When is artificially opening Intermittently Closed Estuaries (ICE) most effective?

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Key Points

- Intermittently Closed Estuaries present a complex range of management issues due to their dynamic entrance condition and the need to alleviate the adverse effects of prolonged entrance closure.
- The duration of opening is a function of the offshore marine conditions regardless of the channel dimensions obtained following opening or the estuary lagoon water depth at the time of opening.
- When waves approach at a shore normal direction, significant wave height is >4 m and outflow energy is low (due to channel dissipation or low discharge), closure will likely occur within days.
- The relationship between berm crest elevation, channel cross-sectional area and lagoon water depth as a function of their opening value are key controls on opening duration at individual sites.

Abstract

Intermittently Closed Estuaries (ICE) are a form of wave-dominated estuary that experience periodic closure during times of low river flow. Prolonged entrance closure results in an array of management issues including flooding of surrounding property and a progressive decline in water quality. Managers invest many thousands of dollars annually to alleviate these effects by artificially opening ICE. Artificial openings however often fail to achieve their planned outcome of draining water accumulated within the estuary. This occurs due to a lack of understanding of the processes driving the entrance condition. In this study, the change in entrance channel morphology was monitored following entrance opening at three ICE in Victoria, Australia. The duration of opening was controlled by offshore marine conditions and river discharge in relation to the mean annual flow. The change in channel morphology was related to continuous measurements of estuary hydrodynamics and fluvial and marine conditions. The channel cross-sectional area, berm crest elevation and backing lagoon water depth in relation to their value at the time of opening can be used to distinguish whether the estuary is in an erosional or depositional state. Closure was most rapid when offshore significant wave height was >4 m, the direction of wave approach was shore normal and when the channel was sufficiently long to dissipate outflow energy. A predictive model of entrance morphodynamics is presented where the proximity to closure or opening can be determined to identify whether implementing an artificial opening will likely be successful.

Keywords

Estuary, artificial opening, ICOLL, coastal lagoon

Introduction

Intermittently Closed Estuaries (ICE) are estuaries characterised by periodic entrance closure to the ocean (Roy*,* 1984; Cooper, 2001). They are widespread along wave-dominated microtidal coastlines and are particularly abundant in the mid-latitudes (Cooper, 2001; Morris and Turner, 2010; Perissinotto *et al.,* 2013). ICE constitute >85% of all estuaries along the coast of Victoria and are also the dominant estuarine form in New South Wales (McSweeney *et al.,* 2014). Entrance closures can persist for days to years and can result in flooding and deterioration of water quality within the enclosed lagoon (Mondon *et al.,* 2003; Saintilan, 2004; Jones and West, 2005; Lloyd *et al.* 2012). In order to provide relief from flooding and poor water quality, artificial entrance openings are undertaken to reconnect the estuary to the ocean by an excavated channel.

Artificial entrance openings are however expensive, costing tens of thousands of dollars at a time, and often only provide a temporary relief requiring reimplementation days to weeks later. The dynamic entrance therefore presents a major management issue and is exacerbated by a lack of understanding of the precise geomorphic controls on entrance closure. Currently, ICE are artificially opened due to socioeconomic pressure from landholders, catchment flooding and decreasing water quality (Arundel, 2006). In Australia, artificial opening attempts are typically made during falling tides, lower-energy waves and when basin water depth reaches a trigger height established by regional councils (Barton and Sherwood, 2004). Often, mounting pressure from stakeholders can override these factors and lead to opening in less than ideal conditions.

This study investigates the dynamics of entrance opening and closure in ICE over a daily scale through field based monitoring of channel change morphology following entrance opening. Monitoring is undertaken throughout a variety of fluvial and marine conditions. From this dataset, the processes which are responsible for driving deposition and therefore closure, are identified. A predictive model of entrance behavior is created to assist decision making in management whereby the conditions favoring a long-lived artificial entrance opening are identified. This will ultimately save managers many thousands of dollars by better understanding the geomorphic drivers of rapid deposition within the estuary channel.

Field Sites and Methods

Methods

The change in entrance channel morphology and estuary basin water depth was monitored following multiple entrance openings at ICE in Victoria under a range of concurrent coastal and fluvial conditions. Two natural and five artificial openings were included within the study period (Table 1).

Table 1. Entrance opening events included in the study period. For the 25 June 2014 natural opening of Aire River, only the first 10 days were able to be monitored so the final opening duration was unknown.

