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Climate Change Impacts on Entrance Processes of Intermittently Open/Closed Coastal Lagoons in New South Wales, Australia

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ABSTRACT

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Intermittently open/closed coastal lagoons are a relatively unique feature of the south-east Australian coastline, and NSW in particular. Future climate change is expected to modify a number of climate variables that define the physical and chemical structure and ecological behaviour of the NSW coastal lagoons. These climate variables include mean sea level, wave climate and rainfall behaviour (total depth and storm intensity). Entrance morphodynamic processes are particularly vulnerable to climate change. These processes, which describe the opening and closing cycle of these lagoons, are controlled by dominant coastal (wave and sea level) conditions and episodic catchment runoff events. The magnitude of entrance impacts will depend on the particular characteristics and location of individual lagoons. An increase in mean sea level is likely to move the entrance sand berm upward and landward. An increase in south-easterly waves will cause minor rotations in beach planform alignments with expected net erosion from southern ends of beaches and net accretion at northern ends. For lagoon entrances at the southern end of beaches, this will result in a net loss of sand from the entrance and a shortening of the entrance channel. For lagoon entrances at the northern end of beaches, this will result in a net growth of the entrance berm, possibly offsetting the recession resulting from mean sea level rise. Increased typical lagoon water levels behind the berm are also expected. Marine flood tide deltas may accrete vertically and more landward. A decrease in total rainfall depth is likely to retard the cycle of filling and draining, and reducing the frequency of entrance breakout for mostly closed lagoons. For mostly open lagoons, however, an increase in rainfall storm intensity may actually increase scour through the entrance, thus increasing the longevity of ocean connections.

ADDITIONAL INDEX WORDS: *Entrance morphodynamics, ICOLL, intermittently open estuaries, coastal lakes, sea level rise*

INTRODUCTION

Within Australia, wave-dominated barrier estuaries and coastal lagoons that are intermittently connected to the ocean have been termed Intermittently Closed and Open Lakes and Lagoons (ICOLLs). ICOLLs are relatively abundant on the south-east coast of Australia and New South Wales (NSW) in particular (HAINES *et al.,* 2006). Elsewhere in Australia and across the world, ICOLLs are less common. Comparable examples can be found in south-west Western Australia, South Africa, New Zealand, Mexico, the Atlantic coast of Brazil, Uruguay, Portugal and Spain (HAINES, 2006).

Coastal lagoons and ICOLLs in particular are recognised as the most sensitive type of estuary to human intervention due to their irregular connection with the ocean and associated low degree of tidal exchange (HRC, 2002; BOYD *et al.,* 1992). Coastal lagoons also tend to be natural ecotones, influenced by both marine and freshwater (catchment) processes (VADINEANU, 2005).

Climatic conditions in the future are expected to change as a result of increased 'greenhouse gases' within the Earth's atmosphere (i.e. the 'enhanced Greenhouse Effect') (IPCC, 2001). Whilst it is recognised that the Earth undergoes natural cycles of warming and cooling (including El Nino/Southern Oscillation [ENSO] and Interdecadal Pacific Oscillation [IPO]), there is conclusive evidence to suggest that the global warming experienced over the past 50 years is primarily due to greenhouse gases rather than natural cyclic change (IPCC, 2001; BOESCH, 2002; DEH, 2003).

Given the complex environmental process interactions experienced within ICOLLs (HAINES, 2006), continued climate change in the future is expected to have a range of impacts on lagoon condition, structure and function. Of particular interest are the likely impacts of climate change on entrance processes and behaviour. Given that entrance conditions already largely control the sensitivity of ICOLLs, any significant change to these conditions is likely to have major repercussions for other physical, chemical and biological processes within the lagoon.

