Coastal Lagoon Entrance Management – What Can Models Tell Us?

D Wainwright[1,2], T Baldock[1], D Callaghan[1]
[1]University of Queensland, St Lucia, QLD
[2]BMT WBM, Newcastle, NSW

1. Abstract

In New South Wales, low lying flooding around the fringes of intermittently open coastal lagoons (ICOLL's) is commonly managed through artificial breaching. The plans which specify the water level at which manual breach operations occur are often governed by the degree to which the community will tolerate nuisance flooding. The actual mechanics of the manual breach operation (when, where, how) are typically informed by 'gut' feel, past experience and detailed field studies of selected lagoons, primarily undertaken in the 1970's and 1980's.

Numerical modelling presents an opportunity to gain insight into the impact of broad scale policy decisions on the one hand, and the manual breach methods on the other. Recent research has aimed to improve the ability of available models, and two different models arising from that research are discussed here.

Firstly, a method for long term statistical modelling of the "fill – spill – close" cycle is presented. A model built using that method has been repeatedly executed (5000 times) using random time series (110 years long) of waves and rainfall. Using this method, it was possible to simulate the impact that artificial opening practices and/or climate change will have on key parameters such as percentage time open, exceedance probabilities of berm heights and typical water levels.

Secondly, improvements to the representation of complex breach hydraulics by numerical models are discussed and presented. Using an improved model, the impact of field operations on the effectiveness of proposed breach operations was investigated. Questions which the model can inform include: How does the location of a 'pilot' channel for breaching affect the speed with which a lagoon drains? Or, how does the 'trigger' level affect the final size of the breach?

The models are demonstrated using real world data from Tabourie Lake.

2. Site Description

Tabourie Lake is located around 190 km south of Sydney, on the New South Wales coast. The plan form, bathymetry and scale of Tabourie Lake are shown on Figure 1. The Lake has a 43 km^2 catchment area, draining to a waterway of 1.4 km^2 (NSW Department of Natural Resources, n.d.). The broader expanse of the Lake is connected to the Tasman Sea at its southern end by Tabourie Creek, which is around 2 km long. At the ocean entrance, a tombolo frequently links nearby Crampton Island to the mainland, which complicates the wave run-up processes at this site compared to more exposed systems. Tabourie Creek typically breaches to the north of the tombolo, across Tabourie Beach.

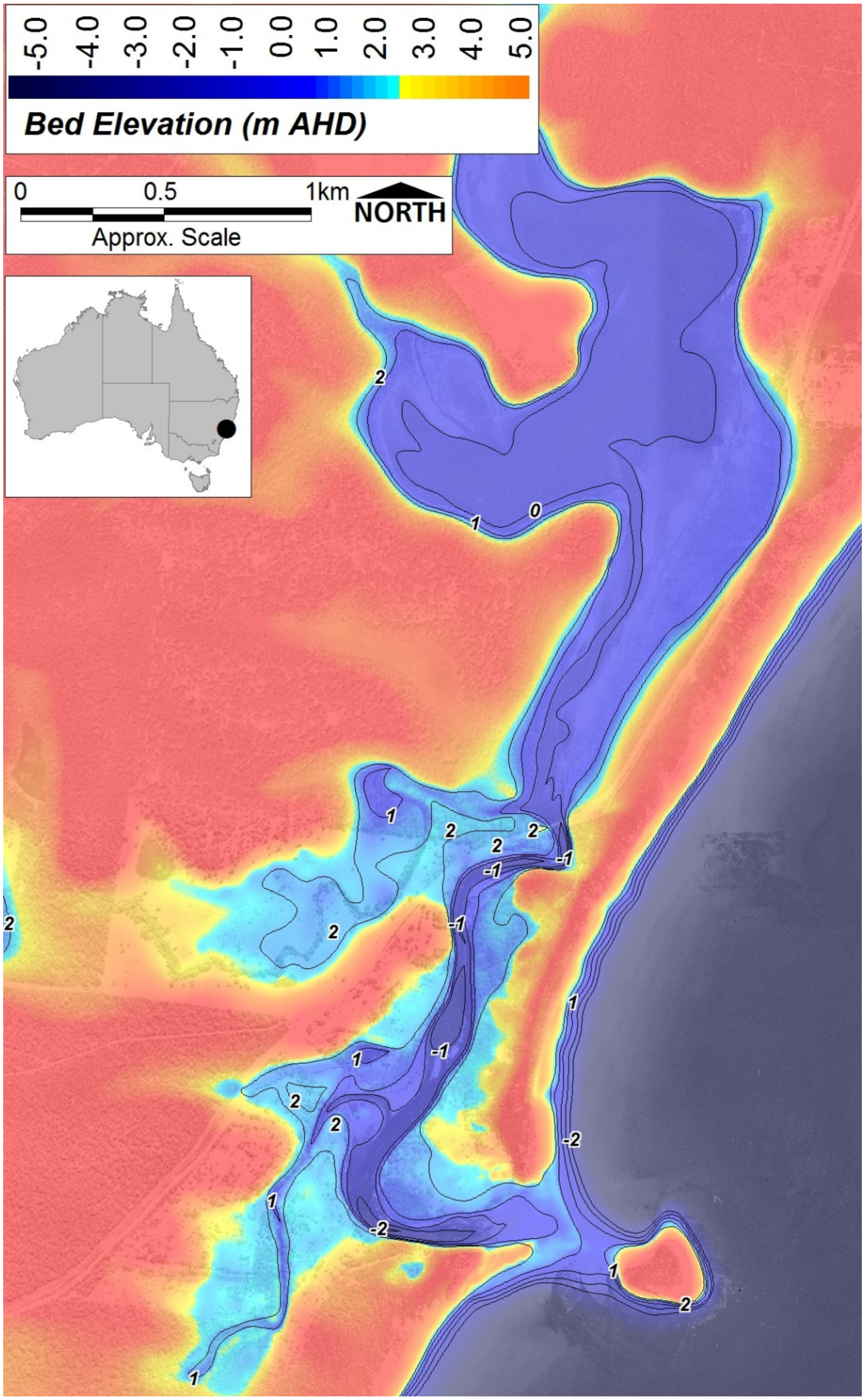

Figure 1 Plan of Tabourie Lake. breaching normally occurs across Tabourie Beach to the north of Crampton Island. The barrier here is protected from the dominant south – east swell wave climate

3. Berm Height Statistical Model

3.1. Description

The complex processes that affect the lagoon water levels, the barrier height and the breaching have been simplified into four discrete physical components: the catchment; the waterway (lagoon); the barrier; and the ocean. Figure 2 shows a conceptual model of the system. The processes within the different components have been formulated and applied using a simplified time stepping model which takes into account rainfall, the movement and storage of water, and the actions of waves and tides in the barrier growth processes, all on an hourly basis.

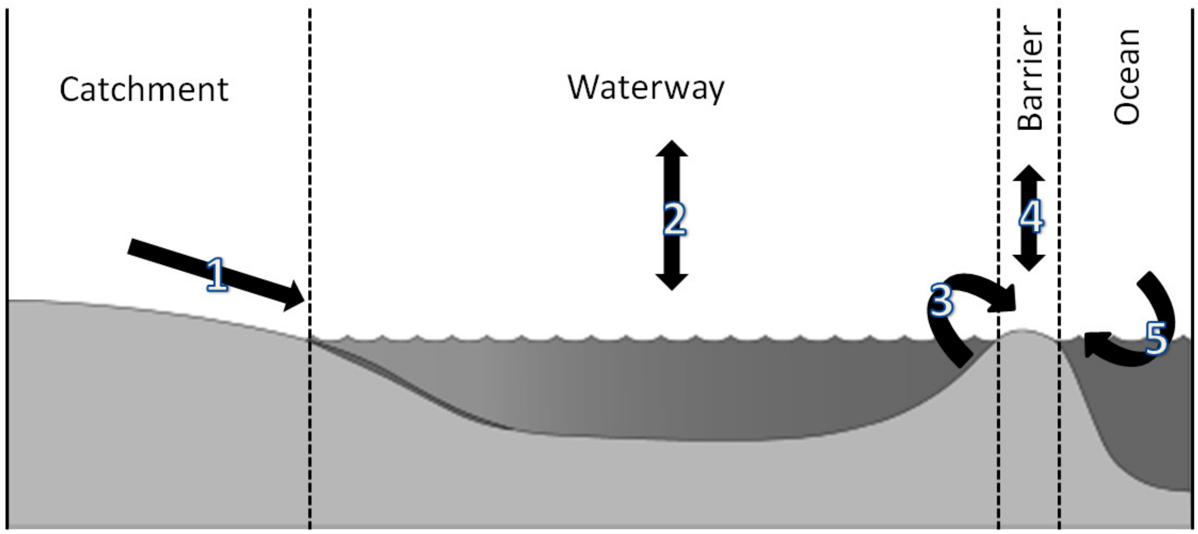

Figure 2 Schematic Arrangement of Model. System is divided into 4 elements, and there are 5 main processes (1) Catchment rainfall and runoff, (2) Water level in main waterway responds to catchment rainfall, breaching and evaporation, (3) Breaching occurs when the water level rises high enough to overtop the barrier (4) Barrier elevation is built by constructive ocean waves, but elevation is reset to low level when it overtops, remaining "open" for a statistically sampled amount of time (5) Ocean waves act to build the barrier.

Underlying image courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).

The main inputs to the model are rainfall, bathymetry, waves and tides. Synthetic time series of waves and rainfall were calculated from statistical analyses of existing data. These time series can be modified to incorporate the effects of climate change or anthropogenic activities over time, with the assumption that appropriate models exist (i.e. rate of SLR, changes in catchment rainfall, changes in land use and run-off).

