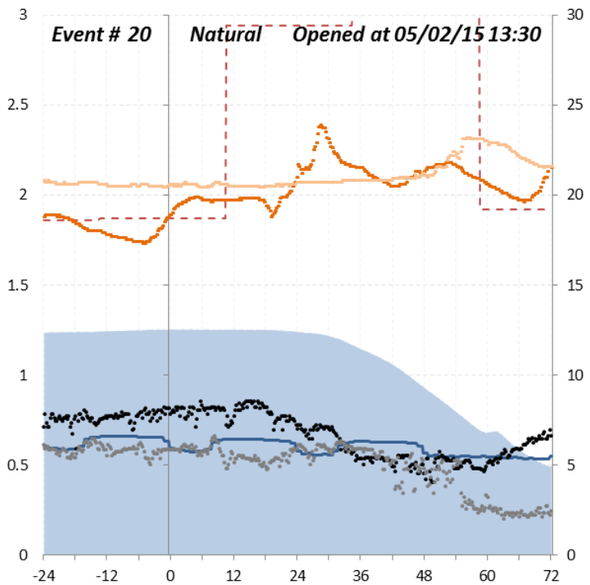
16	Artifical	Plummets	Long dip <~5	Prolonged <~5	DO falls and slow recovery	Steady (low)	Present	Warm	Warm (15-20 deg)	Fast	93	Fresh above

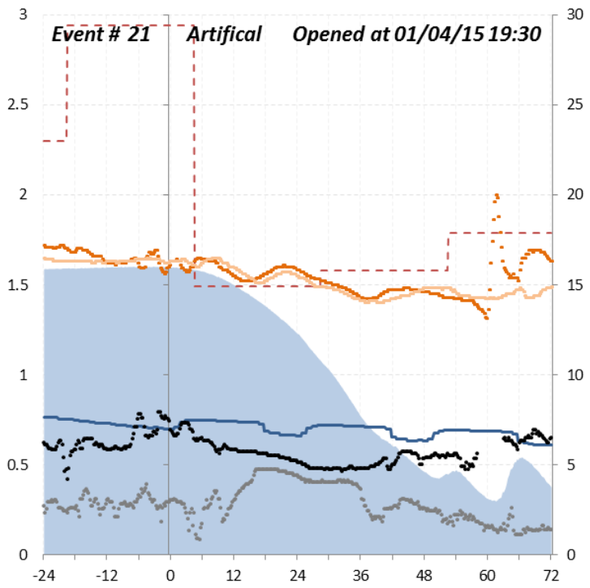


17	Natural	Plummets	Long dip <~5	Mostly >~5	DO falls but quick recovery	Steady (low)	Not present	Cool	Warm (15-20 deg)	Slow	50	Fresh above

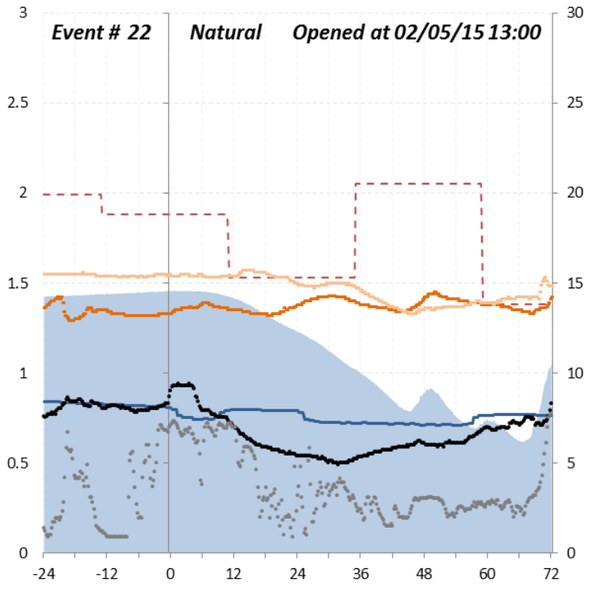


18	Artifical	Plummets	Long dip <~5	Prolonged <~5	DO falls but quick recovery	Steady (low)	Present	Warm	Warm (15-20 deg)	Fast	31.5	>15% mod-high

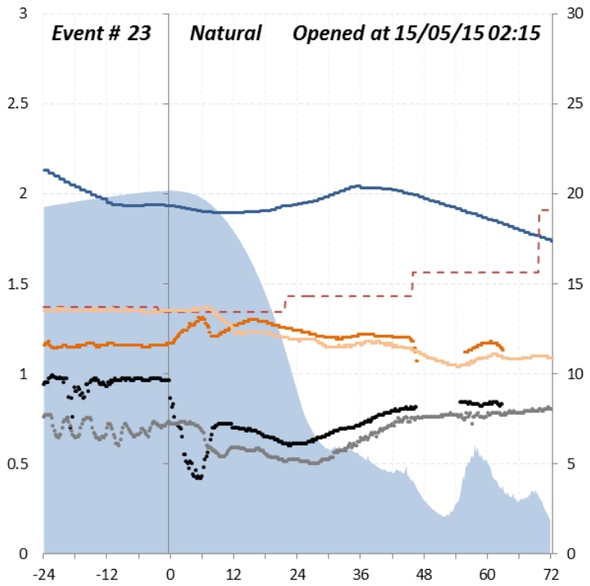
	19	Artifical	Plummets	Long dip <~5	Prolonged <~5	DO falls and slow recovery	High flow	Present	Warm	Warmer (20+ deg)	Med	105.75	Fresh above
	20	Natural	Plummets	Always >~5	Prolonged <~5	DO remains highish	Steady (low)	Not present	Hot	Warmer (20+ deg)	Slow	66.75	Fresh above



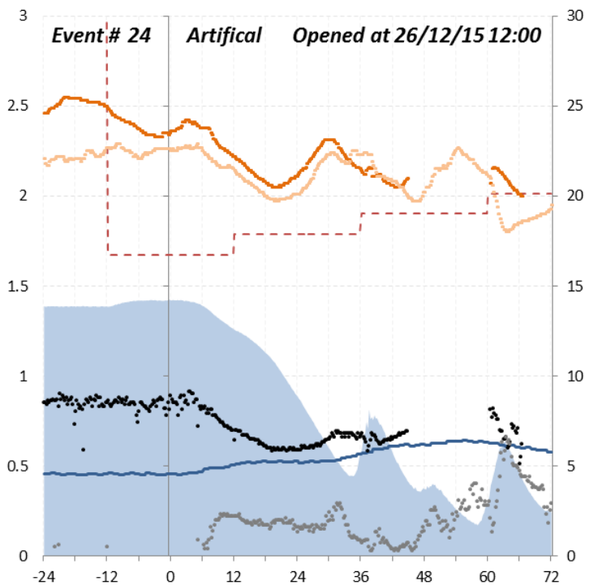
21	Artifical	Gradual decline	Always >~5	Prolonged <~5	DO remains highish	Steady (low)	Present	Hot	Warm (15-20 deg)	Med	63	>15% mod-high



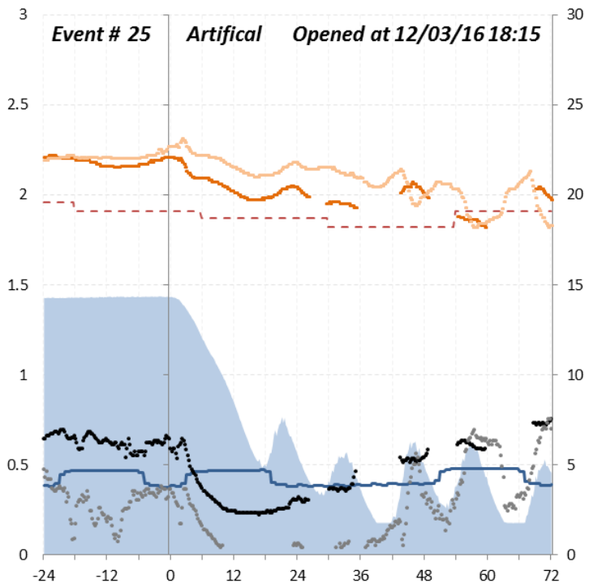
22	Natural	Plummets	Always >~5	Prolonged <~5	DO falls and slow recovery	Steady (low)	Present	Warm	Cool (10-15 deg)	Slow	44.75	>20% mild



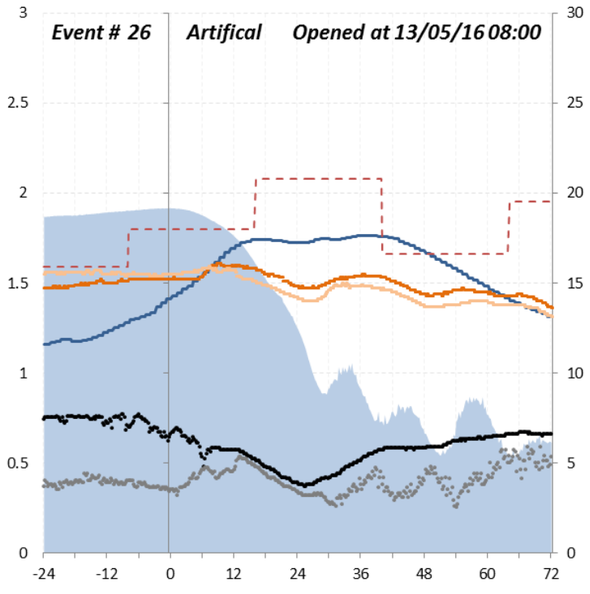
23	Natural	Plummets	Short dip <~5	Mostly >~5	DO falls but quick recovery	High flow	Present	Cool	Cool (10-15 deg)	Fast	7.5	>15% mod-high



24	Artifical	Plummets	Always >~5	Prolonged <~5	DO remains highish	Steady (low)	Present	Hot	Warmer (20+ deg)	Med	60.5	Fresh above



25	Artifical	Plummets	Long dip <~5	Prolonged <~5	DO falls and slow recovery	Steady (low)	Present	Warm	Warmer (20+ deg)	Fast	54.25	>20% mild



26	Artifical	Plummets	Short dip <~5	Prolonged <~5	DO falls and slow recovery	High flow	Present	Warm	Cool (10-15 deg)	Fast	51.75	Fresh above

Attachment E
Estuary entrance dynamics

The Entrance Dynamics of the Gellibrand River Estuary.



Report and analysis prepared for Alluvium Consulting, February 2017.

Sarah L. McSweeney. (Ph.D. Coastal Geomorphology (Science))

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1.0 Introduction

1.1 Geomorphic Classification of the Gellibrand River Estuary

In terms of geomorphology, the Gellibrand River Estuary is classified as an Intermittently Closed and Open Lake and Lagoon (ICOLL) estuary type (Figure 1). ICOLLs are a specific type of microtidal, wave-dominated estuary which experience periodic entrance closure to the ocean.

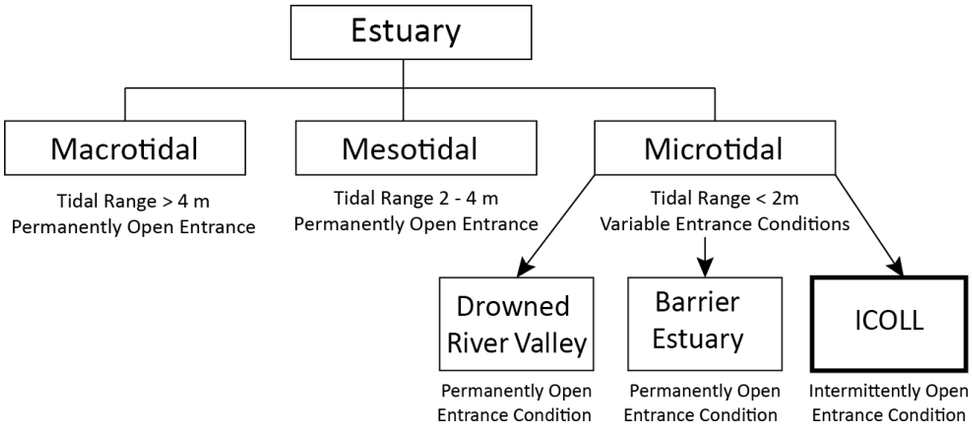
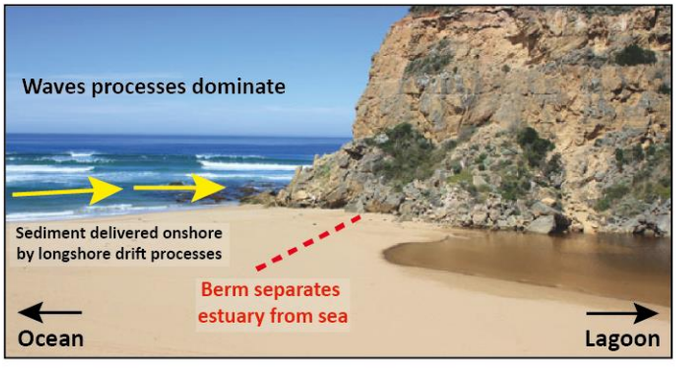


Figure 1: Geomorphic classification of estuaries (after Roy, 1984). The Gellibrand Estuary is classified as an Intermittently Closed and Open Lake and Lagoon (ICOLL). All estuaries along the open coastline of Victoria are microtidal (i.e. wave-dominated) with the majority (91 %) being ICOLLs (McSweeney *et al.,* 2014).

When the estuary entrance of an ICOLL is open, there is a regular exchange of tidal flow between the estuarine lagoon and the ocean through the entrance channel (Figure 2). During periods of closure the estuary becomes completely separated from the ocean by a subaerial beach berm with no tidal exchange occurring (Figure 2). When the estuary remains closed for prolonged durations, a decrease in water quality can occur along with flooding in the catchment as lagoon water levels increase behind the berm. In an open state, tidal and fluvial processes tend to dominate the system with any river flow adding to the ebb-tidal prism. When the entrance is closed, it becomes effectively dominated by wave processes whereby sediment is delivered to the entrance by waves and typically by longshore drift.

(a) Closed Entrance Condition



(b) Open Entrance Condition

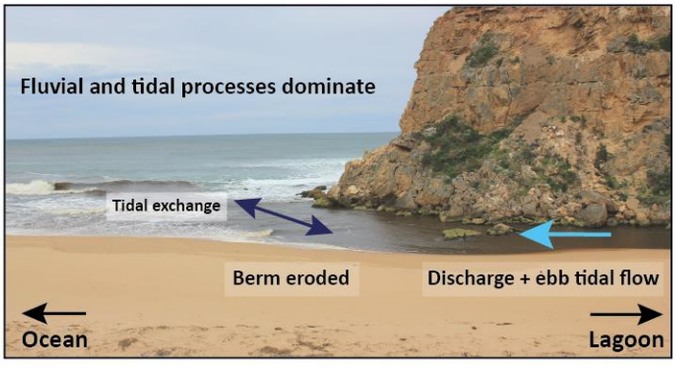


Figure 2: Conceptual diagram of (a) closed and (b) open entrance states. Photos from Estuary Watch Victoria (2017).