ICOLL CHARACTERISTICS

ICOLLs in NSW have evolved by marine sands forming a barrier across natural coastal inlets and bedrock embayments when sea level stabilised some 6000 years ago (ROY, 1984; BIRD, 1994; WOODROFFE, 2002). There are approximately 70 ICOLLs in NSW with a water surface area greater than approximately 1 ha. For approximately 70% of these ICOLLs the barrier has completely enclosed these embayments, preventing regular tidal interaction with the ocean (i.e. they are mostly closed) (HAINES *et al.,* 2006). For the majority of the remaining ICOLLs, entrances are mostly open; resulting in a distinct dichotomy of typical entrance

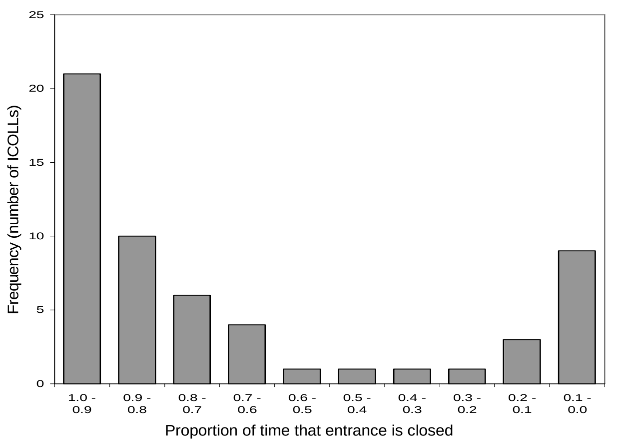

Figure 1. Bimodal behaviour of ICOLL entrances, showing a tendency for either mostly closed conditions, or mostly open conditions (source: HAINES *et al*., 2006)

conditions (Figure 1). ROY *et al*. (2001) states that the degree of 'openness' of ICOLLs depends primarily on exposure to ocean waves and on fluvial discharge, with the latter also influenced by climatic fluctuations on decadal timescales (e.g. El-Nino/La-Nina phenomena and Southern Oscillation variations). HAINES (2006) has found that the ratio between catchment and waterway size, as well as the presence of geomorphic (bedrock) control within the entrance compartment, can also influence typical entrance conditions.

From a geomorphological perspective, ICOLLs represent an immature form of barrier estuary where terrigenous sedimentary infilling has been relatively limited (ROY, 1984). Therefore, most ICOLLs in NSW are found within relatively small catchments (less than $100km^2$).

The ocean entrances of most ICOLLs are located adjacent to rocky headlands at either the northern or southern end of a coastal beach compartment. Very few ICOLL entrances are located mid-way along a beach and as such, these are not considered further in this paper.

For ICOLLs that are mostly closed to the ocean, catchment rainfall and associated runoff results in increasing water levels until levels reach the crest of the entrance sand berm. Once the sand berm becomes overtopped, high velocity outflows cause scour and rapid channelisation. Discharge from the ICOLL continues to enlarge the entrance channel until the lagoon attains a comparable water level to the adjacent ocean. This can be further exacerbated by storm wave erosion cutting into the entrance berm on the ocean side. The resulting 'open' entrance allows tidal exchange between the ocean and the lagoon until marine sands, reworked under the action of tides and waves, once again infill the channel.

CLIMATE CHANGE VARIABLES

Engineers Australia (2004) summarises the key climate change variables applicable to the Australian environment as: mean sea level, ocean currents and temperature, wind climate, wave climate, rainfall/runoff and air temperature. The most important factors influencing the behaviour of ICOLL entrances relate to coastal and catchment processes (HAINES, 2006). These processes are likely to be modified as a result of changes to mean sea level, wave climate and rainfall/runoff patterns due to the enhanced Greenhouse Effect.

With respect to mean sea level, long term data collected from Fort Denison, Sydney shows a progressive increase during the 20th Century (Figure 2). IPCC (2001) projects further increases in mean sea level of between 0.05 and 0.32 metres (with a mid-range scenario increase of 0.16 metres) for the year 2050 and between 0.09 and 0.88 metres (with a mid-range scenario increase of 0.48 metres) for the year 2100 (relative to 1990 mean sea level). HENNESSY *et al.* (2004a) states that waves from the southeast will become more prevalent in NSW as a result of an increase in Tasman lows (during winter), a reduction in Tasman highs (during summer), and an increase in intense frontal systems (during both winter and summer). The increased frequency and intensity of waves originating from the south would be expected to have a greater impact on the southern half of NSW.