Management practices can also be incorporated, such as artificial breaching occurring at a "trigger" lagoon water level. Tide levels were based on the generation of a standard year of tidal water levels, using tidal harmonic constituents derived from long term records, and are easily adjusted to account for sea level rise over time. The tide level is further adjusted using a randomly generated value to account for tidal anomalies, caused by storm surges, coastal trapped waves and other processes. Lagoon water levels and barrier levels are adjusted on the basis of the time series of information calculated for the preceding 24 hours. These processes will vary for different lagoon systems, but the model process is generic to all systems.

3.2. Model Execution

Model execution proceeds as illustrated in Figure 3. A set of output values is calculated for each hour of each simulation. These were sampled at daily intervals in deriving the statistical analyses provided below. Two 10,000 year simulations were executed to examine the impact of artificial opening on berm elevations. Both included a stationary mean sea level with one allowing for natural breaching while a comparable simulation adopted breaching at 1.17 m AHD, the present management level for Tabourie Lake.

Sea Level Rise impact simulations were also executed. The simulations extended from 1990 to 2100, and included a non-stationary mean sea level, approximating New South Wales's present planning benchmark for sea level rise at 2100 (+0.90 m), with a linear increase over the 110 year simulation. In order to obtain robust estimates of barrier height exceedance characteristics, the simulation was repeated 5000 times, although post processing indicated that stable estimates of the 99% exceedance levels could be achieved with around 2500 simulations.

3.3. Impact of Artificial Opening

Exceedance results for the two 10,000 year simulations are presented in Figure 4. The simulation with artificial opening at a trigger level of 1.17 m AHD indicated berm height elevations above the 0.5 exceedance level to be around 0.1 lower than they would otherwise be if the barrier were allowed to breach naturally.

Of interest are the median berm elevations for both simulations. Results for the artificially opened strategy simulation indicate an 0.5 exceedance level elevation of around 2.12 m AHD, comparing favourably to elevations surveyed in January and February of 2008 at Tabourie Lake, between which the barrier rose from 1.8 to 2.0 m AHD. More broadly, Hanslow et al. (2000) provided data indicating that the "saddle" elevation for lagoon barriers facing from south east to east in New South Wales would typically have elevations between 1.8 and 2.2 m AHD. Such barrier alignments are common for lagoons at the southern end of their coastal compartments in southern New South Wales, similar to Tabourie Lake. In comparison, the natural opening simulation indicated a median exceedance elevation of around 2.23 m AHD.

The percentage open statistics were also extracted from the model results. During the natural opening simulation, the Lake was closed 89.4% of the time. Comparatively, the artificial simulation indicated a closed condition 75.8% of the time. The available water level data indicates that Tabourie Lake was closed 65.9% of the time between 1992 and 2008. Regardless, the target management level has not been set rigidly over this entire period, and there are documented cases of 'illegal' opening at water surface elevations below 1.17 m AHD.

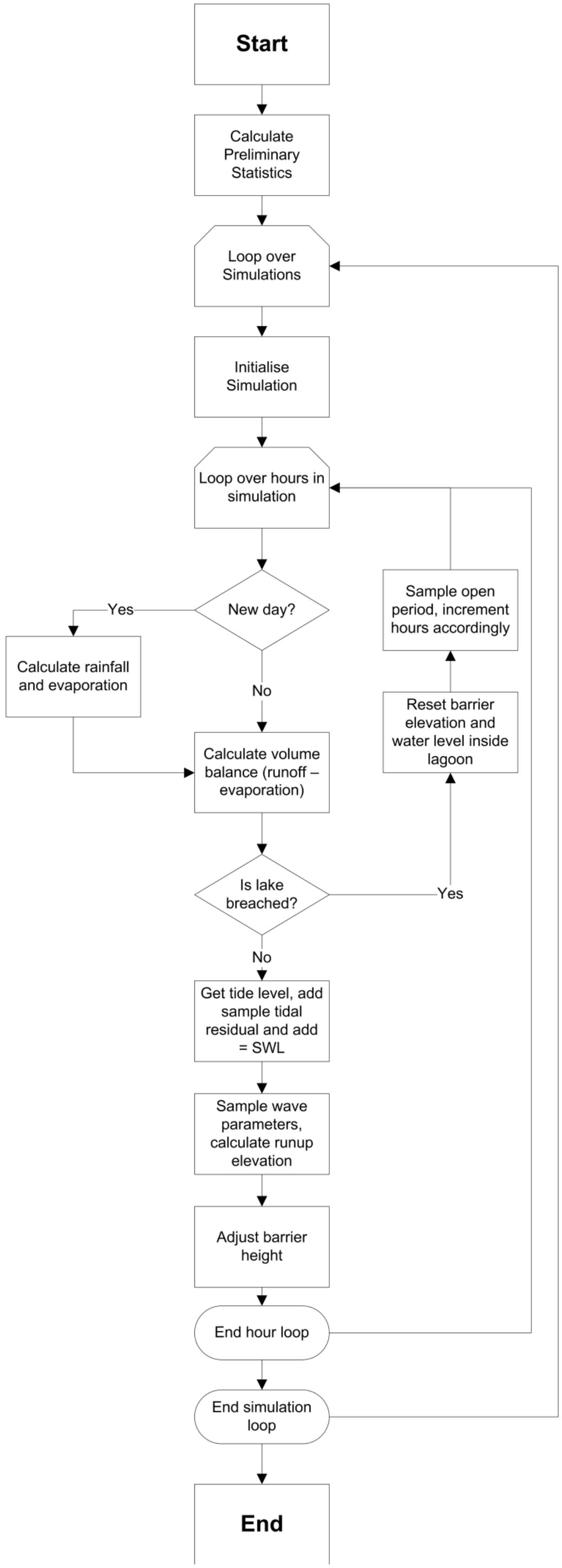

Figure 3 Model Logic Flow Chart

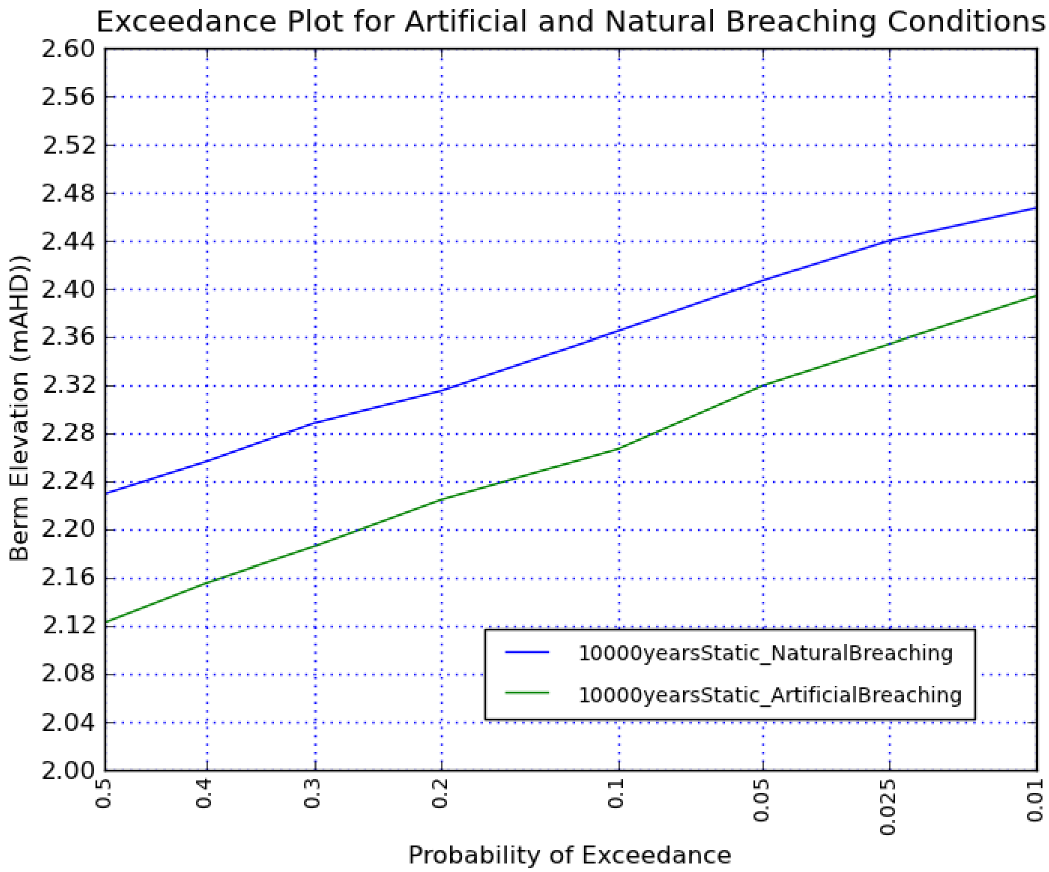

Figure 4 Comparison of Exceedance Levels for Artificial and Natural Breaching Management Strategies

Overall, considering limitations relating to the uncertainties in the representativeness of the data, and the physical representation of the berm building process, the results indicate that the model reasonably replicates existing conditions and is a useful tool for predicting future behaviour of this system.

3.2. Behaviour Under a Climate Change Scenario

For each of the 5000 simulations including SLR, a yearly record of daily barrier elevation values was extracted at 10 yearly intervals (i.e. for years 2000, 2010, 2020 etc.), resulting in ~1.83E6 individual realisations for each year considered. Periods where the model indicated an open lagoon were removed. Under the influence of 0.90 m SLR, the percentage of time closed showed an increasing trend over time, being approximately 89% after 10 years and 93% after 100 years. This corresponds to an increase in the volume of water required to raise the Lake level as water levels increase generally.