1.2 General Boundary Conditions of ICOLLs

Internationally, ICOLLs are found along strongly wave-dominated, microtidal coastlines (tidal range < 2 m). The microtidal range facilitates sediment stabilisation within the entrance channel due to lower tidal current velocities. A strongly wave-dominated coastline facilitates the formation of a subaerial berm which separates estuaries from the ocean and also means that high volumes of sediment are delivered onshore by wave processes. For example, the rate of deposition from longshore drift is increased under larger wave heights and on sandy beaches is directly proportional

to the longshore component of wave power (Komar and Inman, 1970; Takeda and Sunamura, 1987; Jensen *et al.,* 2009). ICOLLs are also located on rivers which have a low mean annual discharge or with inter or intra-annually variable flow regimes. Periods of low flow facilitate sediment deposition within the entrance channel as the ebb-tidal current is weakened thus reducing the amount of sediment which can be eroded from the entrance channel.

1.3 ICOLL Entrance Dynamics

Entrance Closure Mechanisms

In general, entrance closure typically occurs during periods of low fluvial discharge when waves dominate over fluvial and tidal processes. During low flow periods, sediment is delivered onshore at a rate that exceeds the ability of the ebb-tidal current to remove it from the entrance channel. The ebb-tidal current refers to the combined influence of ebb-tides (outgoing) combined with any fluvial discharge which acts to erode sediment from the entrance channel.

There are two mechanisms of entrance closure in ICOLLs (Ranasinghe and Pattiaratchi, 1999; 2003; McSweeney, 2015):

(1) Longshore drift deposition whereby under a weakened ebb-tidal current, longshore drift deposits sediment into the mouth to form a spit across the entrance channel during low river flows (Battalio *et al.,* 2004);
(2) Cross-shore transport whereby near shore normal waves gradually transport sediment onshore by cross-shore processes under a weakened ebb-tidal current.

Regardless of the dominant transport process, sediment transport into the estuary entrance occurs at a higher rate during large swells and low river flows (Morris and Turner, 2010; Hanes *et al.,* 2011).

Entrance Opening Processes

In Victoria, most ICOLLs are opened artificially before they can naturally open and therefore defining natural opening thresholds can be difficult due to a lack of data capturing these often irregular events. The natural opening threshold refers to the point where the beach berm is overtopped by the water within the estuary basin and a channel is formed which connects the lagoon to the ocean. This is driven by the difference in hydraulic head between the water elevation within the estuarine basin and the height of the berm.

There are two main observed mechanisms of natural entrance opening in ICOLLs in Victoria:

(1) Overtopping from the catchment side due to increased fluvial discharge during floods (Cooper, 2001);
(2) Wave overwash from the ocean side occurring during high swells (whereby waves overtop the berm and raise the estuary water level thus increasing hydraulic head between the lagoon and the ocean) (Hart, 2007).

In addition to the critical threshold between the berm elevation and the estuary basin water level, the tidal cycle (i.e. spring or neap) is also influential, especially when wave overwash is an active process influencing the estuary water level. During high and spring tides the landward limit of wave breaking is increased meaning that runup may be more likely to overtop the berm and spill into the lagoon (Hart, 2007; Baldock *et al.,* 2008; Hanes *et al.,* 2011). The beach width is also important as wave runup is more likely to reach the lagoon when the beach is narrow. For openings occurring due to overtopping form the catchment side, any spilling outflow from the lagoon will encounter less resistance in reaching the ocean under a narrow beach width and therefore be more likely to incise a channel.

2.0 Methods

2.1 Identifying Marine and Fluvial Boundary Conditions

2.1.2 Marine Boundary Conditions

Marine boundary conditions were analysed to identify the local wave and tidal processes influencing the entrance morphology of the Gellibrand River Estuary (Table 1). Daily wave data throughout the monitoring period of available

entrance condition data (2007 - 2017) was hindcast from National Oceanic and Atmospheric Administration's (NOAA) WAVEWATCH III model at a grid point 40 km offshore directly adjacent to the rivermouth. Wave hindcasting was undertaken as no permanent wave bouys are present in Victoria. Data was extracted using MatLab software and also presented as a yearly time series (Appendix 1). Parameters included: wave direction and significant wave height (H_s). Tidal range data for the Gellibrand River Estuary was obtained from the Bureau of Meteorology records. The tidal range (i.e. spring or neap) was analysed in relation to the timing of entrance opening and closures.

Table 1: Sources of data used in analysis and extent of monitoring period.

Parameter	Unit	Source	Data Extent	Site
Mean daily fluvial discharge	ML/day	DELWP	1/1/07 - 31/12/16	Burrupa. 235224
Daily rainfall	mm	BOM	1/1/07 - 31/12/16	Gellibrand Forestry. 90134
Estuary basin water depth	m/AHD	DELWP	1/11/08 - 15/11/16	Princetown. 235269
Mean daily significant wave height	m	NOAA WaveWatch III	1/1/07 - 1/10/16	-38.5, 142.5
Mean daily wave direction	°	NOAA WaveWatch III	1/1/07 - 1/10/16	-38.5, 142.5
Entrance opening duration	days	Estuary Watch VIC	31/5/07 - 13/1/17	Gellibrand mouth
Tidal elevation	m	BOM	1/1/07 - 31/12/16	Portland gauge
Morphological surveys	m/MSL	McSweeney, 2015	April - Jan 2014	Gellibrand mouth

2.1.2 Fluvial Conditions

Fluvial parameters analysed included the mean daily discharge, daily rainfall and mean daily water elevation in the estuary basin (to AHD) (Table 1).These were presented as yearly time series (Appendix 1) and analysed in relation to the occurrence of entrance openings and closures.

2.2 Identifying Entrance Dynamics

A daily record of entrance condition was obtained from Estuary Watch Victoria's online database (Table 1). The frequency and duration of entrance closures and openings were analysed in relation to the concurrent marine and fluvial conditions. In addition, data from a recent PhD thesis (McSweeney, 2015) was used to provide surveys of entrance morphology of the Gellibrand Estuary during an artificial opening occurring in April 2014. The change in entrance channel morphology was analysed using a Trimble R6 model Real Time Kinematic (RTK) GPS. A fixed entrance cross section at the mouth (in line with the berm position) and a long profile along the channel thalweg were surveyed. Throughout the monitoring period the first survey was taken 6 hours prior to opening. Survey data had a general accuracy of 3 mm and was referenced to at least two permanent benchmarks established relative to mean sea level (MSL) by RTK GPS (benchmark accuracy 1 - 2 mm). From this data, the berm elevation was analysed in relation to the estuary water elevation (above AHD) to develop a ratio of the likely proximity to entrance closure. The analysis of berm height relative to water elevation was limited to the thesis data due to no other known measurements of berm height referenced to mean sea level. The change in channel morphology was also analysed relative to marine and fluvial conditions in order to identify the dominant processes of deposition within the channel.

2.3 Predictive Model of Opening Duration

Multiple linear regression analysis using a stepwise selection criteria was used to predict the probable duration of entrance openings. The equation was created by using entrance opening data from Estuary Watch Victoria to identify the historic durations of entrance opening (both natural and artificial). One opening with a duration of 988 days (Estuary Watch VIC data) was omitted from the entrance condition record due to a lack of frequent observations and incompatibilities between entrance and flow conditions throughout the monitoring period. Historic daily data of: rainfall, mean daily flow, significant wave height, wave direction and estuary water depth were calculated as averages over each opening period and input as parameters (Table 1). All data were tested for autocorrelations and normality (Appendix 2). The multiple linear regression analysis identified LogMeanDailyDischarge, LogSignificantWaveHeight and WaveDirection as being the strongest predictors of opening duration and were used to build the predictive model.

2.4 Seasonal Probabilities of Opening Duration and Risk Matrix

The historic range of observed discharge, wave height and direction values for each month of the year were tested for normality and fit with Weibull distributions. The Weibull distribution is selected as it provided the best fit for the data along with being recognised as a good fit for many natural datasets which do not show a normal distribution (e.g. ocean wave heights (Battjes, 1972); hydrology (Singh, 1986); rainfall (Wilks, 1989), wood in rivers (Stout, 2016); fire occurrence (Grissino-Mayer, 2000); flood risk (Apel *et al.,* 2006)). Distributions were fit in MatLab R2015b using the maximum likelihood method. The predictive multiple linear regression model was then applied for each month using the historic range of data to output a range of probable opening durations. Opening durations were cut at 1000 days (as only output for the months of July - September) to maintain similarity across the monthly distributions. To populate the model, a Monte Carlo simulation was scripted in Python and run 1000 times for each month sampling at random from each monthly distribution. The output opening durations were then extracted as tables and plotted as exceedance probability graphs. For each month, the exceedance probability was presented for four opening scenarios: (a) 1 day (unsuccessful opening, rapid closure); (b) 1 week; (c) 1 month (31 days); (d) 90 days. Values were input into a table and used to create a risk matrix of the likely probability of an opening exceeding each of the four scenarios for each month of the year. Risk was classified as 20 % intervals. The risk matrix is designed to be used to supplement the predictive equation and as reference for the monthly exceedance probabilities of opening duration for each scenario.

3.0 Boundary Conditions of the Gellibrand River Estuary

3.1 Marine Boundary Conditions

The coastline adjacent to the Gellibrand Estuary is strongly wave-dominated with a microtidal range of 0.90 m at Portland in west Victoria. The average significant wave height (Hs) is high by global standards with a mean annual Hs of 2.44 m (±0.25 m) (Table 2). Wave heights peak during June to October due to the influence of winter storms.

The relative tidal range (RTR) can provide a further quantification of the relative balance of tide vs wave processes acting along a coastline. A value < 3 equates to a wave-dominated coastline whereas values > 3 indicate increasing tidal process dominance. At the Gellibrand Estuary the RTR is 1.45 which is at the upper end of wave-dominance even when compared to the national average for ICOLLs in Australia (Table 3).

Table 2: Historic marine and fluvial conditions at the Gellibrand Estuary including mean daily significant wave height (Hs) (m), wave direction (dir) (°), mean daily discharge (ML/day), mean daily rainfall. Data averaged over 2007 - 2017.

Month	Mean Daily Hs (m)	Mean Daily Wave Dir (°N)	Mean Daily Wave Dir (° shore normal)	Mean Daily Discharge (ML/day)	Mean Daily Rainfall (mm/day)
Jan	2.12	211.45	31.45	189.22	1.32
Feb	2.17	208.94	28.94	118.86	1.12
Mar	2.19	208.60	28.60	125.30	2.13
Apr	2.50	209.44	29.44	169.63	2.80
May	2.57	211.18	31.18	335.99	3.82
Jun	2.65	212.11	32.11	707.94	3.79
Jul	2.62	212.05	32.05	1253.37	4.43
Aug	2.77	214.01	34.01	1935.30	5.16
Sep	2.79	214.24	34.24	1194.01	3.54
Oct	2.60	211.57	31.57	684.86	2.76
Nov	2.21	211.00	31.00	371.71	1.95
Dec	2.15	210.69	30.69	276.91	2.19

Table 3: Summary of geomorphic characteristics of the Gellibrand River Estuary relative to estuaries and ICOLLs in Australia. Data from all estuaries and ICOLLs from NLWRA (2002) estuary dataset (790 estuaries). RTR is calculated by mean spring tidal range/breaking wave height (m) after (Masselink and Short, 1993).

Parameter	Gellibrand	Mean for Estuaries in Australia	Mean for ICOLLs in Australia
Relative tidal range (RTR)	1.45	5.50	1.71
Spring tidal prism (x 10^6 m^3)	17	48.13	5.84
Catchment area (km^2) (Burrupa)	1046	3277.61	632.24

At the Gellibrand River mouth, the dominant direction of wave approach is from the SSW - SW (Table 2). Waves tend to approach the estuary at an angle from the shore-normal of between 28.60 - 32.40° (±1.68°) (Table 2). Despite some seasonal variability, this corresponds to a year round oblique direction of approach which is indicative of longshore drift as a primary mode of onshore sediment delivery. Longshore drift is known to be most efficient at delivering sediment to beaches when the angle of approach relative to the shoreline is between 32 - 45° and the rate of drift deposition increases under larger wave heights (Ranasinghe and Pattiaratchi, 1999; Siegle and Asp, 2007).

3.2 Fluvial Boundary Conditions

The Gellibrand River shows seasonal variability in river discharge with peak flows occurring during June - October. Peak rainfall also occurs during the winter months between May to September. Both river flow and rainfall are also inter annually variable (Appendix 1). Both in Victoria and internationally, ICOLLs tend to be located on rivers with small catchments (< 2000 km^2) (Cooper, 2001; McSweeney, 2015). The catchment of the Gellibrand River is 1046 km^2 which is relatively small when compared to the mean from a sample of estuaries from all states in Australia (Table 3). The catchment of the Gellibrand River is however higher the national average for ICOLLs in Australia (Table 3).

3.3 Tidal Prism

The tidal prism is a further parameter which is influential in maintaining an open entrance condition in estuaries. The tidal prism refers to the intertidal volume of water within an estuary and is a function of the basin area or volume of the estuary and the oceanic tidal range (Barber, 2003). The ebb-tidal prism includes the contribution of any fluvial discharge added to the intertidal volume moving seaward with the ebb-tide. This means that during floods, the ebb-tidal prism can increase and therefore the channel becomes more hydraulically efficient at removing any sediment deposited by waves (Bruun, 1986; Hume and Herdendorf, 1988). Relative to other estuary types, ICOLLs tend to have small tidal prisms and lower tidal current velocities as attributed to their setting in microtidal regions, generally small basin and entrance cross-sectional areas and presence on rivers with low mean annual discharges (Cooper, 2001).

The Gellibrand River Estuary has a tidal prism of 17 x 10^6 m^3 (Table 3). When compared to a sample of all estuary types in Australia, including those along macrotidal coastlines, this value is relatively low (Table 3). In comparison to the national average for ICOLLs however this value becomes quite high as attributed to the large basin area of the estuary relative to the many smaller ICOLLs. It is therefore likely that the larger than average tidal prism and catchment area (relative to the mean value for Australian ICOLLs) provides a higher capacity for the Gellibrand River to erode sediment delivered by waves during periods of high river flow.

3.4 Entrance Condition Overview

On average, the Gellibrand River Estuary is opened twice per year artificially for an average duration of 84 days (Table 4). Natural openings occur once per year and last for 205 days on average. The estuary closes on average 2.70 times per year for an average duration of 17 days at a time (Table 4). The majority of closures occur between December - April and the majority of natural openings occur between April - June.

Table 4: Entrance closure and opening duration and frequency 2007 - 2017 (data:Estuary Watch Victoria, 2017).

	Artificial Openings	Natural Openings	All Openings
Openings			
Mean Opening Duration (days)	84	205	123
St.Dev. (days)	98	313	203
Mean Opening Frequency (openings/year)	2	1	3.10
St.Dev. (openings)	0.90	1	1.60
Closures			**All Closures**
Mean Closure Frequency (closures/year)			2.70
Standard Deviation (closures)			1.70
Mean Closure Duration (days)			17
Standard Deviation (days)			15

4.0 Results

4.1 Processes Driving Entrance Closure

At the Gellibrand River, the dominant process of entrance closure is deposition by longshore drift under a weakened ebb-tidal current (Figure 3). As the majority of waves observed in all years of historic data approach the shore at an oblique angle between 28 - 45°, longshore drift (as opposed to cross-shore, shore normal transport) is a primary driver of berm building and entrance closure.