Site	Type of opening (natural/artificial)	Date of Opening	Opening duration (days)	Mean daily survey frequency (surveys/day)
Anglesea River	Artificial	14 Feb 2014	8	1.75
Aire River	Artificial	20 Mar 2014	21	1
Aire River	Artificial	1 May 2014	1	1.33
Aire River	Artificial	10 May 2014	11	1
Aire River	Natural	23 May 2014	25	0.50
Aire River	Natural	25 Jun 2014	-	-
Gellibrand River	Artificial	11 Apr 2014	249	0.30

Topographic surveys were undertaken to show the change in entrance morphology following entrance opening. A Trimble R6 model Real Time Kinematic Global Positioning System (rtkGPS was used to complete the surveys. Surveys were taken across the entrance channel at a fixed position across the berm, in addition to a single long profile along the channel thalweg. For each entrance opening, the first survey was taken within the 24 hours prior to opening to establish the berm elevation prior to channel incision. Following opening, survey frequency was at a maximum (>3 surveys daily) during the first 2 - 3 days and when the estuary was nearing closure to ensure any rapid change was captured. Survey data had an accuracy of 3 mm and was referenced to at least 2 permanent benchmarks (accuracy 1 mm) established relative to MSL.

Four pressure sensors (Solinist Levelogger 30001) were anchored on concrete blocks on the channel bed to monitor the change in water depth. These were placed; (i) at the mouth, (ii) 200 - 300 m, (iii) 500 m, and (iv) 1.2 – 1.8 km inland of the mouth (i.e. central basin, submerged adjacent to the gauge board). Data from the most upstream site was used in this study. A logging frequency of 5 sec was used to allow for maximum data storage. Water depth data were corrected for barometric pressure using a Barologger 30001 located within a 2 km radius of all loggers. The change in channel morphology was then compared to the concurrent fluvial and marine conditions throughout each opening. Rainfall data was sourced from the Bureau of Meteorology (BOM) and discharge data from Department of Environment, Land, Water and Planning (DELWP). Both rainfall and discharge data were taken from stations located within 7 km of each estuary mouth. Offshore daily tidal data was sourced from BOM. As no permanent wave buoys are present in Victoria, wave data was hindcast from National Oceanic and Atmospheric Administration's WAVEWATCH III model. Wave data was analysed using MatLab software. The change in berm elevation, basin water depth and cross-sectional area was compared relative to the value at the time of opening. The duration of each monitoring period is presented as a percentage of its maximum duration to allow a relative comparison across all sites.

Regional Setting

The open coast of western Victoria, Australia, is microtidal with a spring tidal range of 0.8 - 1.6 m. There is a prevailing SW swell (Hodgkin and Hesp, 1998) and the mean annual significant wave height (H_s) is 2.49 m at Port Campbell (Figure 1). Waves are highest during May to September as associated with an increase in the frequency of low-pressure systems from the Southern Ocean. The mean annual wave period is 7.65 sec, mean direction is 213° and mean maximum wave height is 4.13 m. Winds from the south and southwest are dominant during autumn and winter resulting in a predominantly easterly longshore drift. During spring and summer however winds from the southeast increase in intensity shifting this direction to the northwest (Barton and Sherwood, 2004). Victoria has a temperate climate with rainfall being both seasonally and interannually variable (Puckridge *et al.,* 1998; Risbey *et al.,* 2009). This results in peak river discharge occurring in winter and spring and low flows during summer (Mondon *et al.,* 2003) (Table 2).

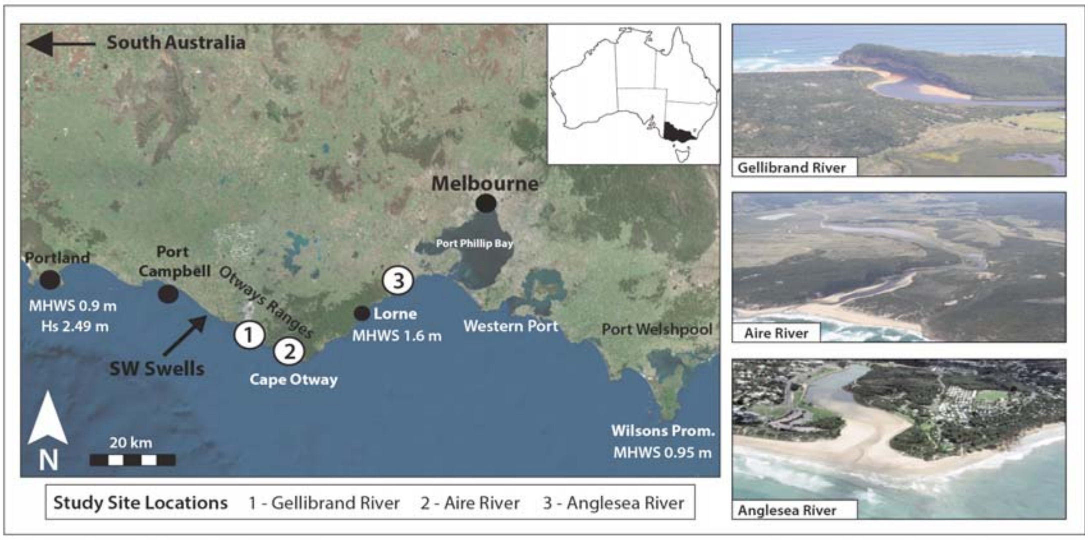

Figure 1. Location of field sites (Aire, Gellibrand and Anglesea River estuaries) and coastal setting of west-Victoria, Australia. Oblique aerial photos courtesy of Neville Rosengren.