Exceedance estimates for the barrier or barrier elevation were determined empirically from the ensemble of values (excluding 'open' periods) thus acquired. The resulting variation in exceedance levels over the course of time, under the influence of sea level rise is shown on Figure 5. Unsurprisingly, exceedance elevations tend to follow a linear trend commensurate with the assumed rate of sea level rise. This indicates that the Lake's stage-volume relationship, at this site, does not lead to a non-linear relationship between barrier exceedance elevations and SLR. If the stage-volume relationship were significantly non-linear above present day water levels, as would be the case if fringing floodplain areas newly inundated by SLR were dramatically larger than the existing water body's surface area, the typical barrier elevations reached before breaching would rise at a faster rate than sea level. The future behaviour of individual systems will depend largely on the characteristics of the present day floodplain and other low lying areas surrounding the estuary being considered.

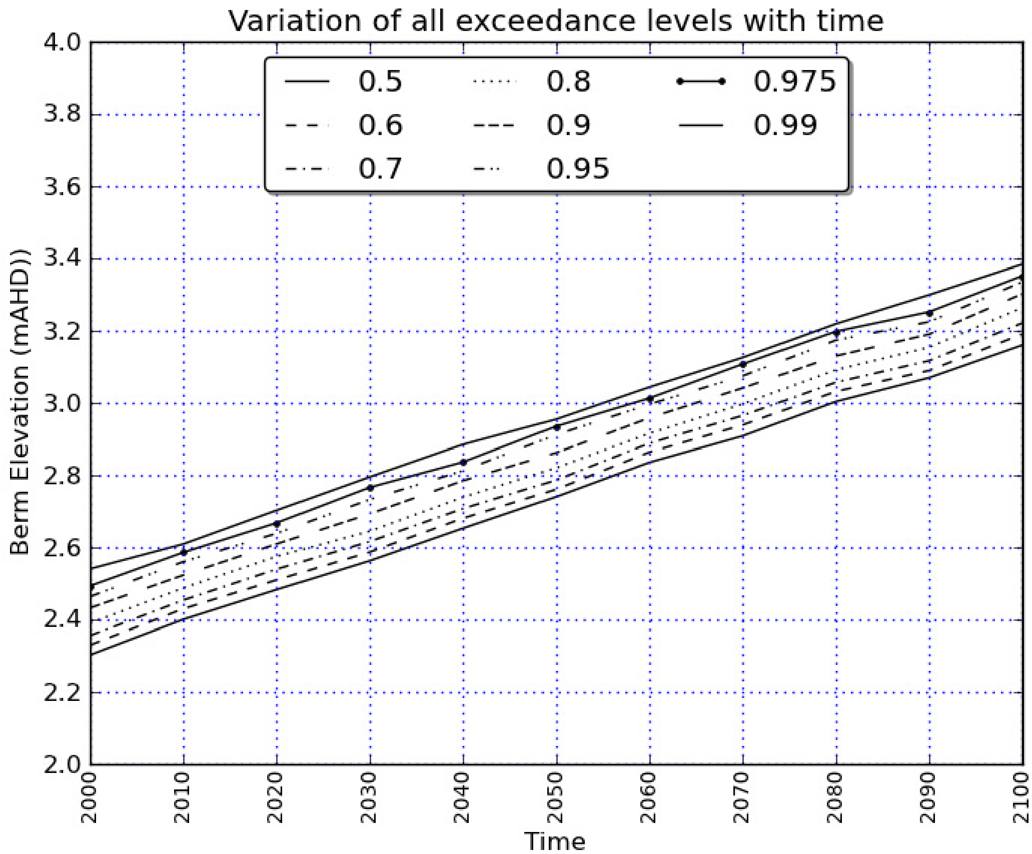

Figure 5 Predicted Variation of Exceedance Elevations with Time

4. Lagoon Breach Modelling

4.1. Description and Validation

A morphological module was developed for the TUFLOW flood modelling software package from BMT WBM. An early version of this module has been previously presented (Wainwright et al., 2004) and substantial improvements, restructuring and testing of the model code were undertaken in subsequent years. In the context of lagoon breaching, the shortcomings of this, and most other available codes were described in Wainwright et al. (2011). While numerous coastal lagoon studies have utilised a dynamic morphological model in New South Wales during the past decade, key deficiencies include:

- A lack of available data against which to validate the models;

- Uncertainties relating to sediment transport rates in the transcritical flow regime present during breaching; and
- Non-physical representation of the discrete side wall collapse process.

‘Calibration’ of the models typically involves scaling of the sediment transport flux rates. In addition, to achieve a realistic rate of widening, an avalanching process has been commonly adopted (HR Wallingford, 1994, Odd et al., 1995, Wainwright et al., 2004, Wainwright et al., 2011). The nature of the avalanching process is illustrated in Figure 7, showing the transfer of sand between adjacent cells (or ‘elements’, or ‘control volumes’) to correct an oversteepened condition. In other words, the model has to erode downwards to effect widening. However, the process is actually governed by the direct erosion of immediately adjacent to a near vertical sand face (Figure 6), and the rate of that lateral erosion exerts significant control over the rate of channel widening.

Figure 6 Tabourie Lake 13/02/2008, Breach side walls collapse in shallow slipping failures. The process is small compared to typical cell, element or grid sizes used in numerical modelling and is a challenge to represent reasonably.

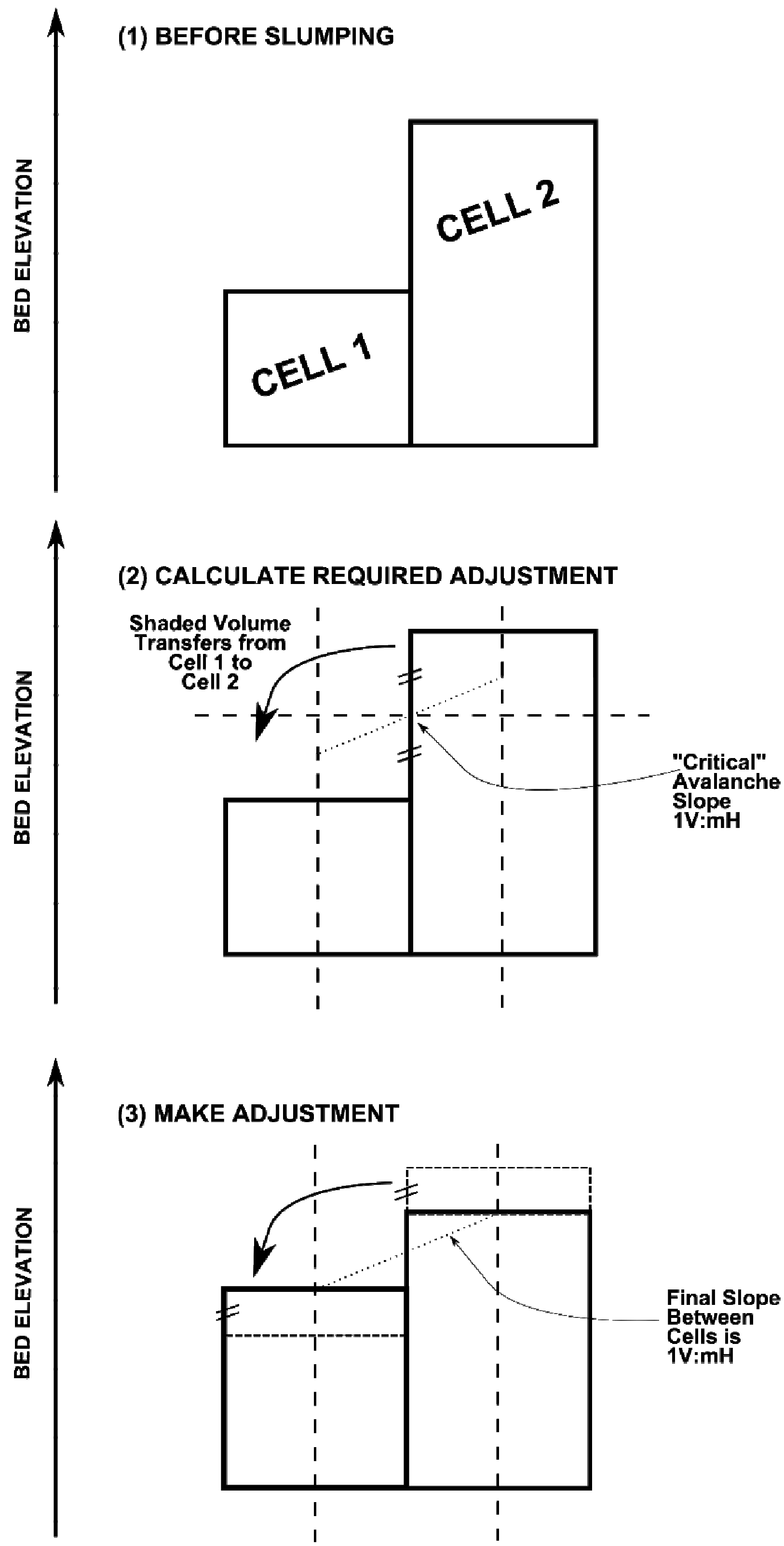

Figure 7 'Avalanching' Breach Widening Algorithm

To partly address the lack of available field data, a comprehensive set of field data was captured during an artificial breach at Tabourie Lake in February, 2008. This was combined with another reasonably comprehensive data set from Wamberal Lagoon (NSW Public Works Department, 1993) to test of various strategies for handling the breach widening process (not reported here).