Following opening, the lagoon typically drains to a minimum depth within 48 hours following opening (Appendix 1; Figure 3a). Following drainage, the hydraulic head between the estuary and the ocean is removed and the opening duration becomes a function of the relative balance between wave driven deposition and the ebb-tidal current (i.e. tidal flow + river discharge). If river flow remains low (typically < 150 ML/day), the channel cross-sectional area at the mouth progressively decreases and the berm elevation increases to constrict the channel (Figure 3b - c). The growth of a spit across the entrance in the direction of drift is a further morphological indicator of this process. If river flow increases, the entrance spit can be eroded and the opening duration extended until low flows again occur (Figure 3d).

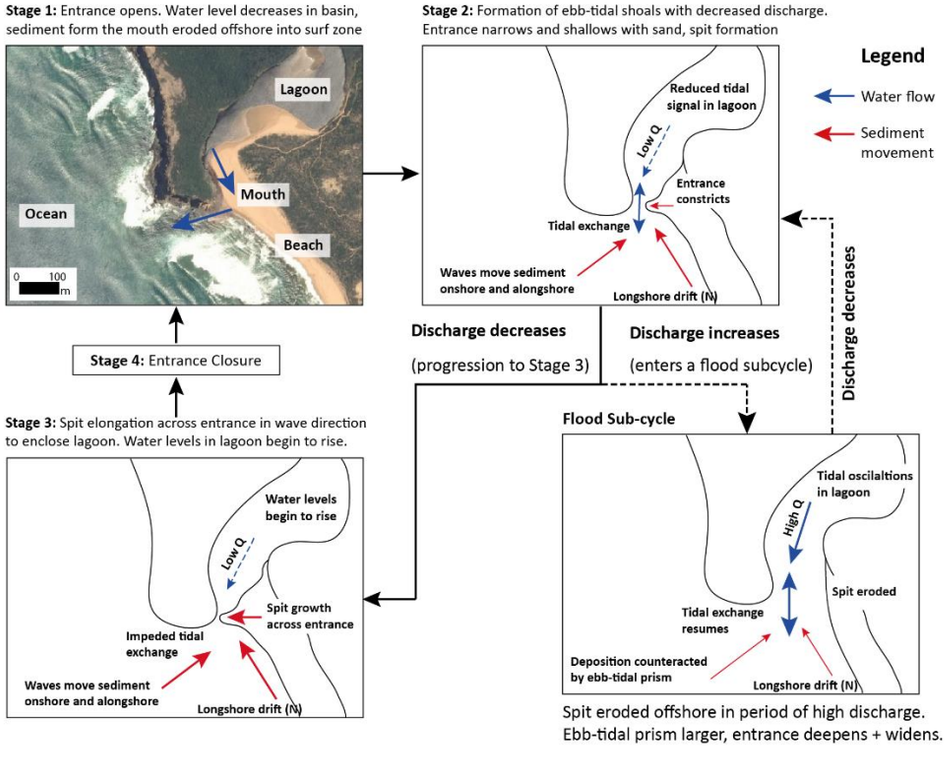


Figure 3: Conceptual model of sequence of entrance closure at the Gellibrand River Estuary.

4.2 2014 Case Study

The change in entrance channel morphology was surveyed as part of a recent PhD thesis (McSweeney, 2015) following an artificial entrance opening on 11 April 2014 and lasting for 249 days. The coinciding change in marine and fluvial conditions, along with estuary basin water depth are presented in Table 5; Figure 4a - h; Figure 5a -c.

At the time of artificial opening, a berm +3.79 m MSL was present at the mouth of the Gellibrand River. Two days after excavation, the channel bed at the former berm position attained its maximum depth (- 0.49 m MSL) and cross-sectional area (165 m^2) concurrently while the estuarine lagoon decreased from +1.44 to 0.20 m MSL (. Following day 2, the channel thalweg diverted to the west and maintained an area of deeper scour alongside the base of the cliff where it remained until closure. By day 60, the berm had rebuilt to +0.45 MSL coinciding with a period of discharge below the mean annual flow. From late June to September the mean daily river flow for 2014 (482.04 ML/day) and rainfall (2.50 mm/day) were exceeded. Throughout this time, the estuary bed depth at the former berm position again incised to below MSL. The estuary water depth fluctuated between +0.15 - 1.40 m AHD, increasing in association with spring tides and winter storm surges. Despite two winter storm surges with Hs > 5 m, deposition in the channel was minimal due to the counteracting influence of high discharge. For example, 200 days after opening the channel bed depth at the berm position was -0.23 m MSL. Following a decrease in discharge below the mean annual flow, infill of the entrance channel became apparent with aggradation of the berm above MSL and infill progressing from the eastern side of the channel in the form of an entrance spit. From late November onwards, berm building steadily persisted coinciding with a further decrease in mean daily river discharge to < 150 ML/day. A final berm elevation of +1.33 m MSL was attained on day 249 (16 Dec) when closure occurred by the westward migration of the entrance spit across the mouth under sustained oblique waves (i.e. indicative of longshore drift). A decrease in H_s occurred from November onwards and at the time of closure H_s was 2.09 m with waves approaching from the SSW (Dir. = 202° N).

Table 5: Change in channel morphology during 11 April 2014 opening of Gellibrand River with berm height and cross-sectional area (at mouth) (Ac) and the corresponding fluctuations in marine and fluvial conditions.

Days since opening	Berm height (m/MSL)	Ac (m^2)	Basin Water Elevation (m AHD)	H_s (m)	Wave dir. (°N)	Wave dir. at shore normal (°)
0 (pre-survey)	3.79	0	1.44	2.21	197.59	17.59
0.5	0.42	22	1.04	2.01	197.70	17.7
1	0.06	57	0.63	1.44	198.33	18.33
2	-0.49	165	0.20	1.34	203.91	23.91
4	-0.22	133	0.31	1.80	204.63	24.63
60	0.45	120	0.54	1.27	210.39	30.39
120	0.38	102.50	0.66	2.58	198.41	18.41
200	-0.23	91	1.06	2.95	204.11	24.11
241	0.58	57	0.54	1.61	208.90	28.9
249 (closed)	1.33	0	0.89	2.09	202	22
273 (closed, 9 Jan)	1.35	0	1.38	2.07	204.05	24.05

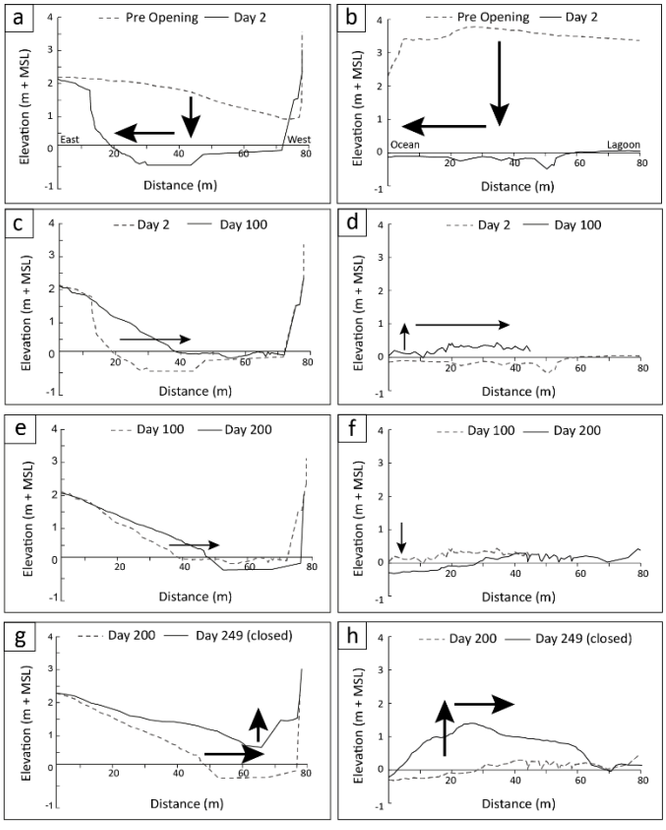


Figure 4: Surveyed change in mouth cross sectional morphology during 11 April 2014 opening of Gellibrand River. Surveys taken from 6 hours prior to opening to closure. Cross sections on left and long profile on right. Arrows indicate the movement of sediment within the profiles and arrow size represents magnitude of sediment transport.

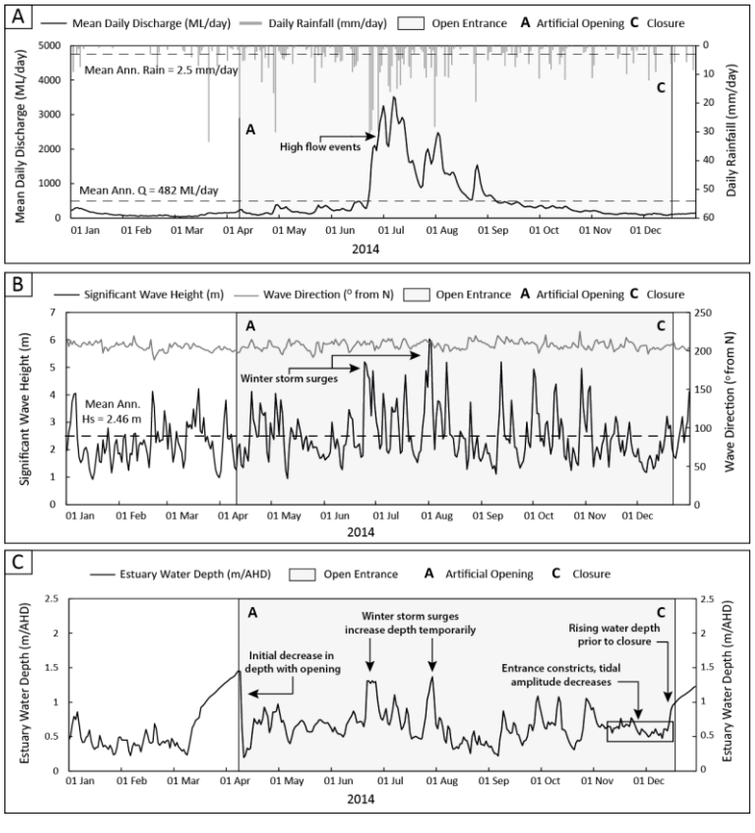


Figure 5: Marine and fluvial conditions during 11 April 2014 opening of Gellibrand River. (a) Mean daily discharge and daily rainfall; (b) daily significant wave height and direction; (c) change in basin water depth with key observations annotated. The artificial opening duration is highlighted in grey.

Key Observations:

- Entrance closure occurred during oblique waves and the supporting morphological evidence from the channel surveys confirms that longshore drift is a primary mode of closure at the Gellibrand River (Figure 4; Figure 5b).
- Although high waves would typically be correlated with increased deposition and therefore be likely to close an entrance more rapidly, when high swells occur with coinciding high discharge, deposition is limited within the channel. The basin water depth does however increase temporarily as a result of storm surge propagation into the basin. Therefore if a high swell event occurs when discharge is well above the mean annual flow, the chance of closure is reduced as the ebb-tidal prism (tidal current + discharge) has a higher capacity to remove sediment.
- Entrance closure occurred at the peak of a spring tidal cycle. Under low flow conditions, spring tides are likely to assist closure by moving the wave runup limit further landward therefore allowing sediment to be deposited further inland. This would be expected to build the beach berm more rapidly.
- A progressive decrease in entrance cross-sectional area and an increase in berm height indicates the estuary is in a depositional state and should be used as indicators of nearing close proximity to closure (Figure 4; Table 5).
- Although often thought that a higher water level at the time of opening can drive a longer or more successful opening, once the lagoon drains to a minimum depth, the impact of water level is controlled by tides and river discharge as hydraulic head is removed (Figure 5c). While the water depth is proportional to the maximum dimensions of the channel during opening, it is not related to the opening duration (McSweeney, 2015).

4.3 Observed Closure Scenarios

From an analysis of yearly observations of marine and fluvial conditions (Appendix 1) in addition to historic records of entrance condition and photo observations, three scenarios of closure can be observed at the Gellibrand River:

(1) <u>Rapid entrance closure due to seasonal low flow</u>

In the absence of any significant river flow in the days-weeks following opening, there is no energy to counteract wave driven deposition at the mouth. This means that even though wave heights may remain low-moderate (i.e. at or below the mean annual Hs value of 2.44 m), due to the absence of high flow, the estuary rapidly transitions to be dominated by depositional wave processes and closes. Closure typically occurs within days to weeks.

Conditions for closure

- Typically occurring between low flow months (December - April)
- Low river flow (typically < 100 ML/day) and rainfall (< 2 mm/day)
- Moderate - low wave heights (1.50 - 2.44 m)
  NB. Can occur with higher waves but would likely to increase deposition and decrease opening duration
- Oblique angle of wave approach (20 - 45° to the shore normal, SW - SSW waves)
- Opening duration of days-weeks.

Example

A good example of this can be seen in Appendix 1 whereby following artificial opening on 26 Dec 2015 the estuary closed on 18 Jan 2016 thus equating to a 23 day opening duration. The mean daily flow throughout the opening period was 31 ML/day thus being extremely low (Appendix 1: Figure 9; 10). At the time of closure, the wave height was moderate (1.46 m) with waves moving onshore at a strongly oblique angle (38.2°) to the shore normal (212.8° N) (Appendix 1: Figure 9; 10). The water depth in the basin was 1.38 m above AHD which once draining to a minimum 24 hours after opening, began to increase daily over the opening duration.

A second example can be observed on 11 April 2016 whereby an artificial opening was unsuccessful and the estuary closed within one day (Appendix 1: Figure 10). In this case, the estuary was opened when mean daily flow was 82 ML/day, wave height was 3.52 m and the wave direction was oblique angle (28.2°) to the shore normal (208° N). The estuary water level at the time of opening was 1.15 m above AHD. The low flow (< 100 ML/day) and high waves (> 3 m) led to rapid infill of the channel and entrance closure.

(2) Closure due to seasonal low flow following a long opening duration

Entrance opening can persist for a longer duration when immediately followed by a sustained period of high river discharge. Discharge is added the ebb-tidal prism and therefore increases the hydraulic efficiency of the channel to erode sediment deposited by waves. During the opening period, despite the occurrence of high swells, closure does not occur as deposition is counteracted by fluvial processes. Entrance closure only occurs when discharge decreases with the onset of low flow season.

Conditions for closure

- Typically occurring between low flow months (December - April)
- Low river flow (typically < 150 ML/day) and rainfall (< 2 mm/day)
- Moderate - low wave heights (1.50 - 2.50 m)
  NB. Can occur with higher waves but would likely to increase deposition and decrease opening duration
- Oblique angle of wave approach (20 - 45° to the shore normal, SW - SSW waves)
- Opening duration of weeks-months.