With respect to rainfall, a decrease in average rainfall is predicted by HENNESSY *et al.* (2004b), particularly during winter and spring and is likely to result in an increase of droughts by about 70% by the year 2030 and by more than 200% by the year 2070 (HENNESSY *et al.*, 2004a). An increase in actual rainfall storm intensity is also predicted (WALSH, 2004a; HENNESSY *et al.*, 2004a). Further, in response to increased global air temperatures, evaporation is likely to increase by between 1% and 8% by the year 2030 and by between 2% and 24% by 2070 (relative to 1990 levels) (HENNESSY *et al.*, 2004b).

DISCUSSION OF CONCEPTUAL IMPACTS

ICOLL Water Levels

An increase in sea level (IPCC, 2001) will result in an upward shift in water levels within the ICOLL across the full spectrum of possible lagoon levels. Firstly, the base water level of the ICOLL would increase by an equivalent amount to the sea level rise, as the base level is controlled by ocean levels when the entrance is open. Secondly, the maximum water level of the ICOLL would increase by an equivalent amount to sea level rise as this level is controlled by the entrance berm height, which is expected to increase contemporaneously with sea level (BRUUN, 1962; DEAN and MAURMEYER, 1983; HANSLOW *et al.,* 2000).

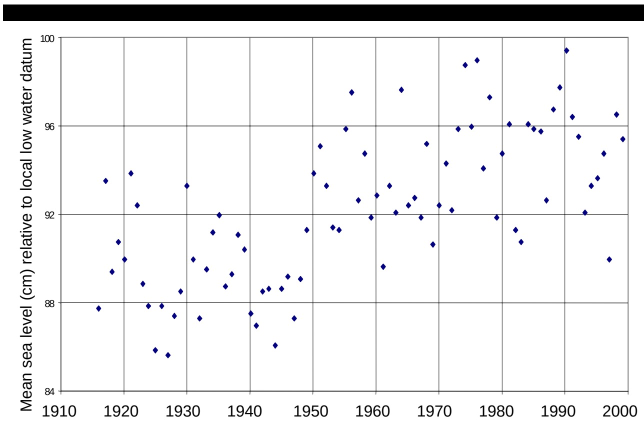

Figure 2. Annual averaged mean tidal levels at Fort Denison, Sydney, 1915 – 2000, relative to local low water datum (source: HAINES, 2006)

Longshore Sediment Transport

Existing longshore sediment processes, particularly those in closed sediment compartments, which largely characterise the south coast of NSW, are generally in a state of 'dynamic equilibrium' (ROY and THOM, 1981). That is, sand is transported northward or southward along the shoreline, depending on prevailing wave conditions. With an increased prevalence for swell from the south/south-east (HENNESSY *et al.*, 2004a), it can be expected that south-to-north sediment transport will increase within the embayment until the alignment of the shoreline adjusts to the altered wave climate. The increased south-to-north sediment transport will typically result in increased erosion at the southern end of beaches and increased accretion at the northern ends, essentially 'rotating' the beach alignment to become oriented more perpendicular to the south. Beach rotation has previously been linked to inter-decadal shifts in climate associated with El-Nino/La Nina cycles (SHORT and TREMBANIS, 2000).

Additionally, the influence of sub-surface controls, such as offshore reefs or rocky outcrops, on the longshore transport potential may be modified in response to general sea level rise (LORD and GIBBS, 2004). That is, with increasing sea levels, submerged offshore controls may become less influential (possibly releasing sediment currently locked up in salients or tombolos behind such controls), while shoreline recession may unearth controls along the shore that subsequently act as groynes and impede longshore drift. The degree to which sediment transport patterns are potentially modified would also depend on other factors, such as the potential increase in typical wave height (an increase in wave height may mean that a submerged offshore control remains within the wave base, despite an increase in mean sea level).

For ICOLLs at the northern end of a coastal compartment (i.e. located to the immediate south of a headland), widening of the beach due to beach rotation may result in more sediment deposited within the ICOLL entrance and an extension of the entrance channel (as the ocean essentially moves further away from the main lagoon waterbody). Conversely, for ICOLLs at the southern end of a beach (i.e. located to the immediate north of a headland), there would be reduced potential for ingress of marine sand into the entrance and a potential loss of entrance sands (and shortening of the channel).