To address the issue surrounding sediment transport rates along the bed, it was found that applying a model which dynamically varied the roughness provided for a much better representation of both flow velocities and discharge rates. For the intense, mobile bed flow rates present during the breach process, a body of evidence has developed in recent decades which indicates that flow resistance reduces dramatically (Verbanck, 2008, Ackers, 1988, Huybrechts et al., 2011b, Nanson and Huang, 2008). These correspond to the findings of Gordon (1981), which imply a Froude Number of 1.0 (i.e. minimisation of specific energy) during the majority of the breach process. By applying the Vortex drag roughness model presented in Huybrechts et al. (2011a), it was found that scaling of the sediment transport rate was no longer required, except for very shallow flows (i.e. < ~ 5 cm). Sediment transport rates were calculated using the methods of van Rijn (1989).

To represent the breach collapse method, a sub-grid scale model which tracks the location of the laterally eroding face was introduced (Figure 8). The erosion rate was determined using a standard excess shear formulation, adjusted for variations in shear stress against channel walls (when compared to the bed).

$$E = k_d b(c\tau - d\tau_c)^a$$

Where:

$E = \text{erosion rate}\left(\frac{m^3}{m^2 s}\right)$

k_d

$= \text{erodibility coefficient (Section Error! Reference source not found. discusses the dimensionality of this parame}$

a and b = dimensionless parameters 1.0 and 1.5 adopted respectively

c = correction for bed shear stress at sides of channel (0.75 adopted)

d = correction for reduction in near bank critical stress, a "Schoklitsch" type factor (1.0 used)

Introduction of this model caused qualitative behaviour which was more in line with field observations. The main parameter which could be legitimately varied for calibration was the erodibility coefficient. Testing against the Lake Tabourie data set to determine a valid range for this parameter was undertaken and the results are shown in Figures 9 through 12. In these figures, the ‘Base’ scenario corresponds to an erodibility coefficient of 1.0E-4.

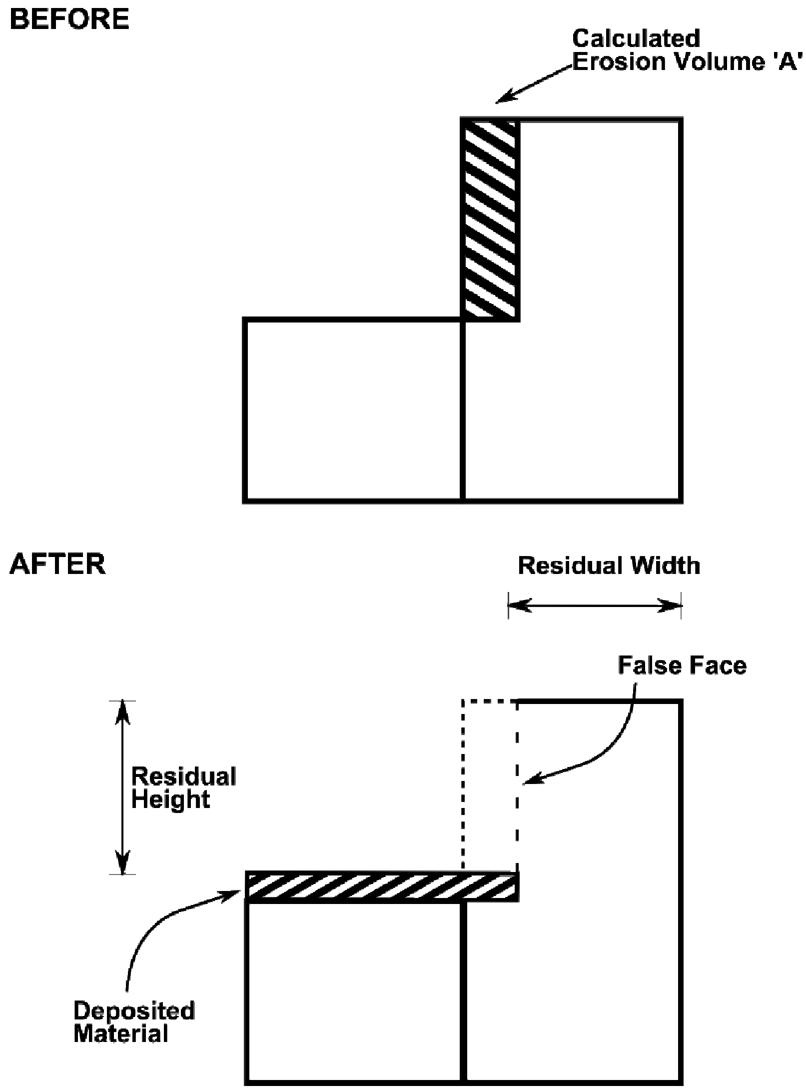

Figure 8 Sub Grid Scale Model Breach Widening Formulation

In determining a preferred value for that parameter, performance against a number of field measurements was considered. The two best result for predicting areal growth during the initial stages and not excessively over predicting the final area seems to occur somewhere around k_d = 5E-5 and 2.5E-5. Further, there was some uncertainty with the representative eroded depth data values, particularly as the breach event proceeds, due to difficulties in capturing depths in the fast flowing water. The Lake water level responds too slowly in the initial stages, although all four simulations trend towards the measured water level between 6 – 7 hours post breaching. The best results were obtained for larger k_d values. On balance, a k_d value of k_d = 5E-5 was adopted for scenario testing.