Example

The case study described in section 4.2 is a good example of this process. Entrance opening on the 11 April 2014 persisted for 249 days as followed by a period of high rainfall and river flow (Figure 5; Table 5; Appendix 1: Figure 8). Despite high waves occurring during June - July (Hs > 5 m), entrance closure only in December occurred once discharge decreased below < 150 ML/day.

(3) Entrance closure due to high swells under low-moderate river flow

Entrance closure can occur from high swells which increase the rates of longshore drift and berm building respectively (Morris and Turner, 2010; Slinger, 2016). For this scenario to occur, fluvial discharge must remain low-moderate (i.e. approximately at or below the mean daily flow) so that wave driven deposition is not eroded from the mouth by river flow which would increase the ebb-tidal prism. This mode of entrance closure is less common as high swells typically coincide with winter storms which simultaneously increase rainfall and river flow. The majority of these closures are of a short duration (weeks on average) as they tend to occur during autumn and prior to the onset of seasonal high flows. Following closure however flooding of the catchment is more likely to occur until a natural threshold is reached or the estuary is artificially opened as flow (i.e. erosional effect) and swells (i.e. depositional effect) increase concurrently during the winter months.

Conditions for closure

- Occurs during low-moderate flow months (Nov - May) (mostly in autumn)
- Low-moderate river flow (typically < 150 – 300 ML/day)
- High wave heights (> 2.44 m)
- Ideal strongly oblique angle of wave approach (32 - 45° to the shore normal, SW - SSW waves)
- Can reopen rapidly following closure if seasonal flow increases as approaching winter high flow period.

Example

An example of this scenario of closure can be seen in Appendix 1 whereby following artificial opening on 11 May 2008 the entrance remained open for 40 days until closing on 20 June 2008. Mean daily discharge throughout the opening period was 198 ML/day and at in the week prior to closure mean daily wave height was 3 m increasing to 3.58 m on the day of closure (Appendix 1: Figure 2). The wave direction at the time of closure was strongly oblique approaching at 42° to the shore normal (222° N). Closure persisted for five days until the estuary was again artificially opened (Appendix 1: Figure 2).

4.4 Predicting Opening Duration in Different Conditions

Multivariable linear regression was used to produce an equation capable of predicting the entrance opening duration at the Gellibrand River (Equation 1). LogMeanDailyDischarge, LogSignificantWaveHeight and WaveDirection were found to be the strongest predictors of opening duration considering all historic data of marine and fluvial conditions and observed entrance opening durations. The model has an R^2 value of 0.674 meaning it can account for 67.40 % of the variability in entrance opening duration by including these three parameters. The observed vs predicted values of the regression model show good accuracy for entrance openings lasing < 200 days (Figure 6). In practice openings < 100 days constitute the majority of openings occurring at the Gellibrand River Estuary (Appendix 1).

The predictive equation does not however account for change in marine and fluvial conditions over time as it assumes that the conditions remain constant. Substituting the parameter values for LogMeanDailyDischarge, LogSignificantWaveHeight and WaveDirection at any given time can predict the likely opening duration given the conditions for that day. For example if river discharge was to increase from the value on the first day of opening, the updated value should be input to account for this change. Forecast values can also be input into the model to anticipate change over time for example the 7 day forecast wave height and direction can be extracted from BOM's AusWave model online (http://www.bom.gov.au/nwp/doc/auswave/data.shtml).

$$LogOpening\ Duration = -7.882 + (0.778 * LogQ) + (1.561 * LogHs) + (0.034 * Dir) \quad \text{(Equation 1)}$$

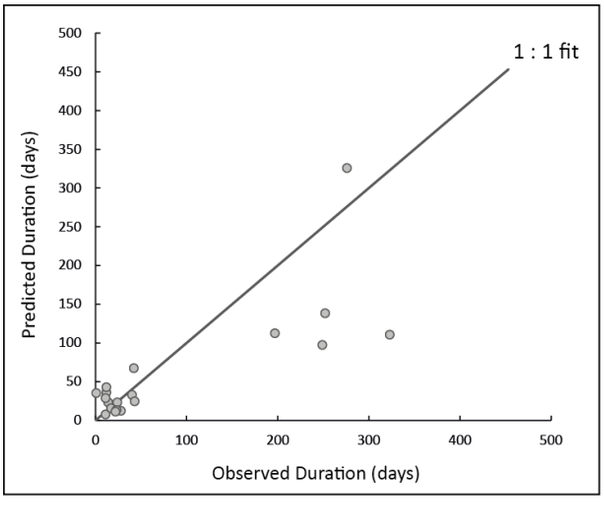


Figure 6: Observed (historic data) vs predicted values of opening duration using linear regression model equation.

4.5 Seasonal Probabilities of Opening Duration

Using the multiple linear regression equation and historic discharge and wave data from 2007 - 2017, the range of likely opening durations for each month of the year were modelled using a Monte Carlo simulation. As a whole, the range of output values for opening duration across all months of the year show an infantile death rate curve which illustrates that despite the range of output values being large in some cases, the majority of openings do not last over 100 days (Figure 7). For example, even during June to September when the predicted maximum opening duration is largest, the mean opening duration remains < 350 days (median < 250 days) (Figure 7; Table 6).

During December to April the predicted opening duration is lowest with February and March having the shortest opening durations of 28 days on average (Table 6). February and March also have the least variability in opening durations overall. In contrast, openings occurring in August last for the longest on average however there is also considerable variability in output values. The predicted opening durations for each month are most strongly correlated to the mean daily discharge indicating that the variability in river flow is in fact the strongest driver of opening duration.

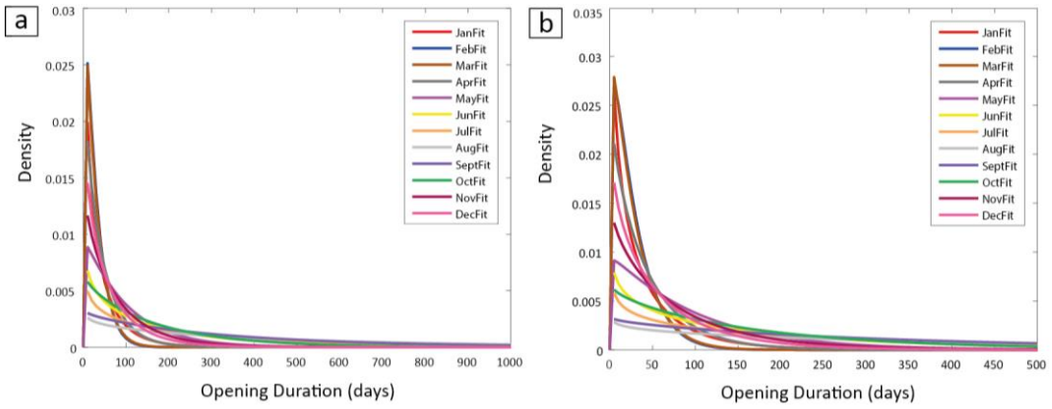


Figure 7: Probability density function of all monthly opening durations showing an infantile death rate decay curve. This shows that although the range of values predicted can be large in some months, the highest likelihood of opening durations are concentrated at lower durations < 100 days. (a) All output; (b) trimmed x-axis at 500 days.

Exceedance probability graphs were created from the modelled distribution of opening durations values for each month (Figure 8). For each month, the exceedance probability was then taken for four opening scenarios: an opening lasting (a) 1 day (to represent an unsuccessful opening); (b) 1 week; (c) 1 month (31 days); (d) 90 days (Table 6). This shows the likelihood of opening in each month to last for these set durations (Figure 8; Table 7).

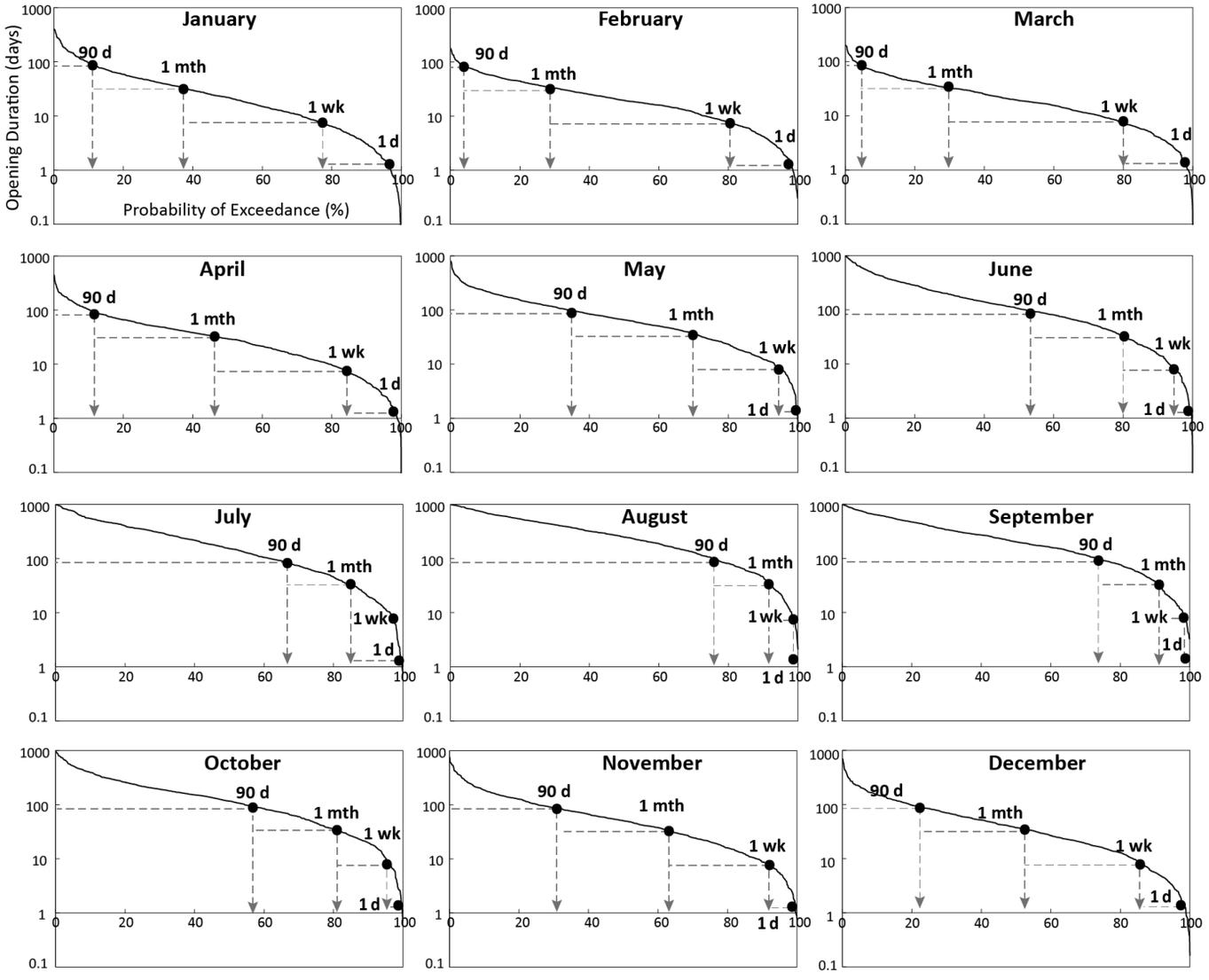


Figure 8: Exceedance probability graphs for the log opening duration for each month of the year. Exceedance probabilities for an opening to last over: 1 day, 1 week, 1 month (31 days), 90 days are annotated on the graphs.

Table 6: Output mean and median values for opening duration for each month of the year.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	40.13	27.63	28.07	44.49	96.99	171.49	232.29	315.48	275.35	166.14	80.91	63.83
Median	22.03	19.54	19.10	29.37	65.59	104.40	152.74	248.87	201.31	116.11	50.54	37.37

4.6 Risk Matrix for Opening

Using the modelled exceedance probabilities, a risk matrix table is presented to show months with the highest risk of entrance closure occurring within: 1 day, 1 week, 1 month (31 days), 90 days for each month of the year (Table 7). Risk is defined on 20 % percentage intervals but probabilities for other set durations can also easily be extracted from the output. An important consideration with the predicted values within the risk matrix is that they assume constant conditions. The table therefore provides a reference guide and if the discharge and wave conditions were forecast to increase or decrease following opening, these should be updated within the linear regression model.

Table 7: Quantitative risk matrix based on modelled exceedance probabilities for an entrance opening to last: 1 day, 1 week, 1 month (31 days), 90 days for each month of the year.

Month	Probability of Opening Duration Exceeding a Set Duration (%)			
	1 day	1 week	1 month	90 days
Jan	96.80	77.82	38.66	10.58
Feb	98.40	81.92	32.07	3.00
Mar	98.60	80.00	33.10	3.60
Apr	98.80	84.60	48.00	12.20
May	99.80	95.40	72.30	37.60
Jun	99.69	95.71	80.67	56.03
Jul	99.68	97.65	85.88	65.03
Aug	99.88	99.06	92.27	77.28
Sep	99.89	98.62	91.70	75.43
Oct	99.79	96.66	82.30	57.74
Nov	99.60	91.80	64.30	29.00
Dec	98.80	86.40	55.50	22.30

= Very high risk, < 20 % chance entrance will remain open for set duration

= High risk, 20 - 40 % chance entrance will remain open for set duration

= Moderate risk, 40 - 60 % chance entrance will remain open for set duration

= Low risk, 60 - 80 % chance entrance will remain open for set duration

= Minimal risk, > 80 % chance entrance will remain open for set duration

4.7 Thresholds of Natural Entrance Opening

From an analysis of the historic timing of natural entrance openings and the concurrent marine and fluvial conditions, natural openings tend to occur during the thresholds presented in Table 8. Natural openings occurring throughout the monitoring period did however show considerable variability for each observed parameter. This is attributed to the different processes governing entrance opening (section 1.2) which cannot be easily quantified without morphological observations of the entrance channel. Natural openings tended to occur during spring tidal cycles and those occurring during neap cycles had on average higher fluvial discharge thus meaning that processes operating from the catchment side, as opposed to wave overwash, were a main driver of entrance opening. Incorporating consistent measurements

of berm elevation (to MSL) is recommended to quantify the relative balance between the estuary water depth and berm elevation which remains a critical threshold that determines entrance opening.

Table 8: Observed thresholds for natural openings of the Gellibrand River Estuary. Data averaged for value at time of natural opening for all observed natural openings 2007 - 2017.

