Entrance Modelling and the Influence on ICOLL Flood Behaviour

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ABSTRACT

The morphological changes in the coastal entrance of estuaries and ICOLLs during flood events can be critical in determining design peak flood levels. The changing entrance shape as the scour develops changes the channel conveyance properties, which can significantly impact peak water levels attained in the system during a flood.

The influence of entrance conditions on flood behaviour has been investigated for a number of coastal lake/lagoon systems utilising morphologic routines in the TUFLOW software. These projects have demonstrated the capability of the model of integrating scouring processes at the sand berm and importantly the determination of representative design flood conditions. The scouring rate is based on inter-related parameters: flood flows, initial water levels, downstream ocean levels and, of significant importance, the original sand berm geometry.

The highly dynamic nature of entrance systems with respect to shoaling patterns presents challenges in defining appropriate initial conditions of entrance channel geometry for design flood estimation. The modelling studies investigate various states of closure, from a fully open system through variable degrees of shoaling to a fully closed system. These closure states impact differently dependent on the flooding regime, i.e. catchment or ocean derived flooding.

High level modelling techniques have been applied to investigate flooding behaviour in ICOLL systems with consideration of key influences relating to berm level & location, flooding regimes & coincident flooding conditions, climate change and entrance management techniques.

INTRODUCTION

The nature of Intermittently Closed and Open Lakes and Lagoons (ICOLLs) is such that the entrance condition has a significant influence on the flood behaviour of the lower estuary. In a natural state, the frequency of closure and opening of the entrance to an ICOLL is related to the condition of the entrance berm, waterway storage, contribution of runoff from upstream catchment areas and downstream coastal conditions including waves, tides and storm surge. Conditions at the onset of a flood event are highly variable in response to above factors, and presents a challenge in defining representative conditions in order to derive design flood conditions.

This inherent variability lends itself to adoption of an “envelope” approach to design flood inundation mapping. Both catchment derived and ocean derived flooding mechanisms are considered in establishing design flood conditions in an estuarine system. For systems such as ICOLL’s affected by shoaling in the entrance channel, a closed entrance will typically provide for the worst case condition for catchment derived flooding when considering peak flood levels and inundation. Conversely, an open entrance would typically provide for a worst case condition for ocean flooding events, again considering peak flood water levels. It is important to recognise also that the critical berm configurations for various flood scenarios are often different for water level and velocity conditions attained during a flood event.

Some general guidance in terms of approaches and considerations for investigation of flooding in estuarine systems is provided in the Flood Risk Management Guide (NSW State Government, 2010). Broadly this guidance encompasses:

- Model approach – application of either fixed or dynamic bed model dependent on the nature of the modelled system;
- Entrance geometry - definition of initial conditions to represent entrance conveyance capacity at the start of a modelled flood event (also constraints to lateral and vertical scour);
- Boundary conditions – principally the model forcing incorporating combinations of coincident catchment inflows and ocean tide conditions; and
- Influence of sea level rise –requirements for assessment of potential sea level rise impacts consistent with NSW Government Sea Level Rise Policy Statement (NSW State Government, 2009).

The development of a morphological module for BMT WBM's TUFLOW software has enabled the application of a dynamic model approach for the assessment of flood behaviour in a number of ICOLL systems. Presented in the paper are some experiences in modelling these systems and practical considerations for future flood studies and floodplain management studies in these estuarine environs.

MODEL BACKGROUND

The TUFLOW software is one of the leading hydrodynamic modelling packages having widespread application in Australia, particularly in flood modelling applications. A morphodynamic model, TUFLOW-MORPH, has been developed by BMT WBM as an extension of the hydrodynamic model. The morphodynamic component aims to simulate the typical patterns of sediment transport as governed by the hydrodynamics and applied boundary forcing.

The processes and characteristics incorporated into the model include:

- Sediment transport and bed-evolution (sedimentation and erosion);
- Slumping of unstable slopes;
- Bed load transport rates calculated using van Rijn formulation;
- Threshold velocity for bed load transport calculated based on particle size distributions (D_{10}, D_{50} and D_{90}); and
- Sediment classes and ability to spatially vary sediment properties according to material type.

The morphological routines have been developed specifically around entrance breakout simulation, and coupled with the existing performance and functionality of the TUFLOW hydrodynamic model, provides an integrated software particularly suited to application in ICOLL flood studies.

The linkage with a wave model (e.g. SWAN) can introduce the impacts of waves that can be important in driving sediment transport and morphology of the mouth, which can influence the hydrodynamics in the lower estuary. Sediment supply to the entrance may result from the combined effects of waves and tidal flows. This approach incorporates the important coastal processes occurring within the Estuary that influence its environmental condition and introduce changes to bathymetry over time.