Field Sites

This study was undertaken at 3 ICE in western Victoria: the Gellibrand, Aire and Anglesea estuaries (Table 2; Figure 1). All of these sites are artificially opened at least 1 – 4 times per year. Anglesea River estuary is the smallest in terms of both catchment and estuarine dimensions (Table 2). The estuary has a moderately urbanized catchment (Figure 1) and the entrance is open for ~44 % of the time (Pope, 2006). Directly adjacent to the mouth, wave height is reduced relative to offshore due to refraction in the lee of an offshore reef. Anglesea has a constant discharge maintained by release from the Alcoa power plant (Corangamite CMA, 2012). During this study, Anglesea was opened by artificial opening (Table 2). Aire River estuary is in the late stages of infill as indicated by the expansion of alluvial floodplain (Figure 1) (Mondon *et al.,* 2003). Throughout this study, Aire River opened three times artificially and twice naturally (Table 1). The Gellibrand River is the largest ICE with a floodplain >1 km wide and a central basin also in the late stages of infill (Roy 1984; Table 1; Figure 1). During the study, the Gellibrand was opened once artificially.

Table 2. Study site characteristics. Climate data from BOM (2016) (averaged >40 yrs). River flow data from DELWP (2015) (averaged >75 yrs). Berm height and channel width from >10 repeat surveys in 3 yrs.

Site	Anglesea River	Aire River	Gellibrand River
Location	38.46°S, 144.90°E	38.76°S, 143.51°E	38.69°S, 143.16°E
Catchment size (km^2)	125	250	1184
Berm height (m above MSL)	1.5 - 1.9	2 - 3	2 - 3
Estuary length (km)	3.50	6.70	7.80
Entrance channel width (m)	80	120	80 - 100
Surface water area (when full) (km^2)	0.25	15	20
Mean opening duration (days)	14	28	39
Mean annual rainfall (mm)	635	1077	895
Mean daily discharge (m^3/s)	0.05	0.82	7.94

Results

Aire River Estuary Artificial Opening 1

The first artificial opening at Aire River was undertaken at a berm elevation of +2.49 m MSL and when the backing lagoon water depth was 1.98 m (Figure 2a; Figure 3d). The estuary was opened on a falling high tide and a falling spring tidal cycle (Figure 3d). At the time of opening, offshore H_s was 2.15 m with waves approaching from the SSW at 220°. Within 2 days (~10 % of opening duration), the estuary water depth had reached a minimum of 1.18 m and the channel had expanded to a maximum cross-sectional area of 291.35 m^2 (Figure 2a). Simultaneously the channel at the location of the former berm had incised to its maximum depth of -0.25 m MSL. Throughout days 2 - 11, outflow persisted and maintained the bed depth at the former berm position within +0.30 m of MSL. Waves remained <4 m and approached the shore from the SSW at 210 - 220° (Figure 3a; c). The most marked change in entrance morphology occurred 12 days following entrance opening (60 % total opening duration) when a storm increased H_s to 5.6 m and wave direction to 225 - 230° (SW) (i.e. more shore-normal) (Figure 3a; c). The increased wave height and change in direction corresponded with a rapid decrease in channel area and a concurrent increase in berm elevation (Figure 3a). The storm persisted until day 20 and resulted in closure on day 21 (Table 1; Figure 2a). Throughout the monitoring period, the mean daily discharge remained at or below the mean annual flow and consistently below the 75-year mean (Figure 3b). At the time of closure, the final berm elevation was +1.55 m MSL and the lagoon water depth 1.44 m, both lower than at the time of opening (Figure 3a). Closure occurred following the peak of a spring tidal cycle and when H_s was 4 m (Figure 3a; d).