Parameter	Mean	Standard Deviation	Min Observed	Max Observed
Daily flow (ML/day)	286.13	220.69	64.13	775.50
Estuary water elevation (m AHD)	0.73	0.26	0.58	1.36
Daily rainfall (mm/day)	7.80	11.95	0	38
Hs (m)	1.87	0.34	1.43	2.52
Wave direction (°N)	204.87	5.16	195.50	214.45
Wave direction (° shore)	24.87	5.16	15.50	34.45
Daily tidal range (m)	0.62	0.30	0.25	1.10

In addition to these conditions, the balance between the berm crest elevation and the backing estuary water depth is a key determinant of when the estuary will naturally open. As there is a lack of detailed records of berm elevation over time, specifically in terms of repeat surveys consistently referenced to AHD, the 2014 case study data is used to present a preliminary model of this threshold. A relationship between the ratio of the water level T_{max} (time of opening for this case study) / water level at time of measurement and berm elevation T_{max} (time of opening for this case study) / berm height at time of measurement can be used to illustrate when the estuary is in an erosional or depositional state. In this case, the estuary was in an erosional state (i.e. dominated by fluvial processes) when values are < 1 (Figure 9). As values shift to > 1, the estuary becomes depositional therefore indicating wave processes are dominant. From this case study, a value of 0.3 indicates entrance closure with values around 0.2 indicating a close proximity to closure. At other ICOLLs in Victoria, similar values have been recorded (McSweeney, 2015).

Regular morphological surveys were undertaken (to MSL) could be used to refine the model in combination with water level observations (from DELWP). This would extend the ratio to identify an average berm elevation at which the estuary tends to close (as opposed to using T_{opn} which is in this case dictated by artificial opening).

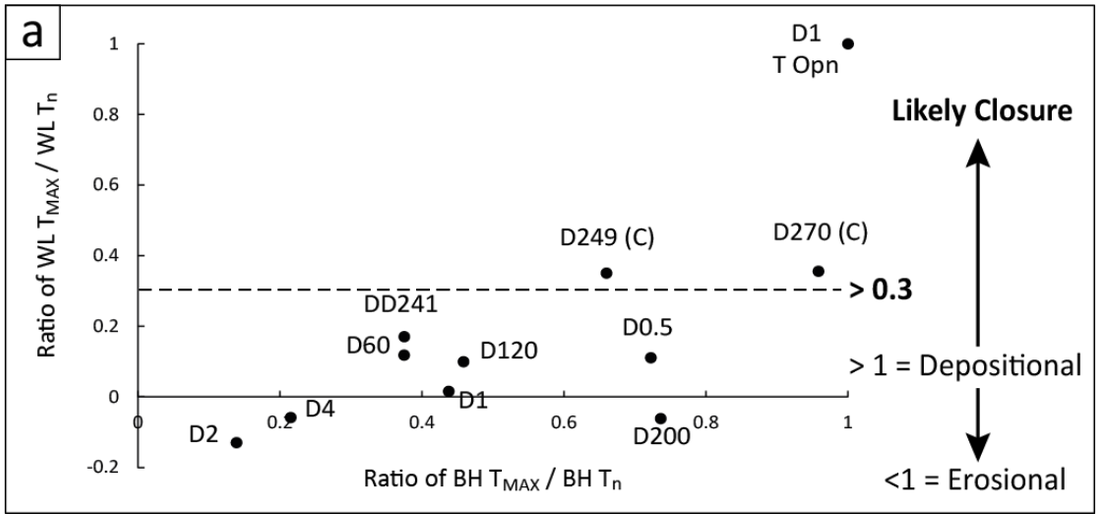


Figure 9: (a) Ratio of water level T_{max} (time of opening for this case study) / water level at time of measurement and berm elevation T_{max} (time of opening for this case study) / berm height at time of measurement. T_{opn} refers to the value at when the estuary was artificially opened and D values are the day since opening when surveys were taken.

5.0 Summary

From the data analysed, conditions which tend to favour a **prolonged entrance opening** (T = > 1 month) include:

- **Daily river discharge:** > 150 ML/day occurring within a week of entrance opening. Sustained high flow following entrance opening will provide energy to maintain erosion of channel sediments deposited by waves.
- **Wave height:** In general, lower waves (< 1.5 m) would reduce the amount of sediment delivered onshore by longshore drift. If fluvial discharge is high however deposition from large swells is likely to be counteracted by the increased ebb-tidal prism.
- **Wave direction:** Wave direction which is not strongly oblique would reduce the efficiency and rate of longshore drift deposition and berm building at the mouth.
- **Estuary water elevation (above AHD):** Although the estuary water depth is important for the timing of natural openings and for reducing flood impacts within the catchment, it does not dictate the opening duration. The effect of entrance opening is to remove the hydraulic head between the lagoon and the ocean which typically occurs within 48 hours following opening (Appendix 1). The fluvial and marine conditions that occur after the lagoon has drained are therefore the critical control on the entrance opening duration.

In contrast, conditions which tend to **close the Gellibrand River Estuary rapidly** (T = < 1 week) include:

- **Daily river discharge:** < 150 - 100 ML/day typically occurring between low flow months (December - April).
- **Wave height:** waves > 1.50 m. Higher waves would increase the longshore drift rate and berm building more rapidly provided river flow remains low.
- **Wave direction:** a more strongly oblique wave direction (32 - 45°) relative to the shore will increase the rate of deposition from longshore drift.
- **Rainfall:** < 2 mm/day. The relationship of rainfall and opening duration however proved to be highly variable. River discharge is more strongly correlated to the opening duration than rainfall using the available dataset.

6.0 Conclusion and Recommendations

- Seasonal predictions of the longshore drift rate could be calculated from wave height, period and direction values and be used as a further parameter to estimate the amount of sediment being delivered onshore. Higher rates of longshore drift would provide more sediment which would be expected to build the beach berm more rapidly and place the estuary at a higher risk of closure. The CERC formula (USACE, 1986) for calculating longshore drift rates could be used with wave values substituted from the BOM AusWave model.

- Undertaking regular field measurements of berm elevation would add data to develop a predictive threshold for natural openings. This would involve measuring the berm crest elevation to mean sea level and would require reference to a permanent benchmark. This could be established by rtk GPS and used to calibrate repeat surveys undertaken by a dumpy level or similar equipment. By consistently referencing surveys to mean sea level, they would then be able to be used in comparison to the estuary water elevation (also to AHD) output by the Princetown water level logger. By developing a dataset of berm elevation, the values at which the estuary naturally opens could be better predicted and used to identify proximity to opening.

- The use of Bayesian statistics and models to further analyse the relationships between marine and fluvial parameters and their influence on opening duration.

7.0 References

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Appendix One: Summary of Yearly Data 2007 - 2017

2007

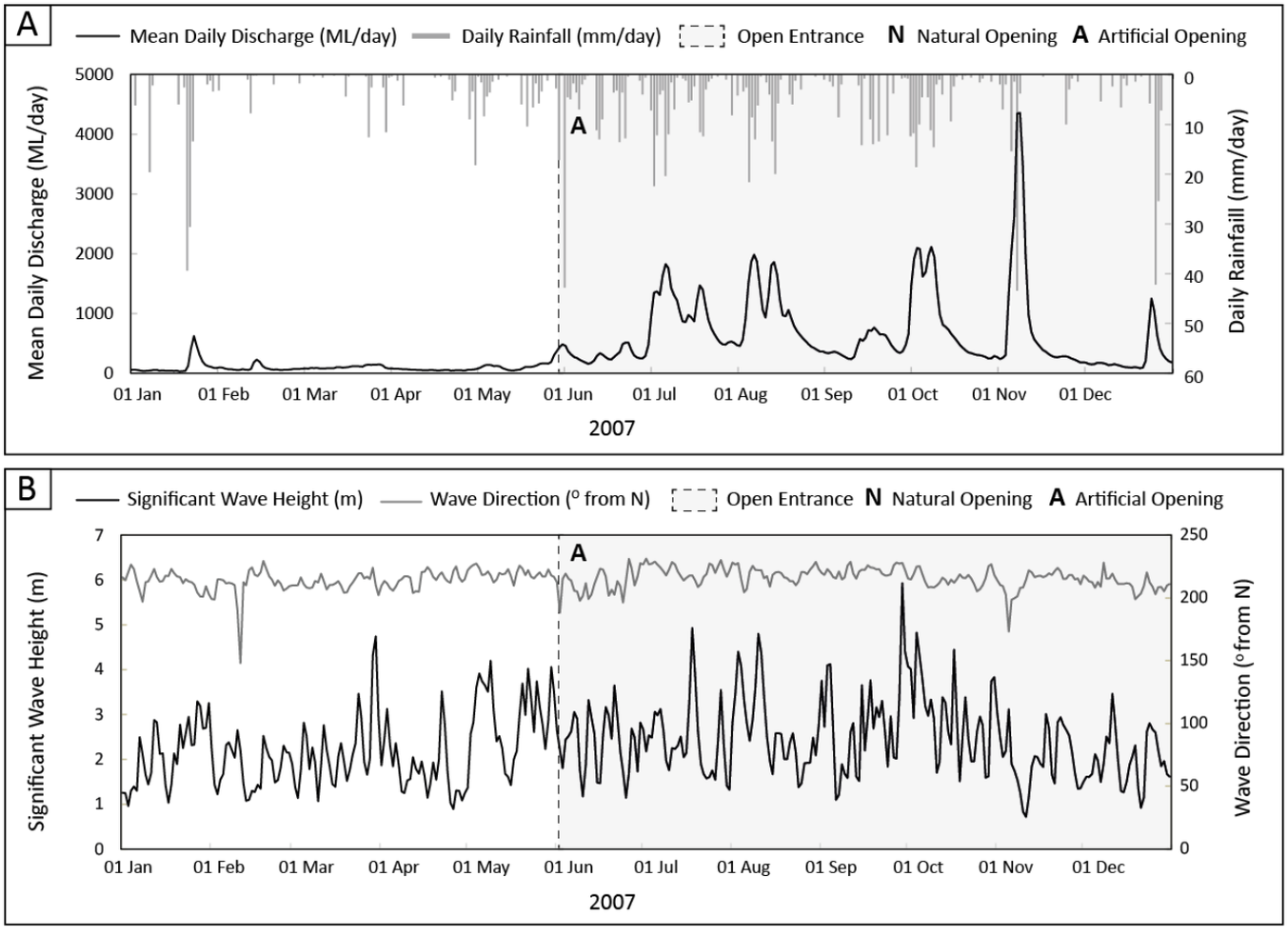

Figure 1: 2007 (a) Mean daily discharge (ML/day) (Burrupa flow gauge (DELWP) site 235224), daily rainfall (mm/day) (BOM, 2017) and entrance condition whereby N refers to a natural opening and A refers to an artificial opening at the commencement of the opening period. (b) Significant wave height (m), wave direction (° from North) (NOAA, 2017) and entrance condition. NB. No water depth data.

2008

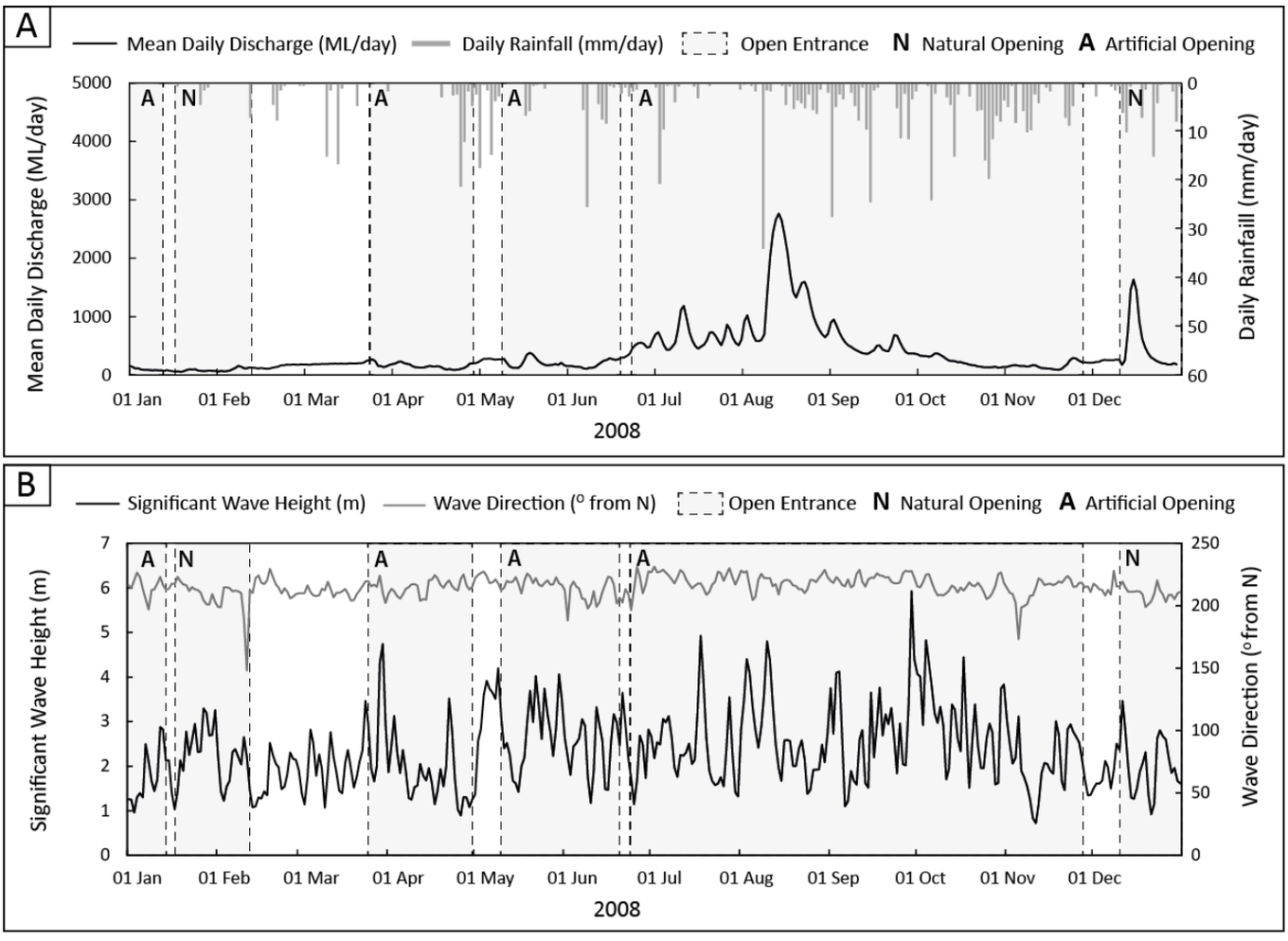

Figure 2: 2008 (a) Mean daily discharge (ML/day) (Burrupa flow gauge (DELWP) site 235224), daily rainfall (mm/day) (BOM, 2017) and entrance condition whereby N refers to a natural opening and A refers to an artificial opening at the commencement of the opening period. (b) Significant wave height (m), wave direction (° from North) (NOAA, 2017) and entrance condition. NB. No water depth data until 11/08.