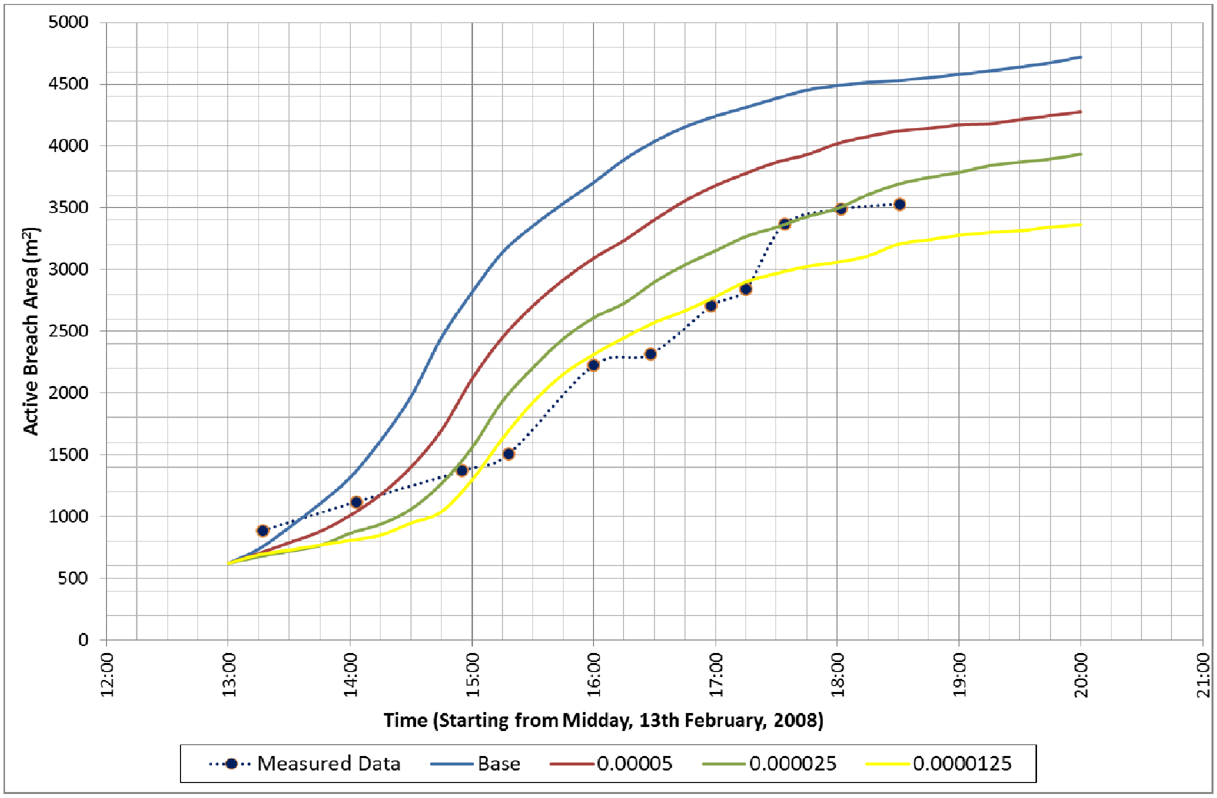

Figure 9 Tabourie Calibration: Breach Area

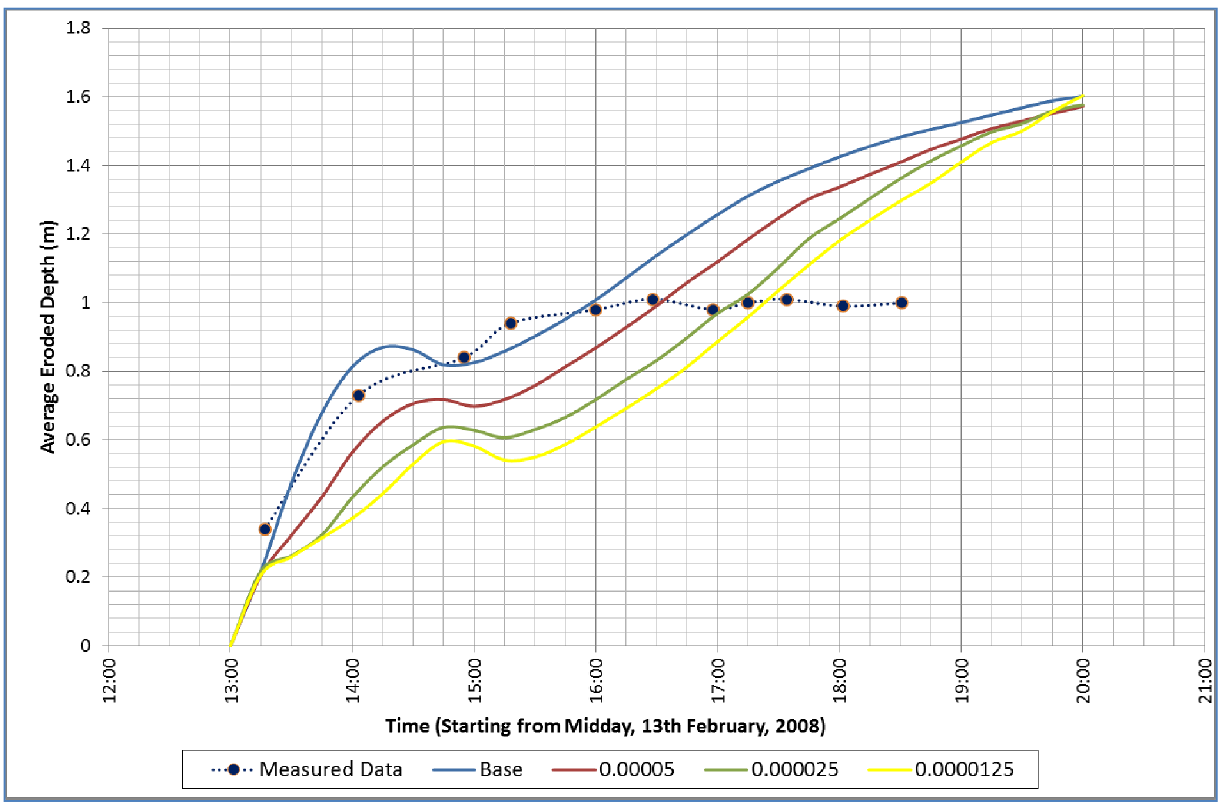

Figure 10 Tabourie Calibration: Active Eroded Depth

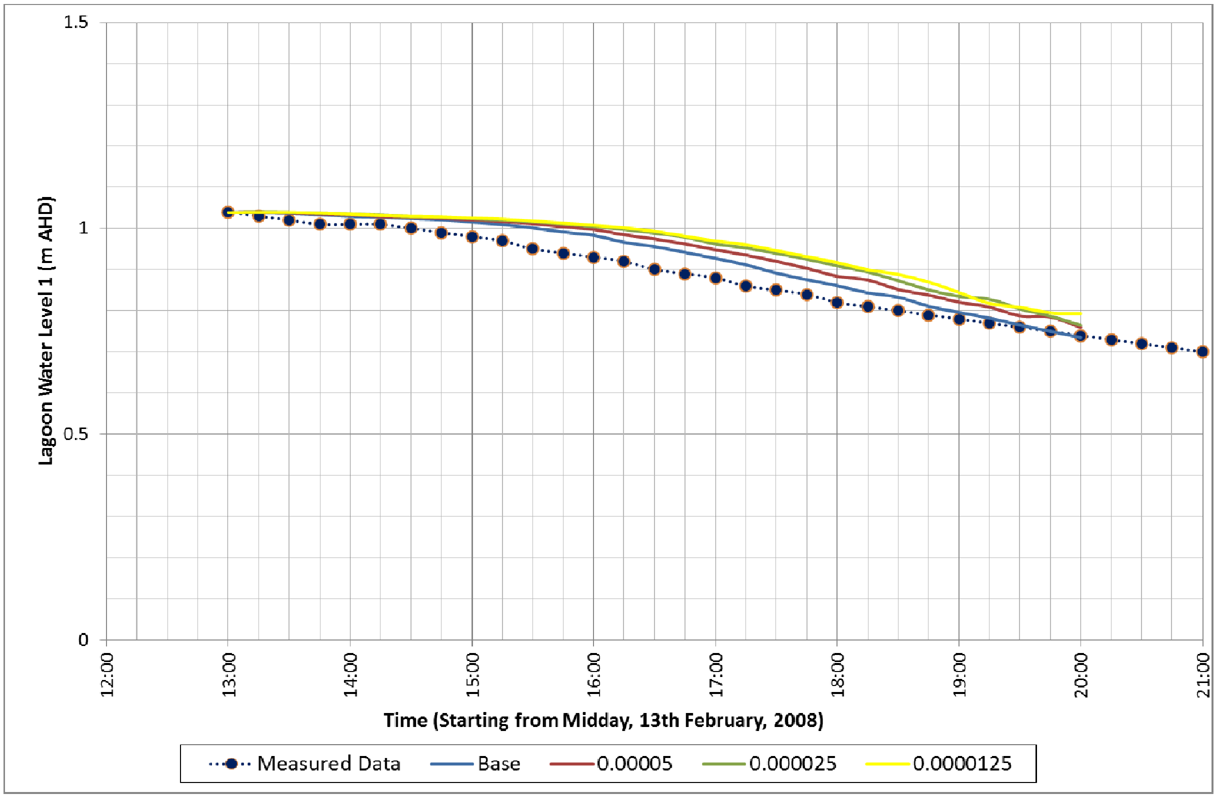

Figure 11 Tabourie Calibration: Lake Water Level

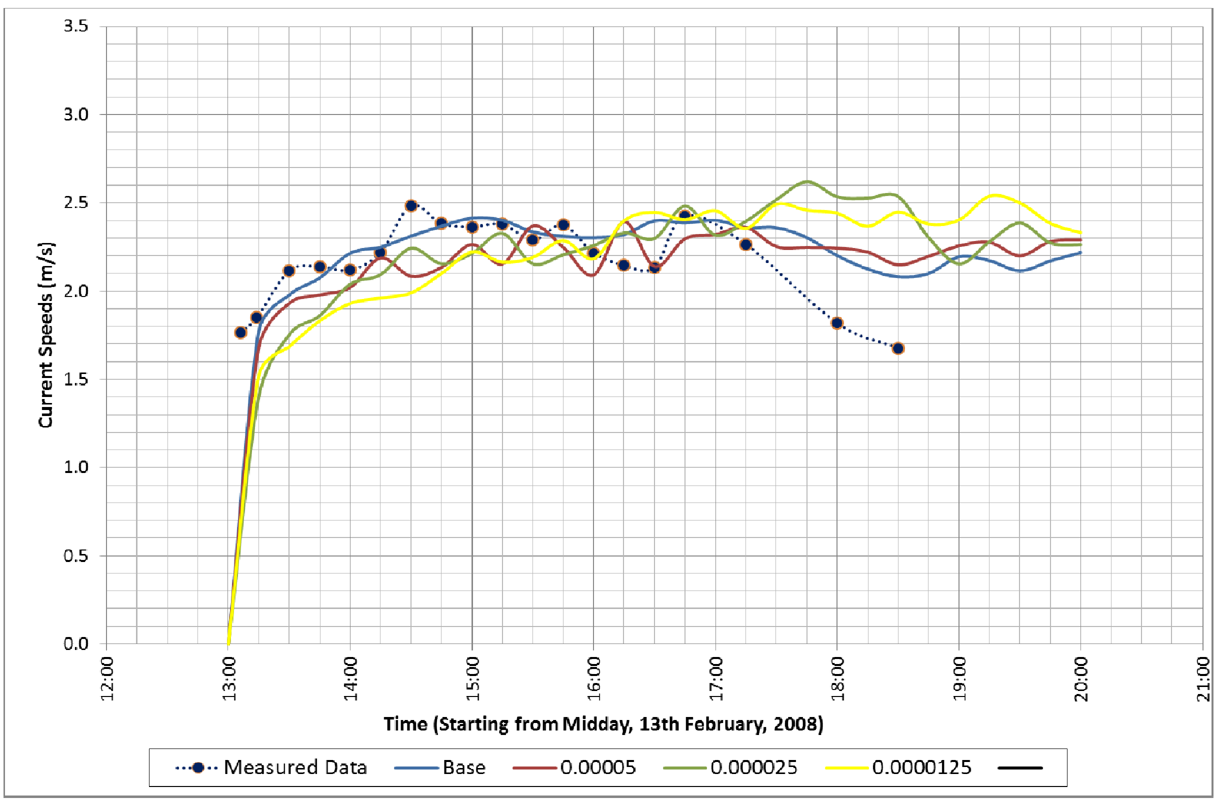

Figure 12 Tabourie Calibration: Breach Flow Speed

4.2. Impact of a Higher Manual Breach Level

During the field data collection exercise, the lagoon was breached at around 1.04 m AHD. The 'Trigger Level' for initiating breaching operations is presently 1.17 m AHD (Peter Spurway and Associates Pty. Ltd., 2005). The sensitivity of the system to the initial water level has been assessed by replicating conditions during the field exercise, but adopting a water level inside the lagoon at the time of breaching of 1.17 m AHD.

The end result is an approximate 10% increase in the simulated volume of erosion when compared to the base scenario. This corresponds to an increase in area (5710 cf. 5640 m^2) and an increase in 'average' eroded depth (1.85 m c.f. 1.73 m. The variation of simulated erosion over time is shown on Figure 13. Figure 14 shows that the water level falls from 1.17 to 0.22 m AHD (cf. 1.04 to 0.30 m AHD). This corresponds to a total cumulative discharge of 3.9 GL, (compared to 3.0 GL). Perhaps most marked is the impact on discharges during the initial stages of the breach, which can be up to twice as large as for the base scenario (Figure 15). This is significant when considering the ability of the breach to mobilise organic deposits from within the main channel of the Lake.