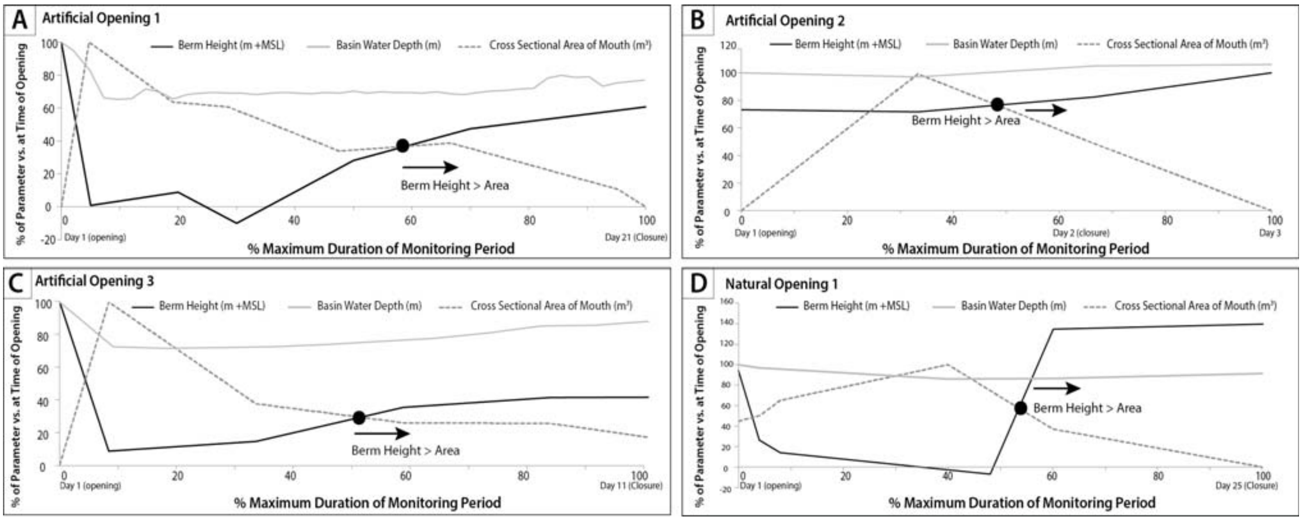

Figure 2. Progressive change in berm crest elevation, basin water depth and cross-sectional area of mouth. (A) Aire Artificial Opening 1. (B) Aire Artificial Opening 2. (C) Aire Artificial Opening 3. (D) Natural Opening.

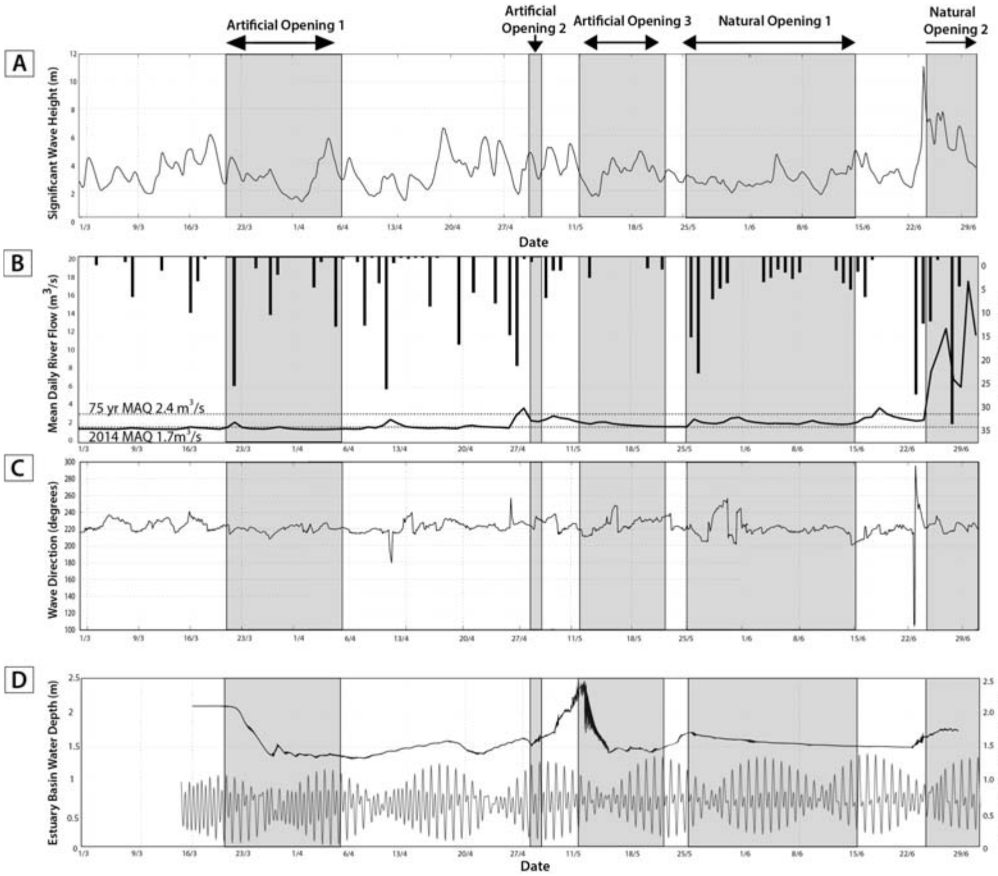

Figure 3. Marine, fluvial and estuarine conditions during all entrance openings at Aire River (A) H_s (B) Rainfall, mean daily discharge (DELWP; BOM) (C) Wave direction (D) Basin water depth, tidal amplitude.

Aire River Estuary Artificial Opening 2

The second artificial opening of Aire River was implemented in response to widespread flooding within the catchment as the basin water depth reached 1.99 m following a period of high rainfall (Figure 3b). The opening occurred during a falling tide but on the peak of a spring tidal cycle and during a storm (H_s >5 m approaching shore normal at 230 - 235° from the SW) (Figure 3a; c; d). The maximum cross-sectional area was reached 6 hours following opening however the high-energy waves rapidly aggraded not only the berm but the whole excavated channel. As a result the estuary closed within 1 day (Figure 2b; Figure 4a-c). Following excavation, the berm elevation only decreased by 0.25 m as waves maintained an area of active deposition. Despite daily discharge being above the 2014 mean, this did not provide sufficient fluvial energy to maintain an open entrance due to the counteracting deposition by waves. Throughout this time, the estuary water depth only decreased slightly to 1.95 m on day 2 before increasing to 2.11 on day 3 (Figure 3d). Following closure, both the resultant berm and water depth were higher than prior to opening (Figure 2b). The rapidity of closure and lack of drainage led to a further opening being conducted within 6 days.