2009

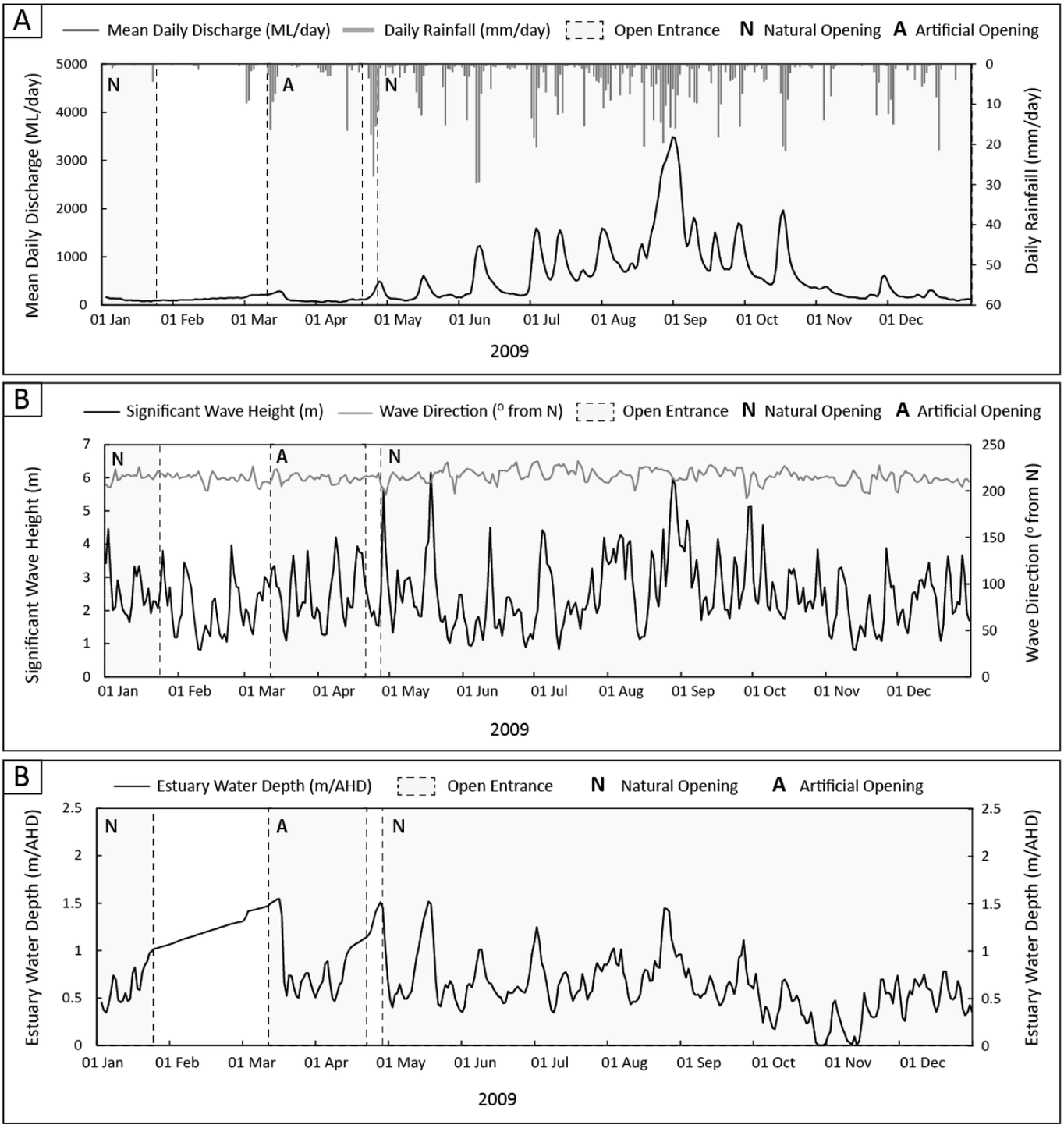

Figure 3: 2009 (a) Mean daily discharge (ML/day) (Burrupa flow gauge (DELWP) site 235224), daily rainfall (mm/day) (BOM, 2017) and entrance condition whereby N refers to a natural opening and A refers to an artificial opening at the commencement of the opening period. (b) Significant wave height (m), wave direction (° from North) (NOAA, 2017) and entrance condition. (c) Estuary water depth (m above AHD) (DELWP, Site 235269).

2010

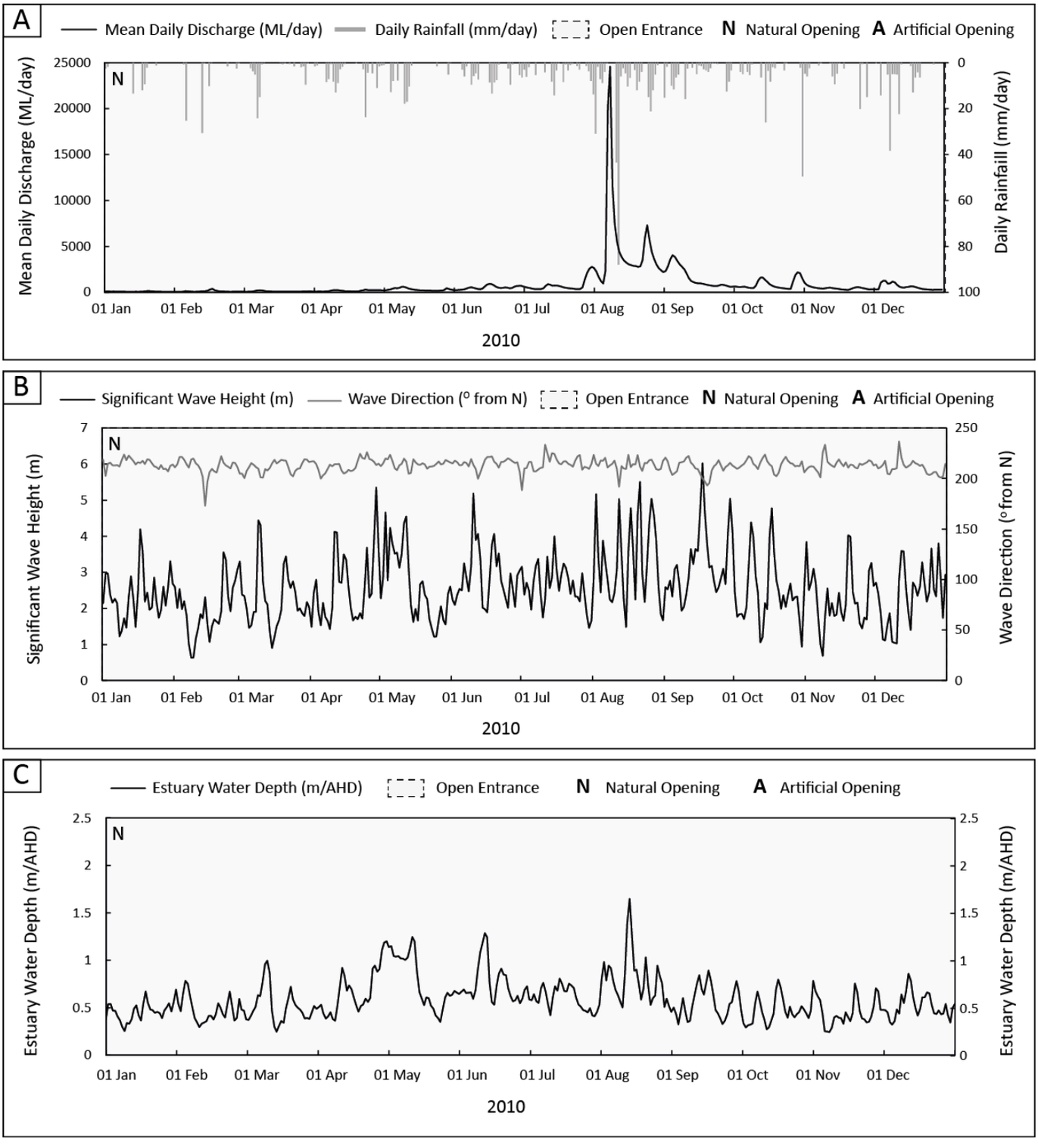

Figure 4: 2010 (a) Mean daily discharge (ML/day) (Burrupa flow gauge (DELWP) site 235224), daily rainfall (mm/day) (BOM, 2017) and entrance condition whereby N refers to a natural opening and A refers to an artificial opening at the commencement of the opening period. (b) Significant wave height (m), wave direction (° from North) (NOAA, 2017) and entrance condition. (c) Estuary water depth (m above AHD) (DELWP, Site 235269).

2011

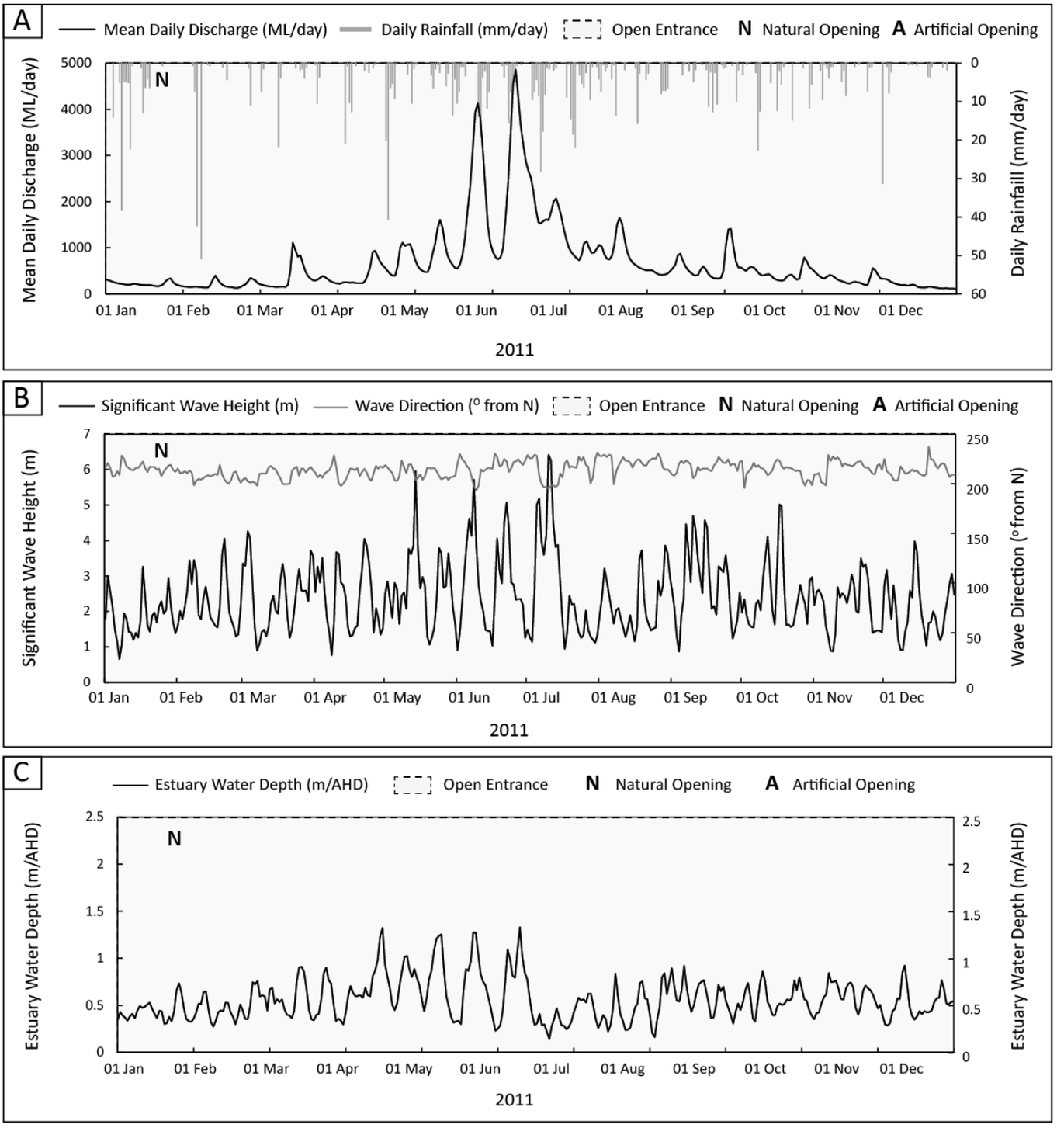

Figure 5: 2011 (a) Mean daily discharge (ML/day) (Burrupa flow gauge (DELWP) site 235224), daily rainfall (mm/day) (BOM, 2017) and entrance condition whereby N refers to a natural opening and A refers to an artificial opening at the commencement of the opening period. (b) Significant wave height (m), wave direction (° from North) (NOAA, 2017) and entrance condition. (c) Estuary water depth (m above AHD) (DELWP, Site 235269).

2012

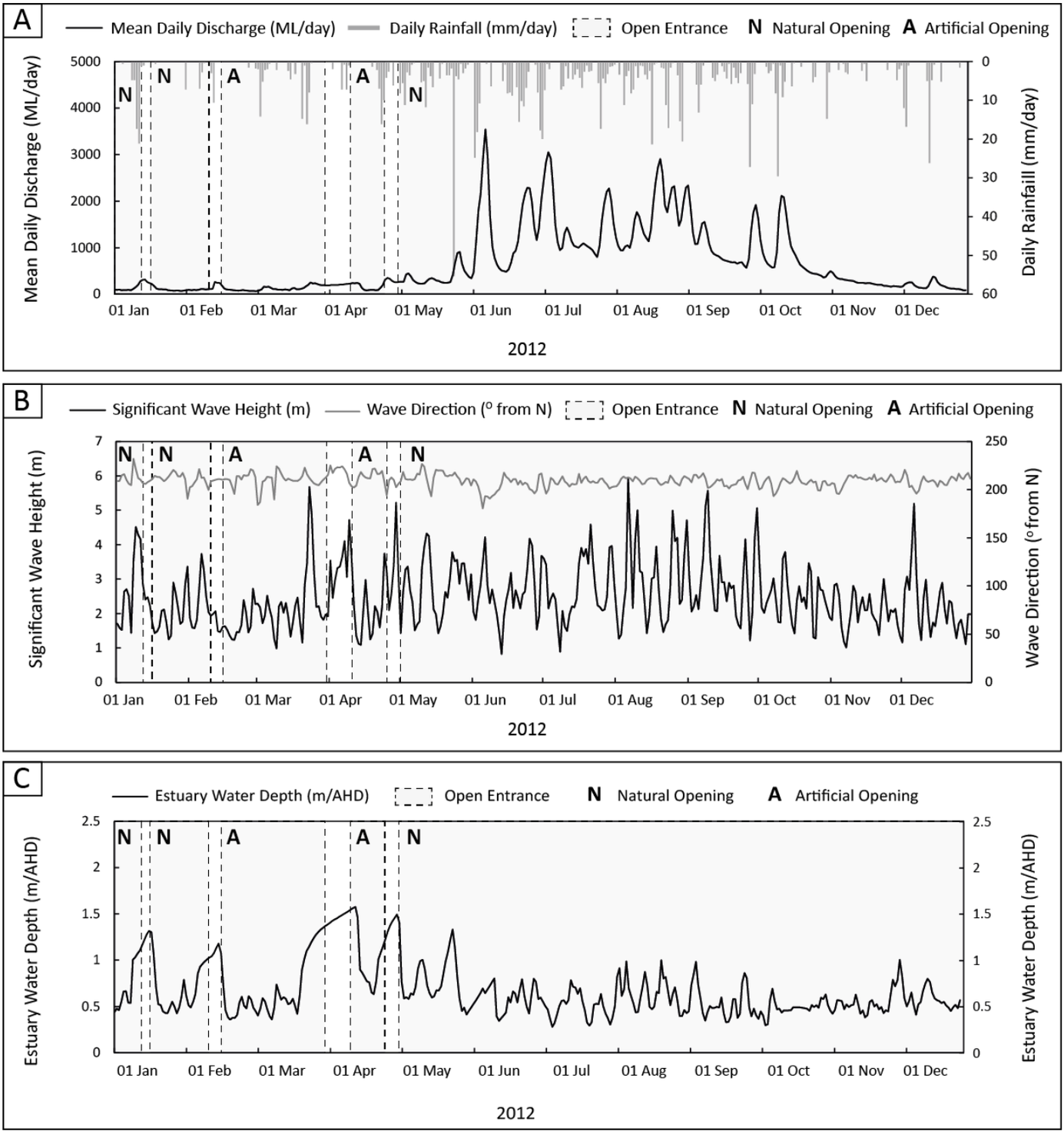

Figure 6: 2012 (a) Mean daily discharge (ML/day) (Burrupa flow gauge (DELWP) site 235224), daily rainfall (mm/day) (BOM, 2017) and entrance condition whereby N refers to a natural opening and A refers to an artificial opening at the commencement of the opening period. (b) Significant wave height (m), wave direction (° from North) (NOAA, 2017) and entrance condition. (c) Estuary water depth (m above AHD) (DELWP, Site 235269).

