DIFFICULTIES DETERMINING AND MANAGING FLOOD RISKS IN INTERMITTENTLY OPEN/CLOSED COASTAL LAKES

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ABSTRACT

The hydrodynamic behaviour of intermittently open and closed coastal lakes (sometimes referred to as ICOLLs) is influenced by coastal processes as well as catchment-based events. Applying the standard flood modelling methodology for determining flood risks, as prescribed in the Floodplain Development Manual (FDM) (NSW Government, 2005) is problematic. Difficulties are experienced in validating numerical models and defining probabilistic design conditions. Further, flooding in coastal lakes can be strongly affected by the height of the entrance berm. A direct relationship between rainfall and design flooding is therefore not always appropriate for coastal lakes.

Within coastal lakes, flood levels are primarily controlled by flows through the entrance. These flows are dependent on a range of factors, such as whether the entrance is initially closed, heavy shoaled or open. Validation of numerical flood models is difficult because specific details of entrance and lake conditions are usually unknown for historical flood events. Further problems arise as the probability of flooding within ICOLLs needs to account for the probability of different entrance conditions. The probability of different berm crest heights is one such variable that should be incorporated into formal probabilistic assessments.

Difficulties in determining existing and future flood risks are compounded by the artificial management of ICOLL entrances, as well as the expected response of ICOLLs to future climate change. This paper provides a discussion on the complexities of flooding processes within ICOLLs and the challenges associated with determining flood risks for future landuse management and planning purposes. It then provides a series of take home messages that should be considered by all authorities responsible for floodplain management and planning around ICOLLs in NSW.

INTRODUCTION

What is an ICOLL?

Coastal lakes or lagoons that have an intermittently open and closed connection to the ocean are termed ICOLLs (Intermittently Closed and Open Lakes or Lagoons). This term is most common in NSW, but is gaining increasing exposure worldwide through international scientific literature. ICOLLs are generally immature barrier estuary systems (Roy, 1984). They have relatively small catchments that have produced limited infilling of paleo valleys, resulting in relatively large open waterbodies trapped behind coastal sand barriers formed by longshore sediment transport closing off mouths of inlets (Bird, 1994; Woodroffe, 2002).

The most unique feature of ICOLLs is the dynamic behaviour of its entrance, and hence its variable interaction with the ocean. 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).

Within NSW, approximately 70% of ICOLLs are disconnected from the ocean (i.e. closed) for the majority of the time, while 25% of ICOLLs are open to the ocean for the majority of the time – there are very few ICOLLs (5%) that have an approximately equal timeframe in both the open and closed states (Haines et al., 2006; Haines, 2006). This means that under normal conditions, the majority of NSW ICOLLs do not receive any regular tidal flushing: in effect they behave like terminal lakes. ICOLLs are thus regarded as the most sensitive estuary type to human intervention (HRC, 2002; Boyd et al., 1992), and are one of the most complex management systems on the NSW coast (Thom, 2004).

There are in the order of 70 ICOLLs in NSW that have a water surface area greater than 1 hectare. Many ICOLLs are located proximate to urban centres, and offer significant recreational and amenity value to local communities. Conflicts between environmental processes and community values, however, sometimes necessitate artificial management of ICOLL entrances. Approximately half of the NSW ICOLLs are artificially opened from time to time, primarily to mitigate the impacts of flooding around foreshore areas.

**Flooding in ICOLLs**

Flooding in coastal areas is complex, due to influences from both tides and ocean storms (NSW Government, 2005). Flooding around ICOLLs is even more complex due to the influence of dynamic entrance morphology. The entrance shoals and berms of ICOLLs typically control upstream flood behaviour. However, the non-cohesive marine sands, which form the basis of the ICOLL entrances, can be easily mobilised during flood events. Therefore, during the course of a flood event, the hydraulic control imposed by the entrance can change significantly.

Flooding within coastal lakes and lagoons can occur as a result of elevated ocean levels, entrance constrictions or closure, floodwaters from inflows and wind generated waves (NSW Government, 2005), or as a combination of these. Flooding due to ocean inundation is relevant only when the entrance of an ICOLL is open. Under these conditions, the elevated ocean waters will penetrate into the ICOLL causing elevated lake water levels. Attenuation will occur across the entrance shoals, as an inverse function of entrance size and depth (ie more attenuation will occur if the entrance is small and shallow).