Figure 4. Second artificial opening at Aire River. (A) Day of opening. (B) Day 2: closed. (C) Day 3: full infill.

Aire River Estuary Artificial Opening 3

The third artificial opening of Aire River was undertaken when the berm elevation was +3.27 m MSL, the backing water depth 2.11 m and during waves 3 m high approaching from the SSW (220°) (Figure 3a; c). The opening occurred on a falling high tide and upon entering a neap tidal cycle (Figure 2d). Within 6 hours of excavation, the channel reached its peak depth (>-2 m MSL) and dimensions (area 773 m^2) (Figure 2c; Figure 3d). Estuary water depth reached a minimum of 1.53 m by day 3 (Figure 3c). From day 4 onwards, the channel decreased in area and increased in bed elevation until it closed 11 days later. Deposition was most rapid during higher waves (e.g, >4 m during days 4 - 10) and as the direction shifted to shore normal (230°) (Figure 3a; c). The lagoon water depth increased in accordance with berm height and the decreasing area (Figure 2c). Discharge fluctuated around the mean value for 2014 throughout the monitoring period with minimal rainfall (Figure 3b). The final berm elevation was 40% lower than at the time of opening (+1.35 m MSL) and the basin water depth upon closure was 1.86 m. Despite larger dimensions attained during opening, closure occurred within 11 days and upon entering an increasing spring tidal cycle.

Aire River Estuary Natural Openings

Two natural openings occurred at Aire River, the first on 25 May 2014 when the berm elevation was +1.35 m MSL and the lagoon depth 1.87 m but increasing due to a period of high rainfall (Figure 3d; c). The opening persisted for 25 days with closure occurring during a period of waves 4 m high (Figure 3a). The berm was eroded to below MSL but the maximum cross-sectional area was attained a week as opposed to hours after opening (Figure 2d). Throughout the opening, discharge was sustained at or above the annual mean (Figure 3b). The final berm elevation was higher at the time of closure and closure occurred on an increasing spring tidal cycle (Figure 3d). A second natural opening occurred on 25 June 2014 in response to high rainfall and discharge despite a 10 m H_s (Figure 3a). Monitoring was not undertaken following 30 June but the opening shows a clear response to increasing rainfall, discharge and basin water depth (Figure 3b).

Anglesea River Estuary

Anglesea Estuary was artificially opened at a berm elevation of +2.37 m MSL and during waves 0.50 m high (Figure 5a). The excavated channel was 110 m long and did not incise below +0.66 m MSL. At the time of opening, the backing lagoon water depth was 0.95 m which led to a gradual drainage of the lagoon to a minimum on day 4 (Figure 5d). The lack of channel incision is attributed to resistance from the long, shallow channel and lower hydraulic head due to opening at a lower water depth relative to the berm elevation. The most marked change in morphology occurred between days 5 - 8 (60 - 100 % opening duration) when a distinct berm formed and infilled the channel (Figure 5d). This coincided with an increase in H_s to 2 m (Figure 5a). The entrance closed on day 9 at a berm elevation of +2.88 m MSL. Wave direction remained between 220 - 190° throughout the opening (S - SSW) and closure occurred on a spring tidal cycle (Figure 5b).