NB. Two artificial openings occurring in 2012 were both illegal openings and not by permit.

2013

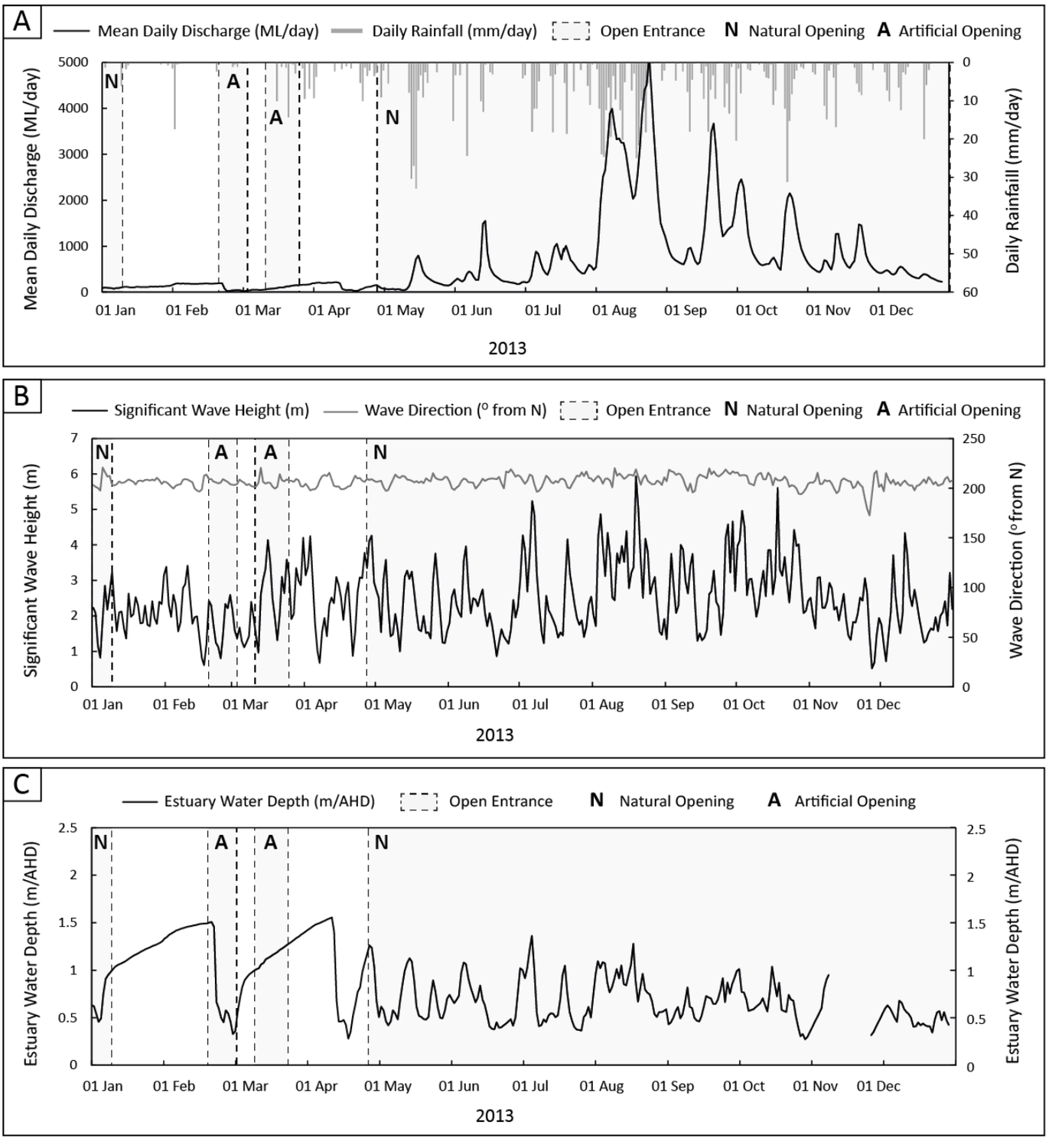

Figure 7: 2013 (a) Mean daily discharge (ML/day) (Burrupa flow gauge (DELWP) site 235224), daily rainfall (mm/day) (BOM, 2017) and entrance condition whereby N refers to a natural opening and A refers to an artificial opening at the commencement of the opening period. (b) Significant wave height (m), wave direction (° from North) (NOAA, 2017) and entrance condition. (c) Estuary water depth (m above AHD) (DELWP, Site 235269).

NB. The artificial opening on 13 March was an illegal opening and not by permit.

2014

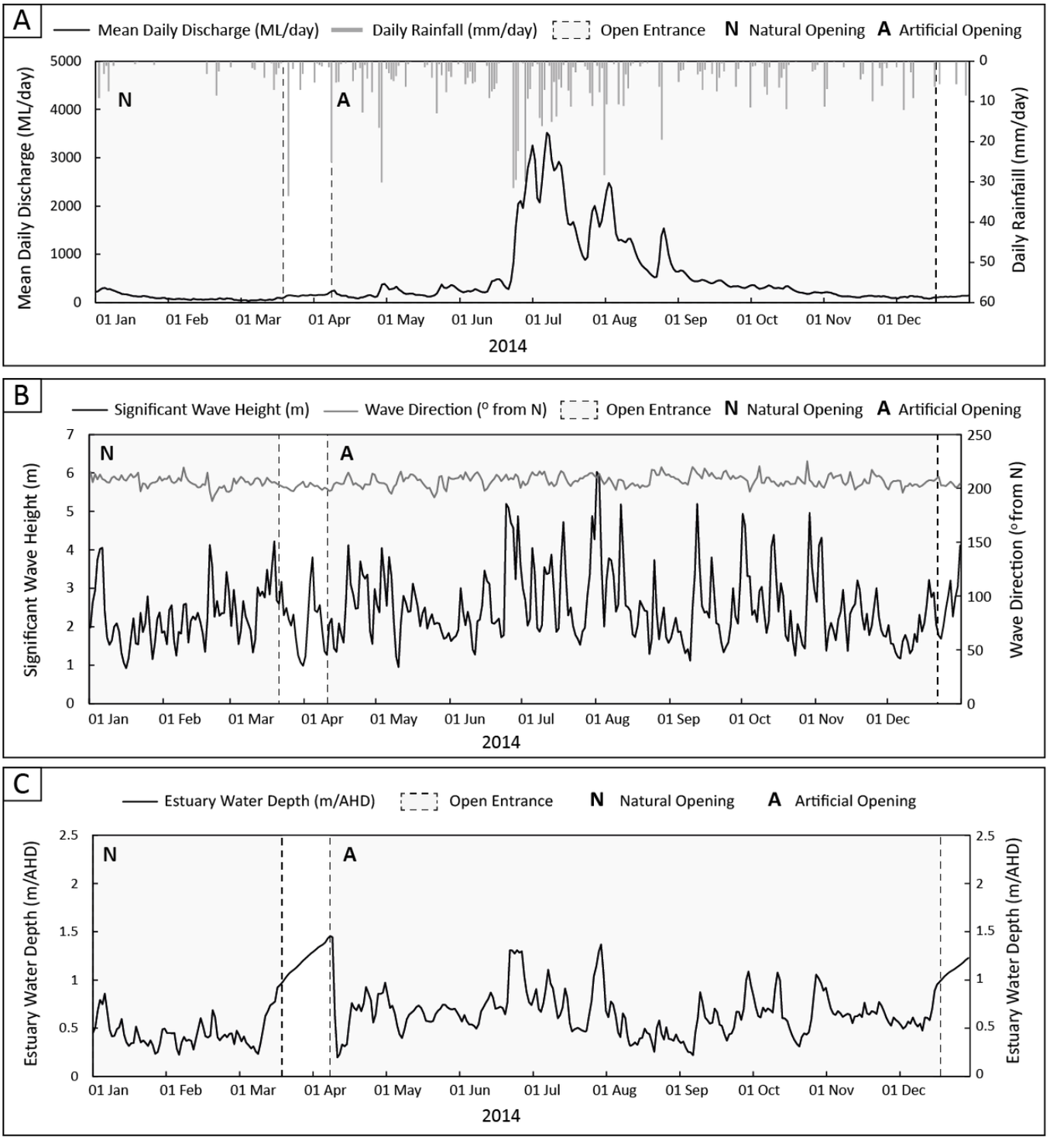

Figure 8: 2014 (a) Mean daily discharge (ML/day) (Burrupa flow gauge (DELWP) site 235224), daily rainfall (mm/day) (BOM, 2017) and entrance condition whereby N refers to a natural opening and A refers to an artificial opening at the commencement of the opening period. (b) Significant wave height (m), wave direction (° from North) (NOAA, 2017) and entrance condition. (c) Estuary water depth (m above AHD) (DELWP, Site 235269).

2015

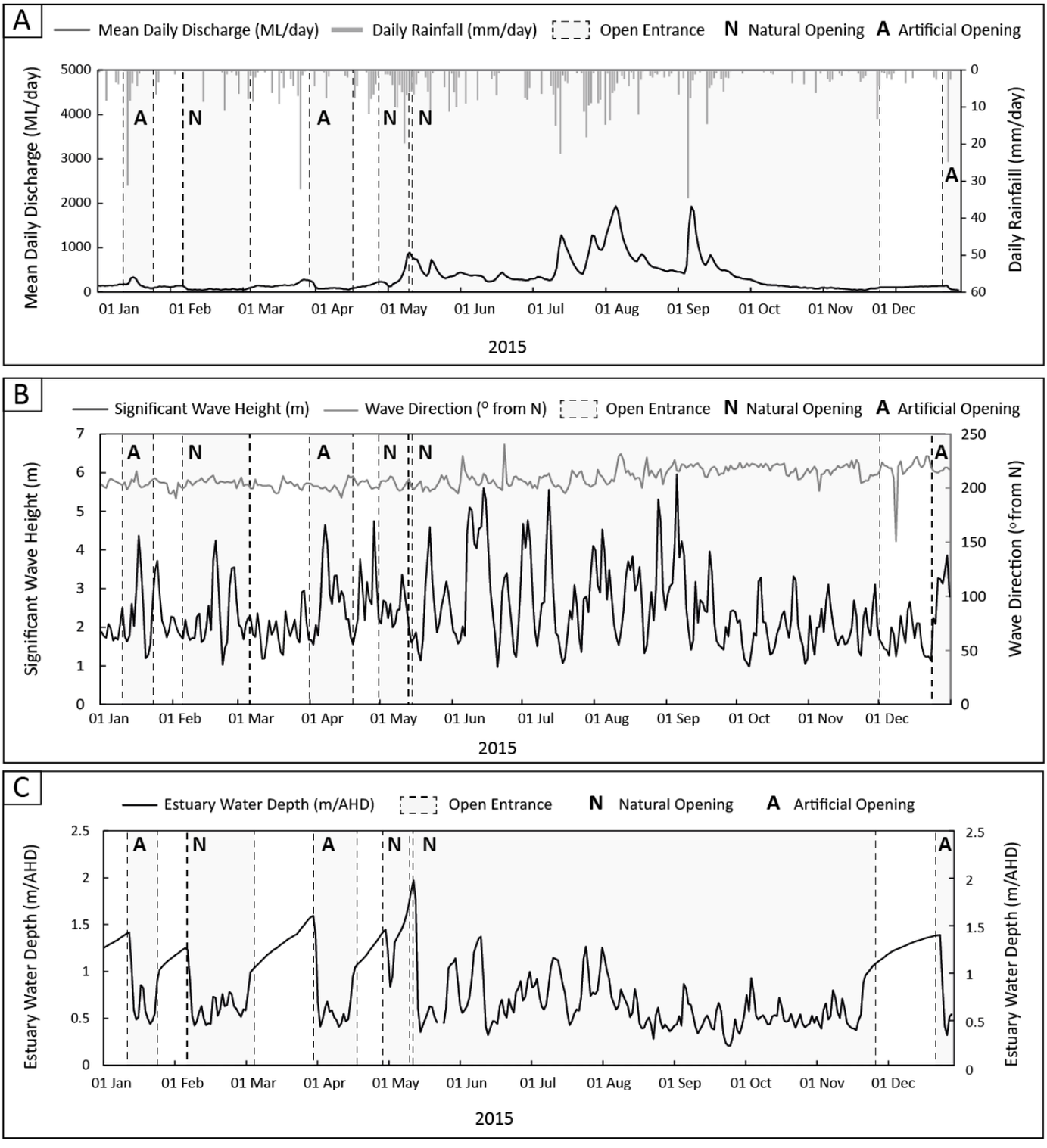

Figure 9: 2015 (a) Mean daily discharge (ML/day) (Burrupa flow gauge (DELWP) site 235224), daily rainfall (mm/day) (BOM, 2017) and entrance condition whereby N refers to a natural opening and A refers to an artificial opening at the commencement of the opening period. (b) Significant wave height (m), wave direction (° from North) (NOAA, 2017) and entrance condition. (c) Estuary water depth (m above AHD) (DELWP, Site 235269).