Flooding can also occur following catchment rainfall and associated runoff. If the lake has an open entrance, flood waters will be discharged to the ocean following detention by the waterbody. A smaller and more heavily shoaled entrance will require a greater hydraulic head to drive a given discharge from the lake. High velocities associated with the outflow will scour the entrance channel, thereby changing the nature of the hydraulic control dramatically with time. If the lake has a closed entrance, the additional volume of runoff is stored within the lake until the water level is high enough to overtop the entrance berm. At this stage, a scour channel begins to form on the ocean face of the berm due to the down-rushing water over the ocean face. This scour then develops into a complete cut through the entrance berm. The crest elevation of the entrance berm is thus an initial controlling factor for flooding of closed ICOLLs.
Flooding can also occur within closed ICOLLs as a result of continuing rainfall conditions (i.e., not associated with significant rainfall events). As flooding in closed ICOLLs is primarily related to available storage within the waterbody, sustained rainfall or a succession of small events could contribute substantial increases in water level. As described above, runoff is stored within the ICOLL, increasing lake water levels until the crest of the entrance berm is overtopped. Once again, the initial crest elevation of the entrance berm is a major determinant on resulting flood conditions.

**Difficulties in Defining Flood Risks**

Given the complexities associated with flooding in ICOLLs, it is very difficult to define the risks associated with flooding around these waterways. In accordance with best practice under the NSW Government’s Floodplain Management Program, flood risks are typically defined by assessing the inundation extents and behaviour for a range of probabilistic design events. It is considered that the typical flood study process requires modification if it is to be successfully applied to ICOLLs, for the following reasons:

- It is difficult to accurately validate predictive computer modelling of flooding processes within ICOLLs given the complex interactions of hydraulic and sediment transport processes. Due to the general lack of reliable validation data on many of the important processes, validation using historical events requires a multitude of assumptions about a wide range of environmental conditions;

- It is difficult to determine the likely probability of flood conditions within ICOLLs. As resulting flooding behaviour is largely influenced by entrance conditions, the probability of the entrance conditions also needs to be considered, in concert with the probability of rainfall (with runoff volume generally being more critical than peak runoff rate), the probability of elevated ocean conditions and the probability of initial water levels within the enclosed waterbody;

- The role of artificial entrance management also influences the definition of flood risks, as the critical flood control can be modified prior to or during the course of a flood. It is difficult to account for artificial entrance management within the context of a flood risk assessment, however, as the risk of works not being undertaken adds another dimension to the risk calculation; and

- Coastal areas are considered to be particularly susceptible to future climate change. Unknown future changes to sea level, wave conditions, and rainfall patterns will affect ICOLL entrance conditions, and thus will have an unknown impact on future flood risks.

These issues are discussed in further detail below.

**VALIDATION OF NUMERICAL FLOOD MODELS**

Numerical models can incorporate equations to simulate sediment transport associated with flood events. Only in recent years has readily available computational processing power been able to incorporate the feedback dynamic
linkage of sediment and hydraulic transport processes at suitable scales in both space and time. However, the very high outflow velocities are generally outside the parameters that fit within most sediment transport equations.

Formal flood studies have been prepared incorporating numerical flood models for a number of ICOLLs, including the mostly open Burrill Lake (BMT WBM, 2007a), the mostly open Lake Conjola (BMT WBM, 2007b) and the mostly closed Saltwater Lagoon (WBM, 2005). These models have incorporated sediment transport modules that allow for progressive scour of the entrance during the course of a flood event (Vienot et al., 2005; Wainwright et al., 2004).

Difficulties have arisen, however, with respect to model calibration and verification. Typically, computational flood model results are compared to recorded historical flood events to determine their validity. A number of model parameters are adjusted to improve predictions. These ‘calibrated’ parameters are then adopted within the model for probabilistic design flood scenarios. Calibration to historical flood events is problematic for ICOLLs, as many of the environmental conditions at the time of the event are unknown. Whilst rainfall and ocean levels can generally be obtained from long term recorders, the condition of the entrance at the time of the flood is usually unknown. Experience has shown that for some historical events, we are not even sure if the entrance was open or closed. As the entrance conditions have a significant impact on flood behaviour in the lake (particularly at the start of the flood), unknown entrance conditions will make reproduction of historical results very difficult.

Further, if the entrance is closed at the time of the flood, then information on the initial water levels within the lake are required. Such specific details are typically unavailable for historical events.

To overcome a lack of input data, sensitivity tests should be carried out using a realistic range of inputs. The broad results should then be compared to the observed flood levels to provide an indication of ‘likely’ calibration parameters. Sensitivity testing should also be carried out as part of subsequent design event modelling, to determine potential worst case conditions for given probability events (Howells et al., 2005).