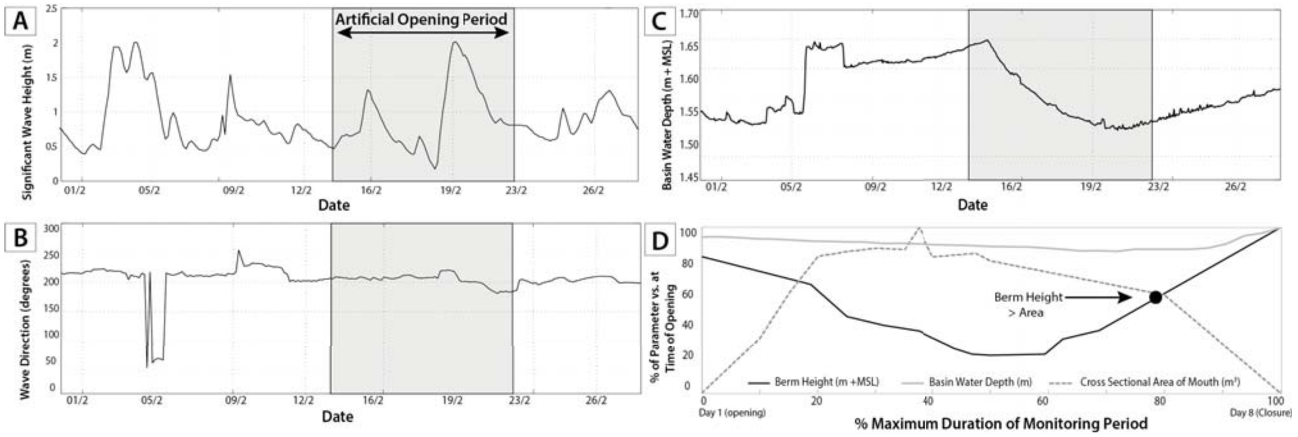

Figure 5. Conditions throughout monitoring of Anglesea. A. Offshore H_s. (B) Estuary water depth. (C) Wave direction. (D) Change in berm elevation, basin water depth and cross-sectional area of mouth. Negligible rainfall (none aside from 5 mm 16 Feb). Discharge 0.05 m^3/s/day (Corangamite CMA, 2012).

Gellibrand River Estuary

The Gellibrand Estuary was artificially opened at a berm elevation was +3.79 m MSL and when the backing lagoon water depth was 1.48 m (Figure 6a). At the time of opening wave height was 2 m with a direction of 210° (SSW) (Figure 6a). Following rapid incision and expansion of the channel over the first 2 days, Gellibrand estuary maintained an open entrance for 249 days. This is attributed to wave heights remaining <4 m for most of the first 2 months followed with an increase in river discharge to above the 2014 mean annual flow which was maintained for 4 months (>50 %) of the opening duration (Figure 6c). The 75-year mean annual discharge was also exceeded for 2 months of the opening. Despite multiple winter storms where the offshore wave height reached between 7 – 7.8 m (Figure 6b), the constant high fluvial discharge inhibited deposition in the entrance channel (Figure 5d). An increase in water depth within the lagoon was evident as a result of storm surges (Figure 6a; Figure 5d). Throughout the period of high discharge, the cross-sectional area of the channel remained within 40% of its maximum value of 165.6 m^2 (attained on day 2) and the berm did not aggrade to higher than within 20% of its minimum value also reached on day 2 (Figure 6d). As fluvial discharge decreased below the mean annual flow upon entering summer low flow season (Nov 2014), deposition within the channel became dominant with a progressive decrease in cross-sectional area. Hereafter berm height increased and channel area decreased (Figure 6c; d). Closure occurred following a week long storm during a spring tide at the start of December which caused 6 m waves (Figure 6b d).