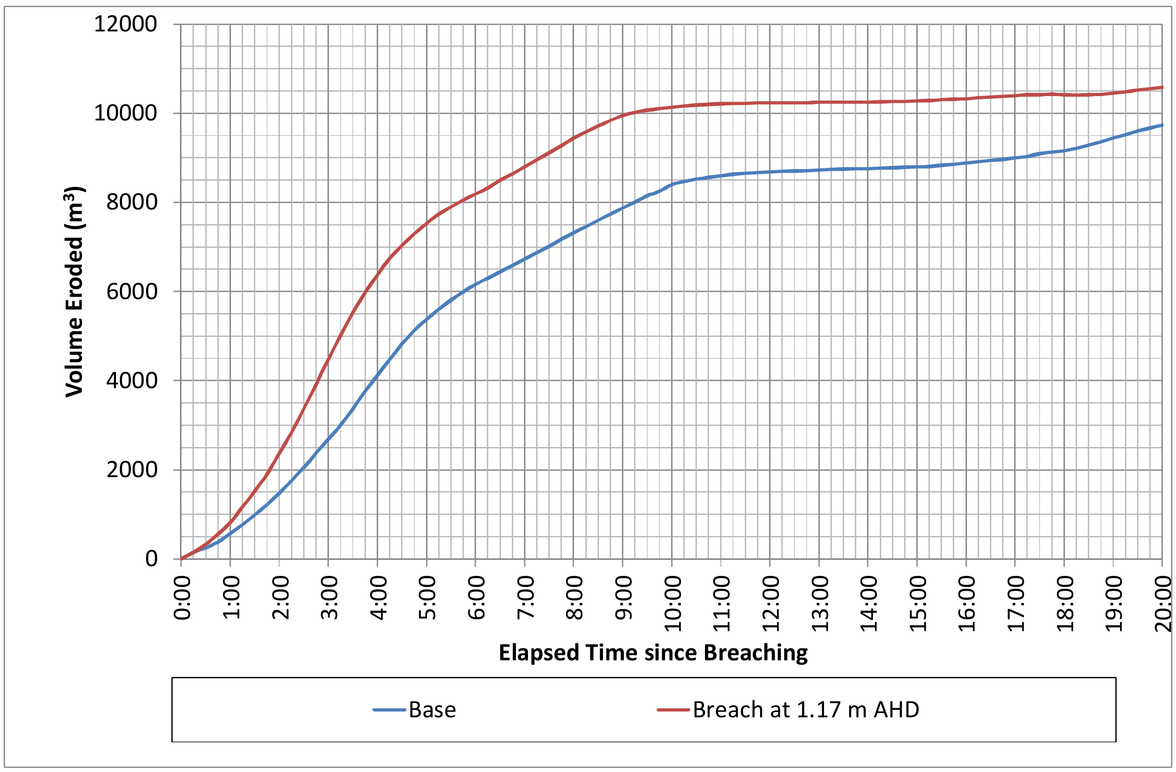

Figure 13 Volume of Sand Scoured: Impact of Higher Breach Level

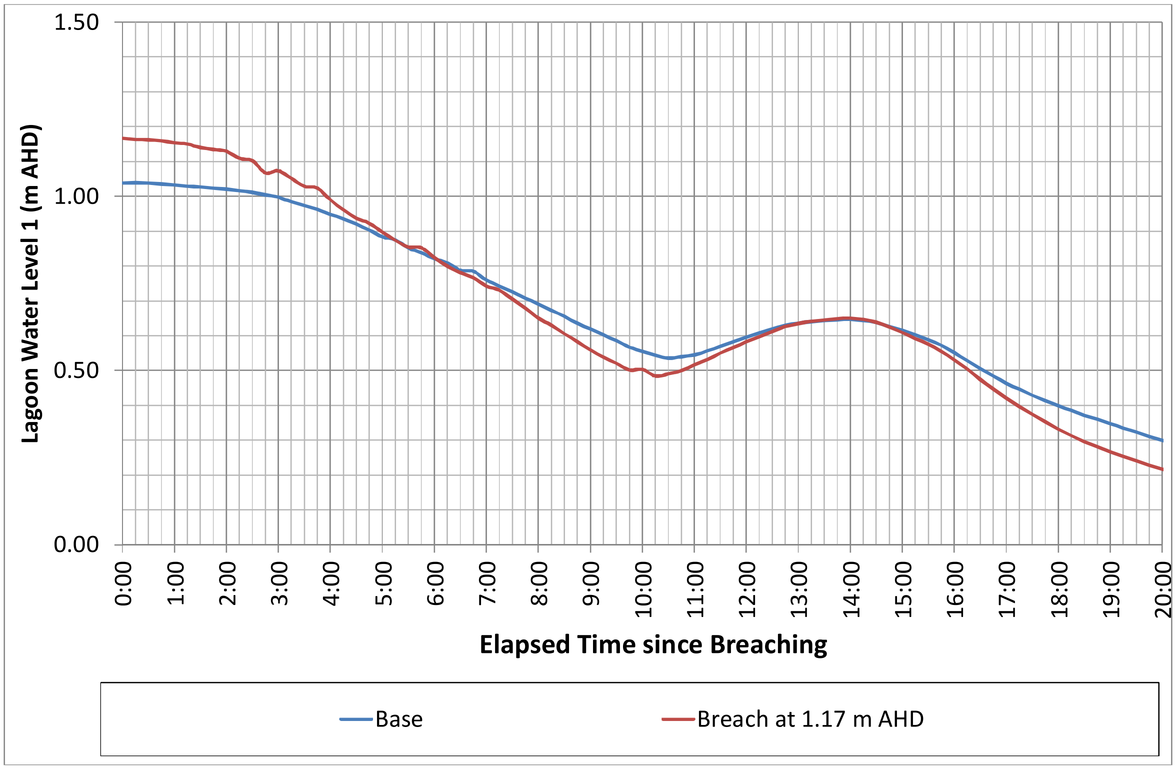

Figure 14 Rate of Water Level Fall: Impact of Higher Breach Level

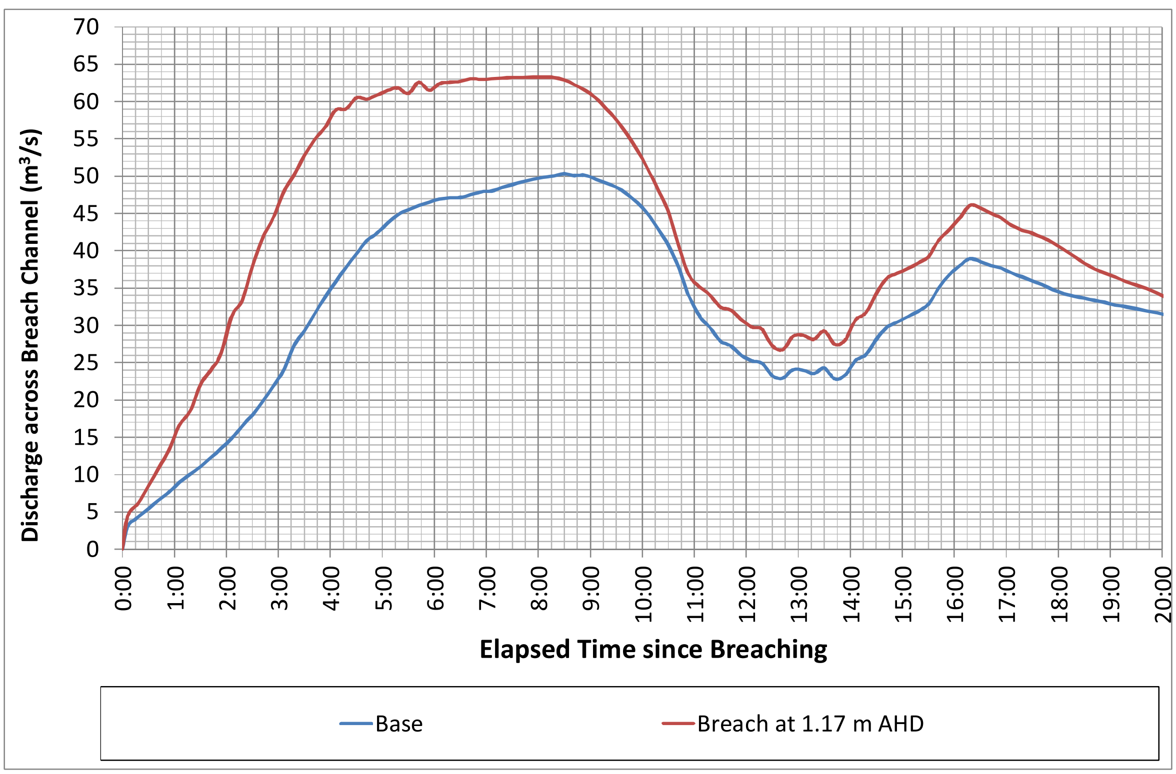

Figure 15 Breach Discharge: Impact of Higher Breach Level

4.3 Testing the Timing of Breach Operations.

Discussions with numerous individuals from Councils, State Government and engineering consultancies during the course of this study have highlighted a common perception that artificial breaching should be undertaken around or shortly after high tide, as documented by Gordon (1990).

However, this perception appears to relate to numerous field investigations on two systems (Dee Why Lagoon and Narrabeen Lagoon) in the 1970's and 1980's (Gordon, 1990, Kulmar et al., 1989). All systems behave differently and it is reasonable to examine the impact of breaching at a different stage of the tide at Tabourie Lake.