INUNDATION BEHIND A CLOSED ENTRANCE BERM

For the situation whereby the entrance of an ICOLL is closed, the height of the entrance berm will have a significant impact on flood levels when the lake fills from catchment runoff. As mentioned previously, the majority of ICOLLs in NSW are closed for the majority of the time. Even mostly open ICOLLs are closed from time to time, albeit rarely.

The height of the entrance berm is dependent on a number of coastal processes. These include wave run-up, which in turn is a product of incident wave conditions (wave height and period) and beach slope (which is related to beach grain size) (Hanslow et al., 2000). Aeolian processes are then responsible for berm building once the crest height exceeds wave run-up levels (MHL, 1989; Gordon, 1990; Hanslow et al., 2000).

Given the Aeolian processes, maximum entrance berm height is also a function of time since the entrance was last open. ICOLLs that break out frequently (or are
mostly open but occasionally close) typically have lower entrance berm crest levels compared to mostly closed ICOLLs that breakout infrequently (only every few years for example). Maximum berm heights at ICOLL entrances in NSW are typically between 2 and 3 metres above mean sea level (Gordon, 1990; Hanslow et al., 2000). The higher berms tend to occur on beaches exposed to the south-east, although considerable scatter is evident, possibly due to other factors, such as proximity to headlands, islands and reefs, and offshore bathymetry, all of which would influence the height of incident waves (Hanslow et al., 2000).

In considering flood mechanisms that are dependent on entrance condition (and entrance berm levels), the probability of the entrance having particular conditions (and berm levels) should be accounted for. To the authors’ knowledge, there have been no attempts to calculate the probability of entrance conditions as part of any formal flood study in NSW. Given that entrance conditions have such a major impact on resulting flood levels, this oversight may have ramifications for future flood management and planning.

A novel approach is currently being trialled as part of the Lake Tabourie Flood Study. For this study, research is being conducted by the University of Queensland to determine the probability of entrance berm heights at the Lake Tabourie entrance. This will follow previous research carried out by University of Sydney in this field (Weir et al., 2004). It is expected that the outcomes from this research will be available within the next 12 months.

ARTIFICIAL MANAGEMENT OF ICOLL ENTRANCES

Approximately 40 ICOLLs in NSW are artificially opened from time to time (Haines, 2006). While it is reported that some opening events are initiated for the purposes of water quality maintenance, the principal purpose of the works is to prevent undesirable foreshore inundation. The works are generally carried out when lake water levels reach a pre-defined trigger value, and when rainfall is predicted that would potentially increase water levels further. The works therefore are carried out in the dry before the onset of rain events. Very rarely are entrances opened during a flood event (ie as water levels are rising rapidly) due to the time taken to mobilise resources and equipment.

The entrance works involve the excavation of a small pilot channel that allows drainage from the lake to the ocean. High outflow velocities develop along this channel, resulting in scour and an increase in channel size. Artificial breakout of a closed entrance has two main impacts on flooding. Firstly, it helps empty the lake, resulting in a lower water level and greater residual storage capacity at the onset of a flood event. Secondly, it generally creates an open entrance channel that allows direct discharge of floodwaters from the lake without adversely impacting on foreshore properties: the larger the entrance channel the more readily flood waters are advected from the lake and the lower the degree of foreshore inundation (in some circumstance, however, the entrance may re-close following artificial breakout before the next flood event arrives).

Artificial management of mostly open ICOLLs is also carried out from time to time, including Cakora, Conjola, Narrabeen, Burrill and Wallaga Lakes. These preventative works primarily aim to keep the entrance in an open condition by way of dredging or sediment removal from within the entrance shoal / marine delta.
It is difficult to incorporate entrance management works into the determination of flood risks. Whilst agencies may be willing to undertake these works today, incorporating these actions into models that then produce flood risk maps upon which future landuse planning decisions are made may have serious and significant ramifications for floodplain management in the future. An example is the Shoalhaven Heads Entrance, where past entrance opening practices have resulted in Council adopting an “open entrance scenario” to determine flood planning levels, which is lower than the “closed entrance scenario” flood levels. This means that Council is now locked into having provisions to open the entrance to protect even more recent development that was allowed at the lower level. Council has subsequently changed their previous decision and adopted the higher “closed entrance scenario” flood levels as the base for future flood risk planning for the Lower Shoalhaven River floodplain, but the risks to these lower lying developments remain.

Furthermore, costs associated with preventative dredging can be high and the approvals processing time can be lengthy. Recent entrance clearance works in Narrabeen Lagoon cost approximately $800,000 (involving removal of some 45,000m$^3$ of sand from the flood tide marine shoal and placement back on the adjacent coastline) (Cameron et al., 2007). It is likely that, for most ICOLLs, substantial preventative works (such as that proposed at Lake Conjola, MHL 2002) would require significant lead time to arrange sufficient funding. The probability of not undertaking these works prior to a significant flood event should therefore be considered and incorporated into future flood risk determination.