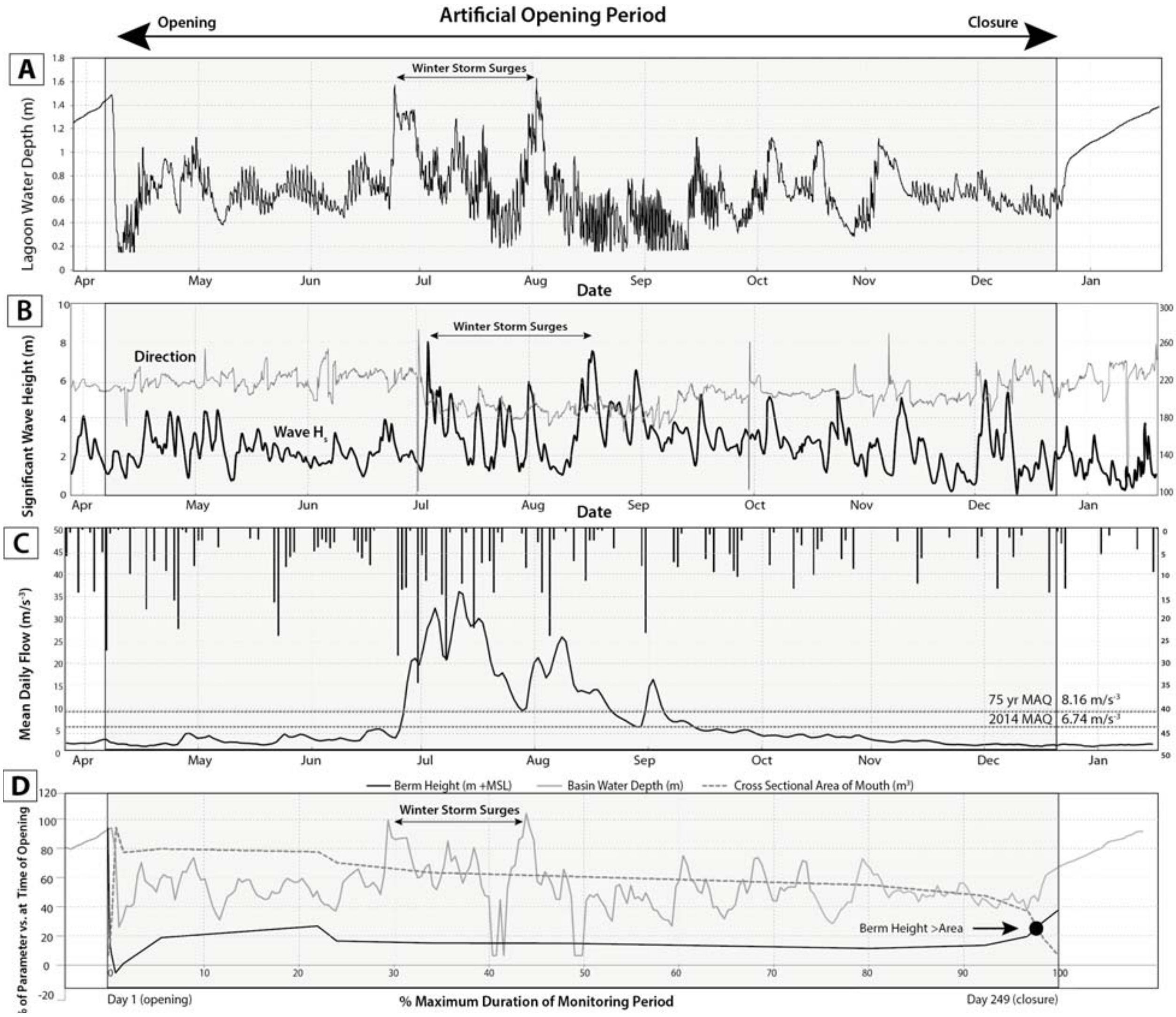

Figure 6. Gellibrand River. (A) Estuary water depth. (B) Offshore H_s, direction. (C) Rainfall, daily discharge (data: DELWP; BOM, 2014). (D) Change in berm elevation, basin water depth, mouth cross-sectional area.

Discussion

ICE entrance openings in Victoria proved most effective under a specific range of marine and fluvial conditions. On a local scale, the influence of wave height, direction and fluvial discharge relative the mean annual discharge are important. On the scale of the individual site, the balance between berm crest elevation, channel cross-sectional area and basin water depth proved important (Figure 7). A decrease in cross-sectional area and an increase in depth of the channel at the former berm position to within 50 – 60% of their maximum indicates a depositional state thus a progression towards closure (Figure 2; Figure 5d; Figure 6d).

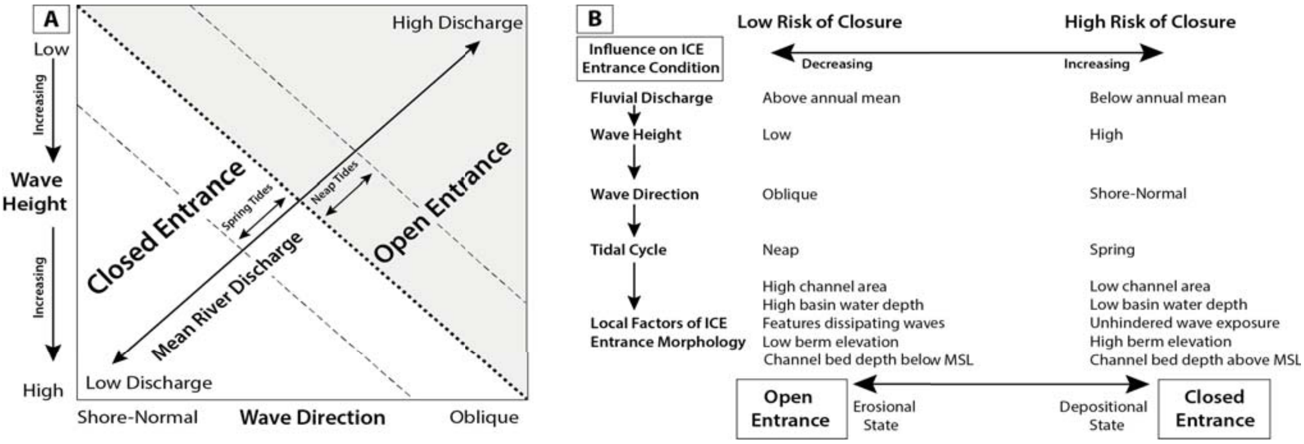

Figure 7: (A) Factors controlling ICE opening and closure. (B.)Hierarchy of controls on entrance condition.

Influence of fluvial discharge

In this study, the Gellibrand River remained open the longest for 249 days. The extended opening duration is attributed to high fluvial discharge where the mean annual flow was exceeded for 4 months following opening and the 75-year mean for >2.5 months (Figure 6c). Only when discharge dropped below the mean annual flow did deposition begin initiate in the channel (Figure 6c; d). This shows that opening an estuary prior to a predicted period of sustained high fluvial discharge, either due to a seasonal increase in flow or preceding a high rainfall event, would increase the effectiveness and duration of the opening. This is because outflow is maintained beyond the initial basin drainage and reduction in hydraulic head post opening (Figure 6b) to provide an ongoing source of energy to counteract marine deposition. Forecasting and consideration of increased discharge post opening is therefore an important factor in increasing entrance opening duration.