For this assessment, the sensitivity of the system to differences in the tide has been tested by representing a model breach at mid tide. For conditions present during the measured breach of February 13th 2008, the high water slack in the ocean occurred between 12:30 and 1:00 AEST (+0.36 m AHD). The breach occurred at 12:00 AEST. The subsequent low water slack occurred between 18:30 and 19:00 AEST (-0.49 m AHD). Accordingly, a mid-tide was assessed as occurring at 15:45, when the tide record indicated an ocean water level of -0.09 m AHD. The starting water level in the lake was set at 1.17 m AHD.

By moving the breach initiation to the mid tide time, this simulation ensures that the period of main breach channel opening (lasting around 5.5 hours) straddles the low tide, theoretically increasing the average difference in water levels between the lake and the ocean and hence the hydraulic slope and sediment transport.

The end result is slightly higher discharge rates during the first 6-7 hours of the breach, but minimal long term increase in the size of the breach. The variation of simulated erosion over time is shown on Figure 16. Figure 17 shows that the water level falls at a similar rate to a comparable simulation (breached around high tide) during the first four hours, although beyond this, the tide begins to affect the water level and it is difficult to perceive an ongoing pattern given these relatively short simulations. A similar moderating effect is seen in the discharge time series' shown on Figure 18.

Overall, the end difference between the two simulations, considering discharge, scour volume and the fall of water levels appears to be marginal for Tabourie Lake.

4.3 Testing the Impact of Pilot Channel Alignment

During the field data collection exercise, and subsequent analysis of the data, it was noted that the breach channel displayed a counter clockwise rotation, which brought it more in line with the approach flow from upstream, this tended to follow the greatest depth in the entrance, adjacent to the southern side of the entrance compartment.

The simulation presented here aims to examine how much impact cutting a pilot channel that is more sympathetic to the incoming flow direction might have on the effectiveness of the breach. In other words, the pilot channel of the base scenario has been rotated to match the alignment of the incoming flows.