Entrance Morphodynamics

The condition of an ICOLL entrance is the result of a dynamic balance between tidal inflow and outflows, wave-driven littoral sand transport and intermittent flood events (ELWANY *et al*., 2003; ROY *et al.*, 2001). Climate change processes that impact on entrance morphodynamics include sea level rise, littoral sand transport and changes to rainfall and flooding behaviour.

Increased sea level rise will result in a landward and upward shift in beach profile (BRUUN, 1962; DEAN and MAURMEYER, 1983; HANSLOW *et al*., 2000; DAVIDSON-ARNOTT, 2006), including the entrance berms of coastal lagoons, as a result of wave run-up and berm overwash processes (Figure 3). For ICOLL entrances at the northern end of a beach, changes to littoral sand transport processes potentially resulting in increased beach accretion adjacent to the entrance may offset or even exceed the progressive shoreline recession associated with sea level rise. For mostly open ICOLLs, the increased tendency for accretion within an ICOLL entrance would make that entrance more susceptible to closure. For ICOLL entrances that are already mostly closed, this would increase the size and extent of the entrance berm (which would then require higher water levels for a natural entrance breakout).

For ICOLL entrances located at the southern end of a beach, shoreline recession associated with sea level rise, combined with sand losses due to beach rotation, may result in significant landward migration of the beach profile. This may remove significant quantities of sediment from ICOLL entrances. The depleted entrance shoals may lead to a more open entrance condition for ICOLLs located at the southern end of beaches, and/or a general lowering of entrance berm heights.

Catchment hydrology has a significant impact on entrance morphodynamics as it is responsible for the episodic scour of large volumes of sediment from the entrance compartment and deposition as adjacent nearshore shoals. For mostly open ICOLLs, it is only large flood events that would impact on entrance dynamics. An increase in intensity of large floods, regardless of the overall reduction in total annual rainfall, will result in an increase in scouring potential of entrance sands. Therefore, for mostly open ICOLL entrances, more intense storms will tend to keep the entrance open for longer periods. For mostly open entrances located at the northern end of a beach, this may offset any tendency for increased shoaling associated with increased longshore sediment drift.

For mostly closed ICOLL entrances, entrance breakouts occur as a function of the total volume of rainfall and runoff (rather than intensity of specific storm events), due to the storage effect of the waterway. Therefore, the predicted reduction in total rainfall, combined with an increase in evaporation, is likely to result in a reduction in frequency of entrance breakouts (as it would take longer for the ICOLL to fill to the entrance berm height). Further, the net upward shift in typical water levels of the ICOLL combined with the generally flat topography of fringing lands means that ICOLLs will store a larger volume of water before breaching of the entrance. This would retard the water level response of the lagoon to catchment runoff inflows and reduce the frequency of entrance breakouts.

The entrance morphodynamics of a small number of NSW ICOLLs are governed by geomorphic controls at the entrance (e.g. shallow bedrock, which keeps tidal velocities high enough to limit sediment accumulation within the channel) (HAINES, 2006). With a net increase in sea level, the influence of such geomorphic controls may reduce, potentially resulting in increased entrance shoaling and more frequent entrance closure.

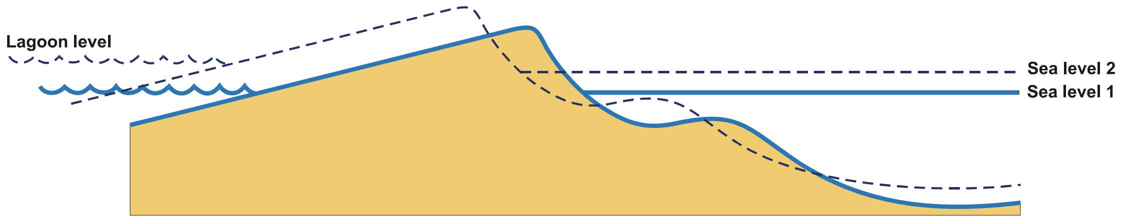

Figure 3. Landward and upward shift in beach profile due to sea level rise (Source: HANSLOW et al., 2000)