Wave height

Opening an estuary during lower wave heights is also important as the reduced wave energy means there is a lower rate of onshore sediment transport (Ranasinghe and Pattiaratchi 1999; 2003). The artificial opening at Gellibrand River was implemented during waves which were low relative to the mean throughout the study period (H_s = 2 m compared to mean H_s 3.8 m) (Figure 6a). For the first 2 months following opening, H_s remained <3 m on average before increasing upon entering winter (Figure 6a). During winter, however, fluvial discharge also increased to surpass the mean annual flow and worked to counteract the theoretical higher rate of wave driven deposition associated with an increase in H_s (Figure 6a; c). This effectively prevented a progression towards closure and increased the opening duration compared to what would likely occur under lower fluvial discharge (Figure 6b). The influence of increased discharge relative to wave height is evident as despite H_s increasing to >7m during two winter storm events, there was no reduction in cross-sectional area which would indicate deposition – only a temporary increase in lagoon water depth as related to the storm surges (Figure 6a; b; d). At Aire River during all entrance openings, an increase in H_s to >4 m occurred in the 1 – 5 days preceding entrance closure thus increasing the rate of deposition (Figure 3a, Figure 3a-d). The more direct influence of increasing H_s at Aire River is also attributed to fluvial discharge remaining at or below the mean annual flow throughout of all openings (Figure 2; Figure 3b). The second natural opening provides the only exception to this where the onset of a winter storm increased H_s to >10 m but as fluvial discharge simultaneously increased to surpass the mean annual flow (by > a factor of 10) (Figure 3a; b), the estuary did not close as may otherwise be expected. This indicates that an increase in wave height as a mode of deposition is only influential when outflow energy has been reduced to a point where marine processes dominate to allow sediment to stabilize within the entrance. Despite a lower overall H_s at Anglesea, there was a positive correlation between wave height and the rate of deposition. For example, during days 5 – 8 when H_s increased, the rate of berm building and decrease in cross-sectional area increased (Figure 5a; d).

Wave direction

The wave direction is also influential in determining the rate of deposition. During shore normal waves, the rate of deposition was increased at all sites. This is attributed to a more direct transfer of sediment onshore while cross-shore processes dominate and as the occurrence of shore-normal waves often occurs during storm events (Cooper *et al.,* 2007; Baldock *et al.,* 2008; Morris and Turner, 2010). For example during the second artificial opening at Aire River, closure occurred within 1 day as waves were directly shore-normal and additionally were >4 m (Figure 2a; c). This occurred irrespective of a basin water depth being high relative to the berm elevation (Figure 3d). A similar process is described at the East Kleinemonde estuary in South Africa which frequently closes within a few tidal cycles during predominantly near shore-normal, high-wave energy conditions (Whitfield *et al.,* 2008). At Anglesea Estuary, closure occurred when waves were moving at an oblique direction onshore although this is attributed to the extremely low outflow energy in the channel. The low outflow resulted from minimal fluvial discharge, dissipation of energy through a long, shallow channel and a lower basin water depth relative to berm elevation (i.e. decreased hydraulic head). Being able to forecast wave height and direction prior to implementing artificial openings would enable a more accurate prediction of sedimentation rates following opening and therefore the effectiveness of the opening.

Tidal conditions

Entrance closures of Anglesea, Gellibrand and Aire River (aside from artificial opening 1) occurred during an increasing spring tidal cycle. This contributed to a higher wave run-up limit and an increased ability to deposit sediment further landward when combined with high waves. Although the timing of closure is determined by wave height and direction relative to fluvial discharge, the increasing tidal range occurring on spring tides is likely to increase the closure likelihood by enhancing overwash deposition (Baldock *et al.,* 2008).

Conclusions

At ICE in west-Victoria, entrance closure was observed to occur rapidly (daily-weekly scale) when: (i) offshore wave-energy was high (H_s >4 m), (ii) the onshore wave direction was near shore-normal, (iii) fluvial discharge was low relative to the mean annual flow and (iv) during a spring tidal cycle where the wave runup limit was further landward (Figure 7). Opening duration was prolonged when the estuary was opened prior to the onset of a period of high fluvial discharge as this maintained erosion of sediment from the entrance channel. Under constant discharge, outflow is maintained following the initial decline in basin water depth and hydraulic head following the first few days of opening. In addition, when low-energy waves (<2 m) moving onshore at an oblique angle were present, the rate of channel infill was more gradual. On the scale of each individual site, analysing the berm crest elevation, cross-sectional area of the channel and estuary water depth in relation to their value at the time of opening provides an insight as to whether the estuary is in an erosional or depositional state. Opening duration was exclusively related to the offshore marine conditions and river discharge in relation to the mean annual flow and not the maximum channel dimensions obtained during opening. Establishing a long term record of both local marine and fluvial conditions in addition to site-specific factors (e.g. berm elevation) will extend the current dataset and strongly assist management of sites by enabling a more accurate prediction of opening duration. Additionally forecasting of wave and fluvial conditions will allow openings to be undertaken to correspond with the established optimum conditions. The underlying entrance geology is also recognized as being able to affect the magnitude of wave processes. At Anglesea for example, H_s was decreased through dissipation from an offshore reef adjacent to the mouth.

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