2016

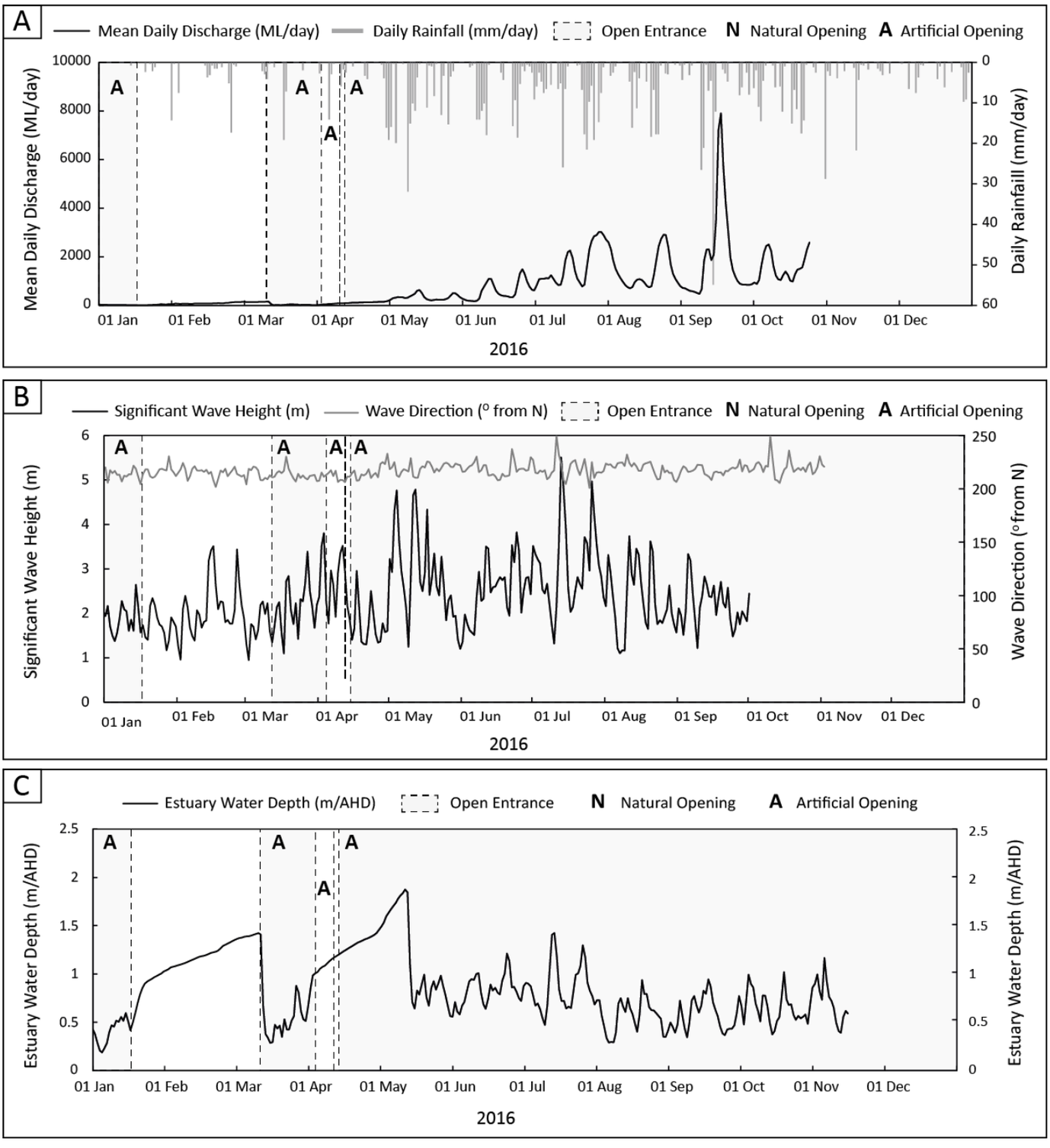

Figure 10: 2016 (a) Mean daily discharge (ML/day) (Burrupa flow gauge (DELWP) site 235224), daily rainfall (mm/day) (BOM, 2017) and entrance condition whereby N refers to a natural opening and A refers to an artificial opening at the commencement of the opening period. (b) Significant wave height (m), wave direction (° from North) (NOAA, 2017) and entrance condition. (c) Estuary water depth (m above AHD) (DELWP, Site 235269).

NB. As of the last Estuary Watch mouth condition entry 13/1/17, the estuary entrance was still open.

Appendix Two: Multiple Linear Regression Analysis

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.821[a]	.674	.604	.34125	2.651

a. Predictors: (Constant), Dir, LogQ, LogHS

b. Dependent Variable: LogDUR

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3.364	3	1.121	9.629	.001[b]
	Residual	1.630	14	.116		
	Total	4.994	17			

a. Dependent Variable: LogDUR

b. Predictors: (Constant), Dir, LogQ, LogHS

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	-7.882	4.233		-1.862	.084
	LogQ	.778	.198	.692	3.941	.001
	LogHS	1.561	1.886	.152	.828	.422
	Dir	.034	.019	.290	1.775	.098

Model		95.0% Confidence Interval for B	
		Lower Bound	Upper Bound
1	(Constant)	-16.960	1.196
	LogQ	.355	1.202
	LogHS	-2.483	5.606
	Dir	-.007	.076

a. Dependent Variable: LogDUR

Coefficient Correlations[a]

Model			Dir	LogQ	LogHS
1	Correlations	Dir	1.000	-.207	.351
		LogQ	-.207	1.000	-.493
		LogHS	.351	-.493	1.000
	Covariances	Dir	.000	-.001	.013
		LogQ	-.001	.039	-.184
		LogHS	.013	-.184	3.556

a. Dependent Variable: LogDUR

Residuals Statistics[a]

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	.9269	2.5623	1.6139	.44484	18
Residual	-.59840	.41793	.00000	.30968	18
Std. Predicted Value	-1.544	2.132	.000	1.000	18
Std. Residual	-1.754	1.225	.000	.907	18

a. Dependent Variable: LogDUR

Attachment F
Flow travel time analysis

This section describes the analysis used to determine indicative travel times along the Gellibrand River to inform flow management as part of the overall Gellibrand River estuary management.

Typical travel times for peak flows can be determined by interrogating the time series data available from flow gauges. By offsetting each time series against the other until the peaks align, the travel time can be determined. This was done for the Gellibrand using typical increases in flow that could be utilised in estuary management.

Travel time analysis from South Otway pump station to Burrupa

The increase in flow considered for estuary management is likely to be 30ML/d. Many different events were checked to establish the travel time. An example is provided here: on 13th February 2012, there was a peak flow that led to an increase in water level at South Otway pump station from 0.6 m to 1.2 m (approximately 100 ML/day to 130 ML/day). A similar peak in water level could be observed in the Burrupa gauge. By trialling different travel times or offsets, 12 hours represents the best alignment between the peaks (Figure 27).

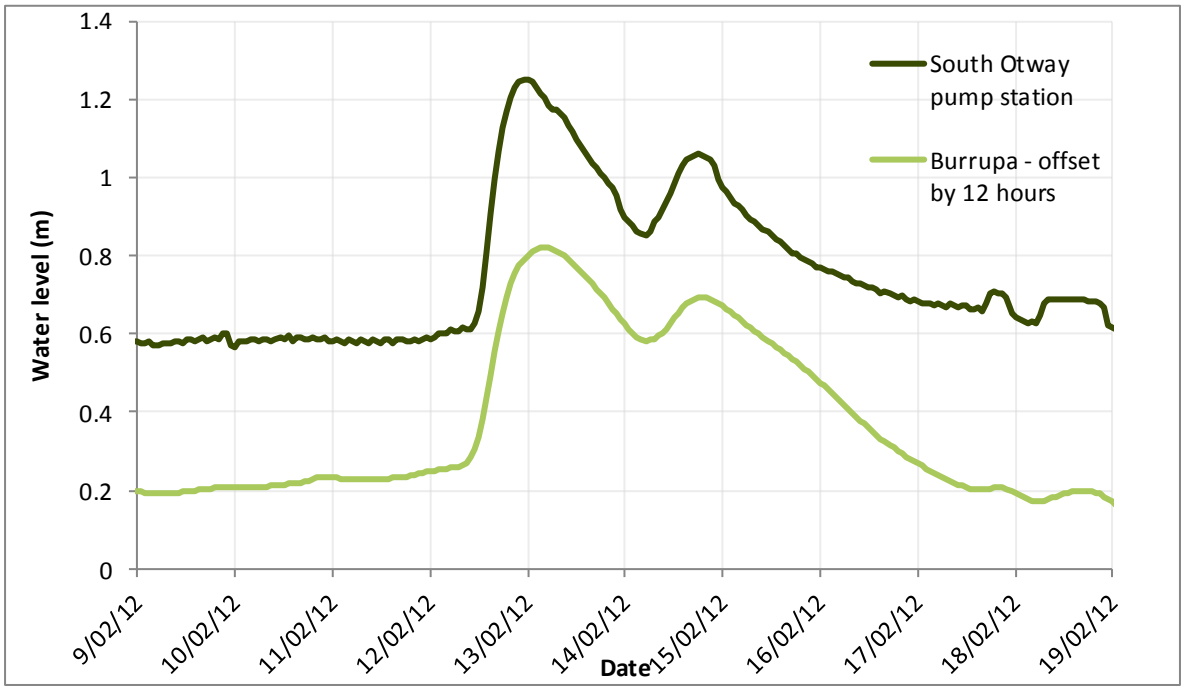

Figure 27. *Flow gauge data (shown as water level) for 13 February 2012 event – South Otway pump station and Burrupa gauge offset by 12 hours*

Another example is provided below for 13th January 2012. This example has a similar peak of 30 ML/day increase at South Otway pump station. This event appears to be more attenuated, while the travel time is similar with 12 hours best representing the best alignment between the peaks (Figure 28).

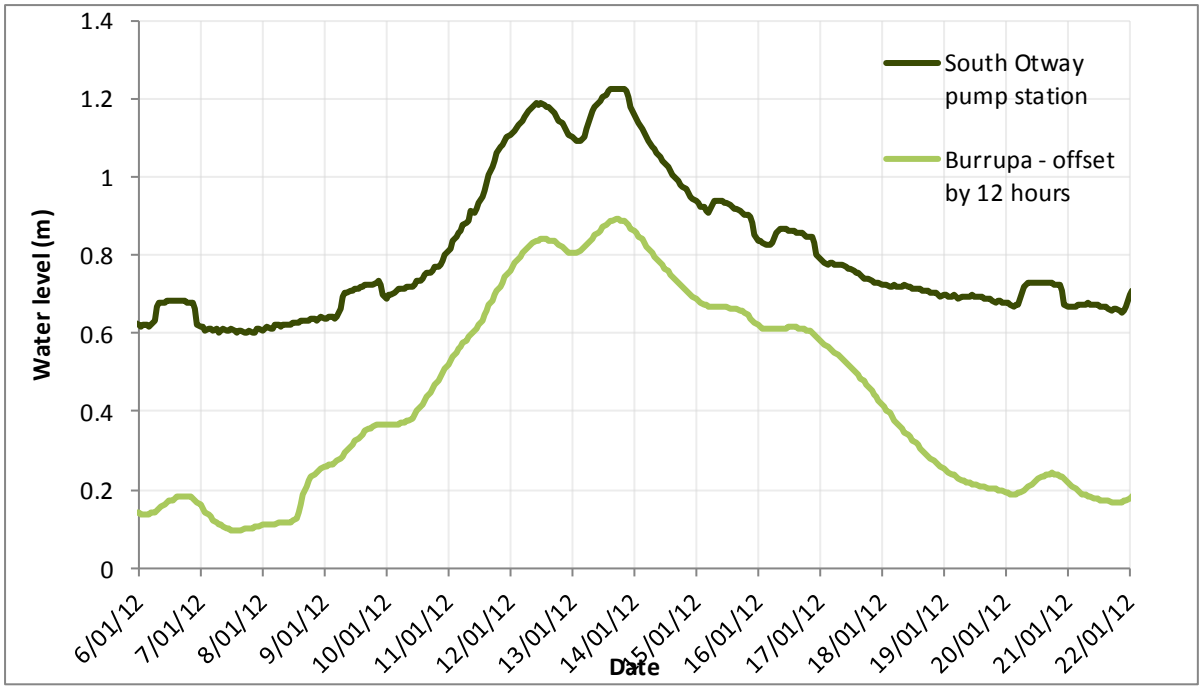

Figure 28. *Flow gauge data (shown as water level) for 13 January 2012 event – South Otway pump station and Burrupa gauge offset by 12 hours*

Travel time analysis from North Otway pump station to South Otway pump station

Similar to the analysis above, we have compared the north and south flow gauges to understand the travel time between the two pump stations. The most likely management scenario at the North Otway pump station is an increase in flow of 11 ML/day. Example events of a similar increase in flow on 26 January 2012 and 1-3 February 2012 are shown below. By trialling different travel times or offsets, 20 hours represents the best alignment between the peaks (Figure 29).

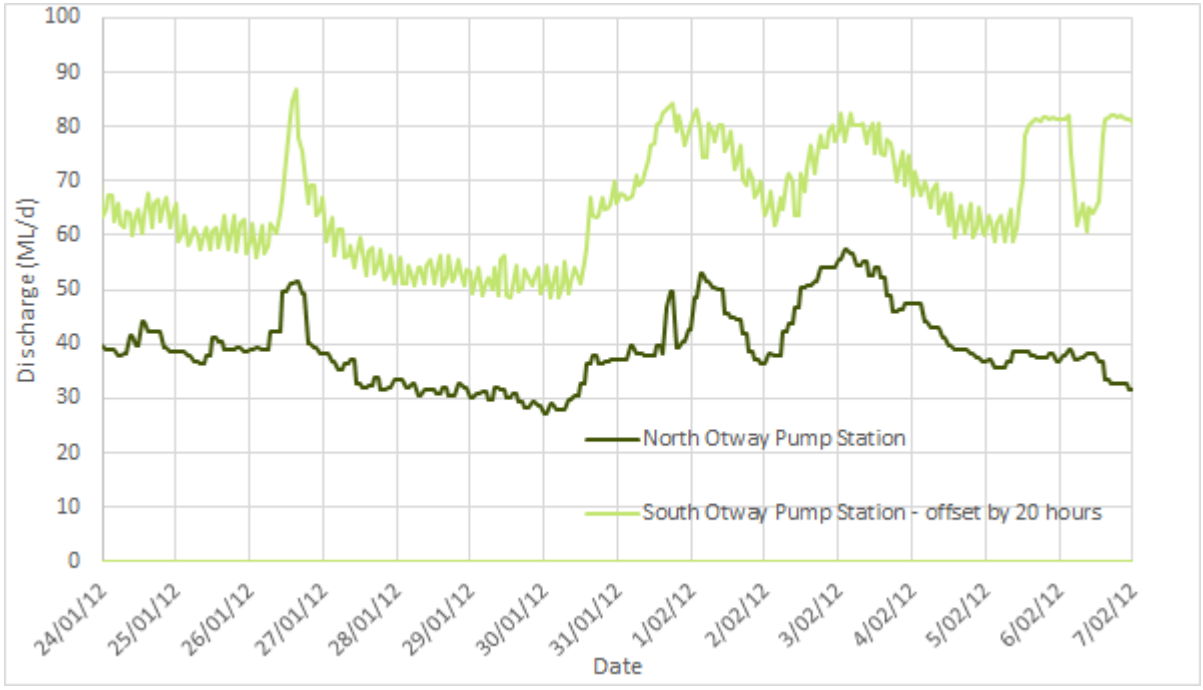

Figure 29. *Flow gauge data – North Otway pump station and South Otway pump station gauge offset by 20 hours*