Marine Flood Tide Delta Formation

The episodic nature of entrance breakout events means that the marine flood tide deltas of ICOLLs are often in a state of flux. Following a breakout event, the delta would be depleted or even removed entirely. Subsequent wave and tidal processes would return marine sands to the flood tide delta, depending on the longevity of the open entrance conditions. With increased sea level the depth of water within the entrance channel will increase, which will reduce the frictional resistance of the bed. This will allow transportation of marine sediment further into the ICOLL and a migration of the delta dropover. However, the increased water depth would also increase the flow conveyance area of the channel, which would potentially reduce flow velocities and may result in a vertical accretion of the marine delta rather than an immediate landward progradation.

Furthermore, as sea level rise will result in a landward migration of the beach profile, the effective length of the entrance channel will shorten which will also reduce the total frictional resistance of the channel bed. As stated previously, this change to channel length could be potentially offset or exacerbated by a rotation of the beach as a result of altered wave climate.

Climate Change Impacts on Other ICOLL Processes

The biophysical processes of ICOLLs are highly inter-related; however, it is the coastal processes and catchment inputs that have the greatest influence on lagoon structure and condition (HAINES, 2006). Whilst this paper has focussed on the impacts of future climate change on the physical entrance processes, it is acknowledged that climate change will also have widespread impacts on other physical, chemical and biological processes of ICOLLs.

For example, changes to typical water levels within ICOLLs will impact on fluvial deposition and foreshore erosion processes. Changes to precipitation could alter the delivery of sediments, nutrients and contaminants to ICOLLs (BOESCH, 2002), while changes to entrance processes will modify the potential for tidal flushing and assimilation of these catchment inputs. Further, increasing water levels will result in inundation of fringing wetlands and saltmarshes (WALSH, 2004b). While it can be expected that some estuarine ecological communities (such as mangroves and saltmarshes) may migrate landward in response to increased water levels (to the detriment of existing brackish and terrigenous vegetation communities (BIRD, 2002; BOESCH, 2002; HUGHES, 2003; GILMAN, 2004)), the rate of climate change may be faster than the rate at which some species can adapt (DEH, 2003; HARTIG *et al.*, 2002).

CONCLUSIONS

Future climate change is expected to have a range of repercussions to almost all environmental processes occurring within the ICOLLs of NSW, Australia. A combination of changes to coastal conditions and catchment runoff processes is likely to result in adjustments to local entrance processes and behaviour. The scope of these adjustments is likely to depend on the typical 'openness' of the entrance, and the location of the entrance in relation to the overall sediment compartment, as summarised in Table 1. No attempt has been made at this stage to assess the impacts of varying rates of sea level rise over the next 50 years or so. It is considered that in some circumstances combinations of climate change impacts would tend to compound impacts on entrance processes, while for other circumstances changing climate variables may offset each other.

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Table 1: Summary of climate change impacts on ICOLL entrance processes and behaviour

Entrance location	Mostly Open ICOLLs	Mostly Closed ICOLLs
northern end of beach	• Recession due to sea level rise • Accretion due to south-to-north longshore sediment drift • Increased intermittent entrance scour due to higher flood intensity • Reduction in influence of geomorphic entrance control Result: may be more open or more closed depending on relativity between factors	• Recession due to sea level rise • Accretion due to south-to-north longshore sediment drift • Reduced intermittent entrance scour due to reduced total rainfall and streamflow, and increased evaporation Result: likely to be increased accretion within entrance, leading to increased period of closure and reduced frequency of entrance breakouts.
southern end of beach	• Recession due to sea level rise • Erosion due to south-to-north longshore sediment drift • Possible expansion of flood tide delta • Increased intermittent entrance scour due to higher flood intensity • Reduction in influence of geomorphic entrance control Result: likely to be overall loss of sand from entrance and increased potential for entrance to remain open	• Recession due to sea level rise • Erosion due to south-to-north longshore sediment drift • Possible expansion of flood tide delta • Reduced intermittent entrance scour due to reduced total rainfall and streamflow, and increased evaporation Result: may be more open or more closed depending on relativity between factors

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