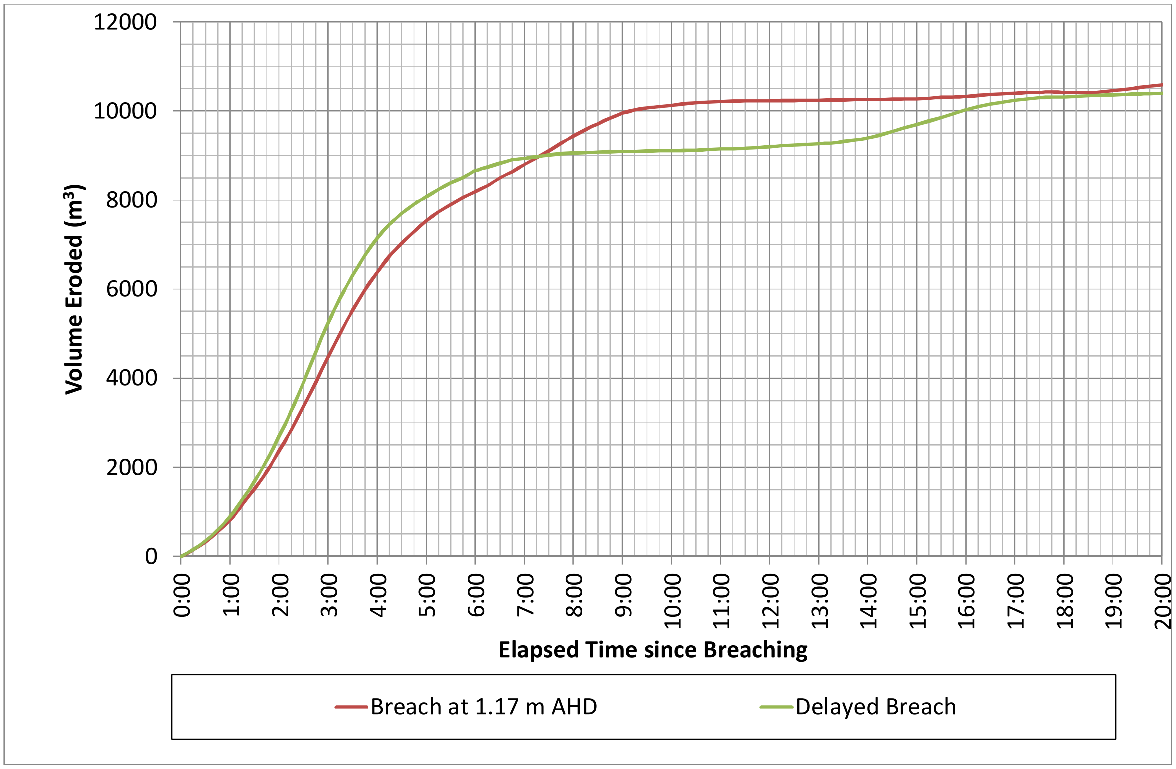

Figure 16 Volume of Sand Scoured: Impact of Breach Timing

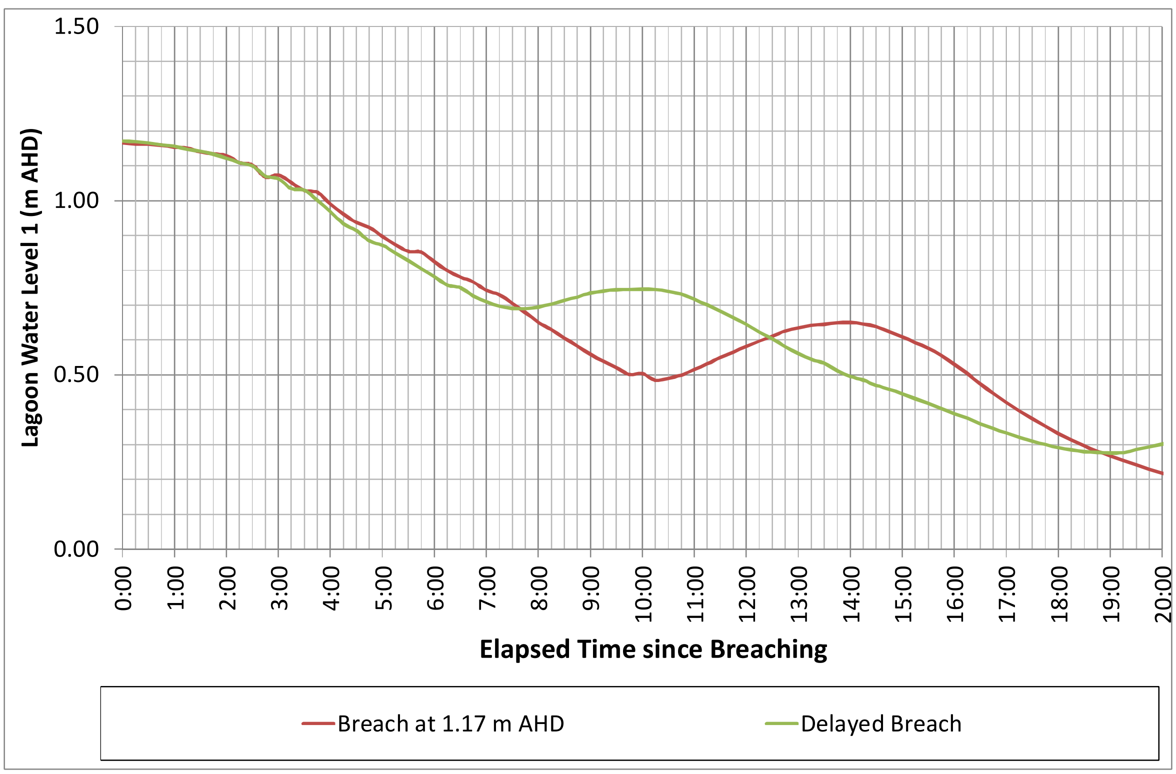

Figure 17 Rate of Water Level Fall: Impact of Breach Timing

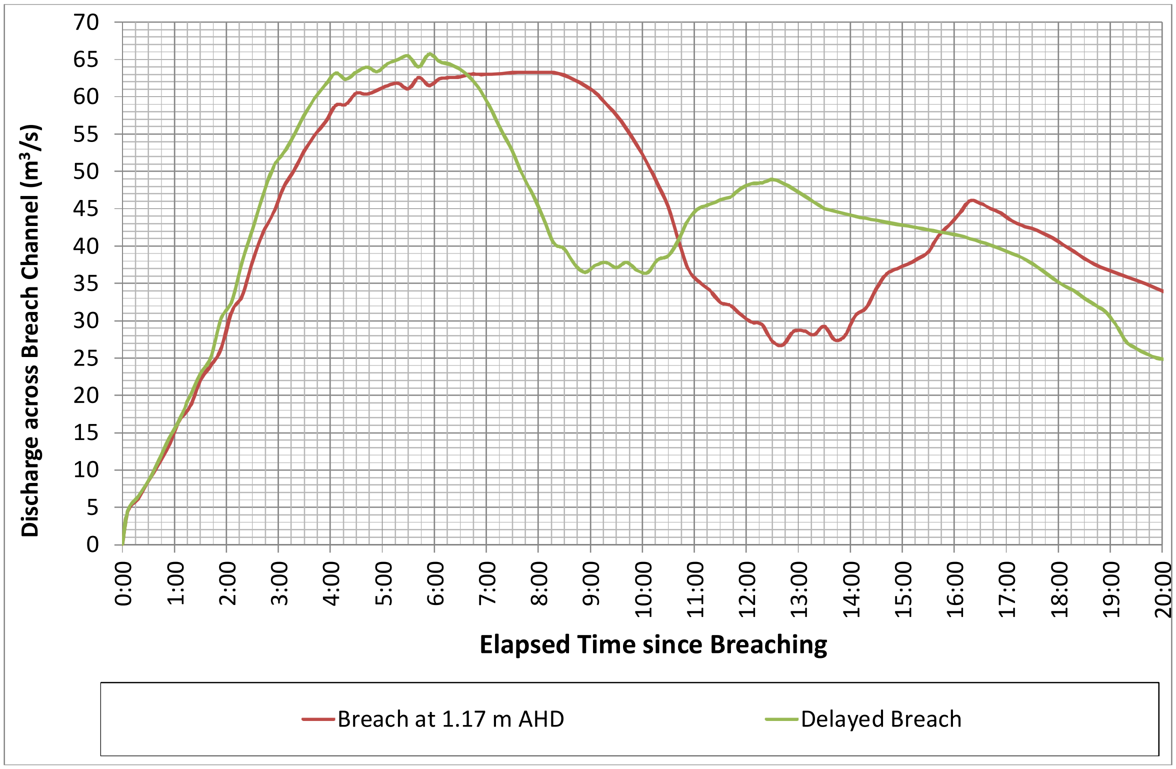

Figure 18 Breach Discharge: Impact of Breach Timing

The results indicate minimal influence arising from rotation of the channel. Surprisingly, the rotation actually causes a reduction in the erosion, water level fall and discharge rates during the initial stages of the breach. This may be due to alignment causing less erosion and widening at the upper end of the breach channel where an obliquely approaching current may actually impinge more notably on the side walls of the channel. Alternatively, the modification to bed elevation shown was fairly imprecise, resulting in the otherwise marginal changes simulated.

Figure19 shows the impact on erosion volume to ultimately be minimal. Similarly, only marginal differences between the fall in water level and discharge rates over time were simulated. Based on these results, it may be concluded that expending significant effort to align the pilot channel to the breach direction will likely not improve the strength of the breach.

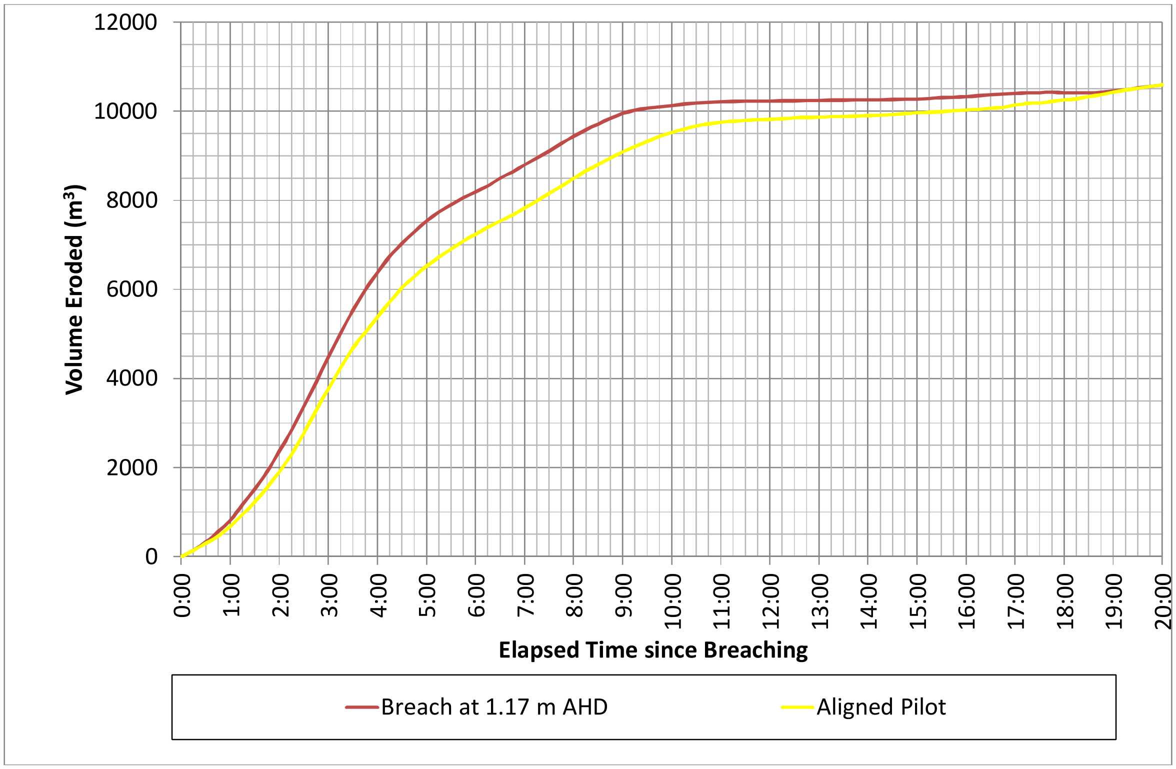

Figure 19 Volume of Sand Scoured: Impact of Channel Alignment

5. Conclusions

Process based models of coastal lagoon barrier behaviour have been developed and improved to inform coastal lagoon entrance management.

Key conclusions from the stochastic barrier model include:

- Barrier height is expected to rise at a similar rate to mean sea level with ongoing climate change. Small local deviations from these patterns could be expected to result from the stage-volume characteristics of individual lagoons;
- Not unexpectedly, the practice of artificial breaching causes barrier heights to be lower. At Lake Tabourie, artificial breaching typically causes barrier heights (at the 'saddle' point) to be around 0.1 m lower than they would be for a natural breaching regime;
- Under the influence of sea level rise, the model indicates that the proportion of time the Lake is closed will increase. For a management strategy of natural breaching this increase is from 89% to 93% at Lake Tabourie.

The main conclusion from morphological breach modelling is that the key determinant of artificial breach "effectiveness", where this quantity may be measured by the volumes of sand scoured and water drained from the lagoon, is the height at which the lagoon is artificially breached. Other strategies such as varying the tidal stage at which the lagoon is breached or being more careful in locating the pilot channel seem unlikely to have a significant impact.

Acknowledgements
Support was provided by Shoalhaven City Council and the Office of Environment and Heritage in New South Wales (OEH), and BMT WBM. The measured wave and tide data used were sourced from the Manly Hydraulics Laboratory, which acts as custodian of this information for OEH.

ACKERS, P. Discussion of Frictional Characteristics of Alluvial Streams in the Lower and Upper Regimes by White, WR, Bettess, R. & Shiqiang, W., 1988. Ice Virtual Library, 685-700.

GORDON, A. The Behaviour of Lagoon Inlets. Fifth Australian Conference on Coastal and Ocean Engineering, 25-27 November 1981 Perth. 54-58.

GORDON, A. Coastal Lagoon Entrance Dynamics. Coastal Engineering - 1990, 1990. 2880-2893.

HANSLOW, D. J., DAVIS, G. A., YOU, B. Z. & ZASTAWNY, J. Berm Height at Coastal Lagoon Entrances in NSW. 10th NSW Coastal Conference, 2000.

HR WALLINGFORD 1994. Wamberal Lagoon Breakout Investigation: Telemac Application. Wallingford: HR Wallingford Ltd.

HUYBRECHTS, N., LUONG, G., ZHANG, Y., VILLARET, C. & VERBANCK, M. 2011a. Dynamic Routing of Flow Resistance and Alluvial Bed Form Changes from the Lower to the Upper Regime. *Journal of Hydraulic Engineering,* 1, 243.

HUYBRECHTS, N., VU LUONG, G., ZHANG, Y. & VERBANCK, M. A. 2011b. Observations of canonical flow resistance in fast-flowing sand bed rivers. *Journal of Hydraulic Research,* 49, 611-616.

KULMAR, M. A., HURST, A. M. & GORDON, A. D. 1989. Narrabeen Lagoon Entrance Study. Sydney: Manly Hydraulics Laboratory.

NANSON, G. C. & HUANG, H. Q. 2008. Least action principle, equilibrium states, iterative adjustment and the stability of alluvial channels. *Earth Surface Processes and Landforms,* 33, 923-942.

NSW DEPARTMENT OF NATURAL RESOURCES. n.d. *Estuaries - Wamberal Lagoon : NSW Government Natural Resources* [Online]. Sydney. Available: http://www.dnr.nsw.gov.au/estuaries/inventory/wamberal.shtml [Accessed 12/08/2010 2010].

NSW PUBLIC WORKS DEPARTMENT 1993. Wamberal Lagoon and Avoca Lagoon Entrance Breakout Data Collection.

ODD, N. V. M., ROBERTS, W. & MADDOCKS, J. Simulation of Lagoon Breakout. 26th Congress of the International Association for Hydraulic Research, 1995. 92-97.

PETER SPURWAY AND ASSOCIATES PTY. LTD. 2005. Tabourie Lake Entrance Management Policy and Review of Environmental Factors.

VAN RIJN, L. C. 1989. *Handbook sediment transport by currents and waves,* Delft, The Netherlands, Delft Hydraulics Laboratory.

VERBANCK, M. 2008. How fast can a river flow over alluvium? *Journal of Hydraulic Research,* 46.

WAINWRIGHT, D., VIENOT, P. & SYME, B. Dynamic Modelling of the Impact of Entrance Scour on Flood Behaviour in Coastal Lakes and Estuaries. NSW Coastal Conference, 2004 Lake Macquarie.

WAINWRIGHT, D. J., KIDD, L. J., GUARD, P. A. & BALDOCK, T. E. 2011. Morphodynamic Modelling of Entrance Breakout for a Coastal Lake. *Coasts and Ports 2011 Diverse and Developing.* Perth, Western Australia.