**CLIMATE CHANGE IMPACTS ON ICOLL FLOOD RISKS**

Climate change as a response to increased greenhouse gases in the Earth’s atmosphere is now a widely accepted phenomenon. Impacts of a changing climate are already beginning to emerge (Steffen, 2006). For example, WMO (2005) state that, with the exception of 1996, the 10 years between 1996 & 2005 were the hottest years on record (globally averaged).

Climate change is expected to modify a range of ICOLL processes and conditions, including entrance morphodynamics, hydrodynamics / water balance, sediment dynamics, water quality and ecology (Haines, 2006). From a flooding perspective, the most significant impacts of climate change will manifest in the structure and behaviour of the ocean entrance. The most up to date predictions of changes to climate variables is provided in NSW-specific investigations by CSIRO (McInnes et al., 2007; Macadam et al., 2007). A description of expected modifications to ICOLL entrance morphodynamics in response to climate change has also been provided by Haines and Thom (2007).

While small changes in dominant wave height and direction are predicted (McInnes et al., 2007), the greatest impact on ICOLL entrance processes will result from an increase in mean sea level. The predicted increase in mean sea level is between 0.18m and 0.91m by mid 2090s (McInnes et al., 2007), which accounts for additional contributions of up to 0.2m from the future rapid dynamic response of the ice sheets (SPM, 2007) and up to 0.12m from local effects on the NSW coast (McInnes et al., 2007). Increased sea level rise will result in a landward and upward shift in the entrance berms of ICOLLs (Bruun, 1962; Dean and Maurmeyer, 1983; Hanslow et al., 2000; Davidson-Arnot, 2006) (Figure 1). Consequently, flood levels within a closed ICOLL will increase commensurately before overtopping of the
entrance berm occurs. This may have significant impacts on property surrounding the ICOLL foreshores.

Figure 1. Landward and upward shift in beach profile due to sea level rise (Source: Hanslow et al., 2000)

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 the entrance berm is overtopped. This would tend to retard the flood hydrograph of the lake in response to catchment runoff inflows, and reduce the frequency of entrance breakouts.

Further, an increase in mean sea level will generally increase the initial water level within the ICOLL at the start of the flood, thus making existing property and infrastructure more vulnerable to flooding due to loss of flood storage potential. This is particularly apparent for ICOLLs that are already open at the beginning of a flood.

Recommendations on future landuse planning around ICOLLs, accommodating future sea level rise impacts, are provided in Haines (2005), and incorporate both vertical and horizontal buffers, or set-backs, taking into account the height of the entrance berm and the likely increase in berm height in the future.

**TAKE HOME MESSAGES**

1. Intermittently closed and open lakes and lagoons (ICOLLs) are one of the most complex coastal environments. Their behaviour during floods is equally complex as hydraulic controls are subject to significant change during the course of a flood event, and from one event to the next. Application of standard flood modelling approaches to ICOLLs is therefore problematic.

2. Their popularity along the NSW coast means that flooding of ICOLLs has impacts on existing property, as well as proposed future property as the coast is progressively developed. Given the difficulties in accurately determining flood risks around ICOLLs, authorities should adopt a conservative, risk averse approach to future floodplain management.

3. Incorporating sophisticated sediment transport algorithms in ICOLL flood studies is considered to be essential, as it provides a more realistic representation of the relevant processes that control flood behaviour. These studies should be carried out cautiously, however, as the additional modelling complexity requires additional data input that are unlikely to be available for historical events. Post flood data collection procedures should include the collection of entrance condition data for any future events.

4. Determining flood planning levels on the basis of artificial entrance management will require such actions to be undertaken for the entire lifetime of the future development if such development is to be afforded reasonable flood protection.
Flood risk planning should consider implications for artificial entrance management to be ceased, or at least reduced, in the future.

5. Determining flood planning levels should also give sufficient consideration to future climate change. In particular, future sea level conditions are likely to increase the vulnerability of low-lying foreshore lands to flooding, whether or not the entrance is open or closed. Mean sea level (and hence mean ICOLL water level) could be up to 0.9m higher by the end of this century. This increase in flood risk should be assessed explicitly, rather than be incorporated simplistically and implicitly within future freeboard provisions.

6. There may be a need to review and amend flood-related planning documents to incorporate provisions for minimum horizontal set-backs, in addition to meeting minimum floor level requirements, to help cater for future climate change impacts and entrance management provisions. This would be regardless of the hydraulic or hazard category for that area.

REFERENCES


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