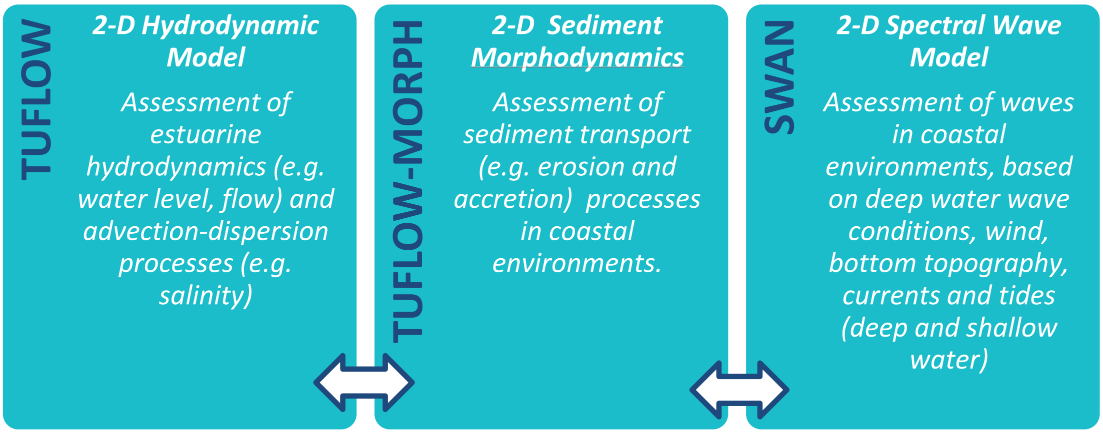

Figure 1 Model Linkage

For most flood studies, the application of a wave model is not required. The focus of the flood study, particularly for ICOLL systems, is the simulation of the breakout processes and the propagation of the flood wave through the lower estuary. For this relatively short, event based modelling, the influence of the wave conditions in driving sediment transport patterns is of less interest. The interaction of the hydrodynamic model and the morphodynamic model is illustrated in the simple process diagram shown in Figure 2.

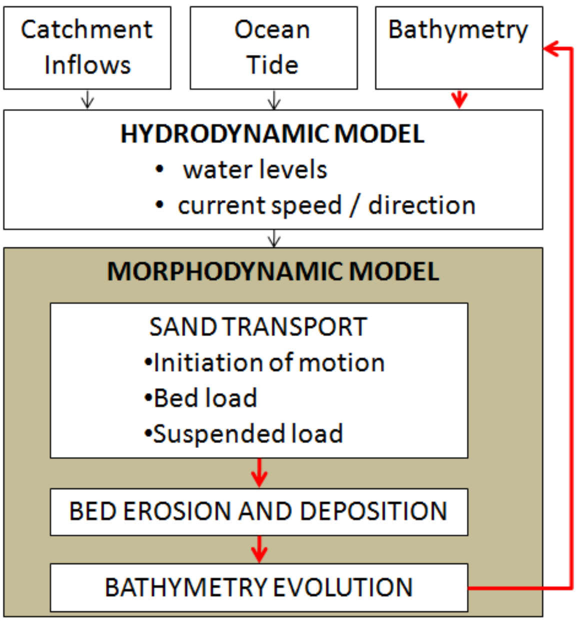

Figure 2 Simplified Model Process

MODEL APPLICATION

The principal application of the model to date is in the simulation of entrance breakout scenarios initiated either through natural flooding regimes or artificial openings. Typically a natural breakout is initiated by rising water levels within the lake in response to heavy rainfall overtopping the entrance sand berm. Artificial openings or breakouts involve a manual intervention typically through excavation of a pilot channel to initiate an opening to lower water levels in the lake. The artificial openings may be undertaken to relieve persistently high water levels in the lake systems during periods of closure or as a flood management procedure providing system capacity for imminent flooding.

Figure 3 shows example results for an entrance breakout simulation providing a comparison of measured and modelled water levels in the lake upstream of the entrance. There are three distinct phases indicated by the water level time series: 1) a period prior to the breakout represented by gradually rising water levels behind a closed entrance, 2) the breakout period where the entrance channel is actively scouring, increasing discharge and lowering lake water levels, and 3) the post breakout period where the entrance channel has fully scoured enabling normal tidal exchange.

For design flood investigations, the validation of the entrance breach process is focused on a reasonable representation of the rate of water level fall in the estuary and the correct tidal transmission characteristics for the days following the breach event. In this regard, the requirement is for the conveyance capacity of the breakout channel to be effectively modelled. In the example shown, the modelled water level during the entrance breakout period conforms well to the observed fall in lake levels, such that the modelled outflow hydrograph from the system can be considered representative of actual conditions. The degree of scour during the breakout process and resulting open entrance condition influences the tidal exchange in the lake system, such that the post breakout time series of water level in the lake can also be a useful model validation reference.

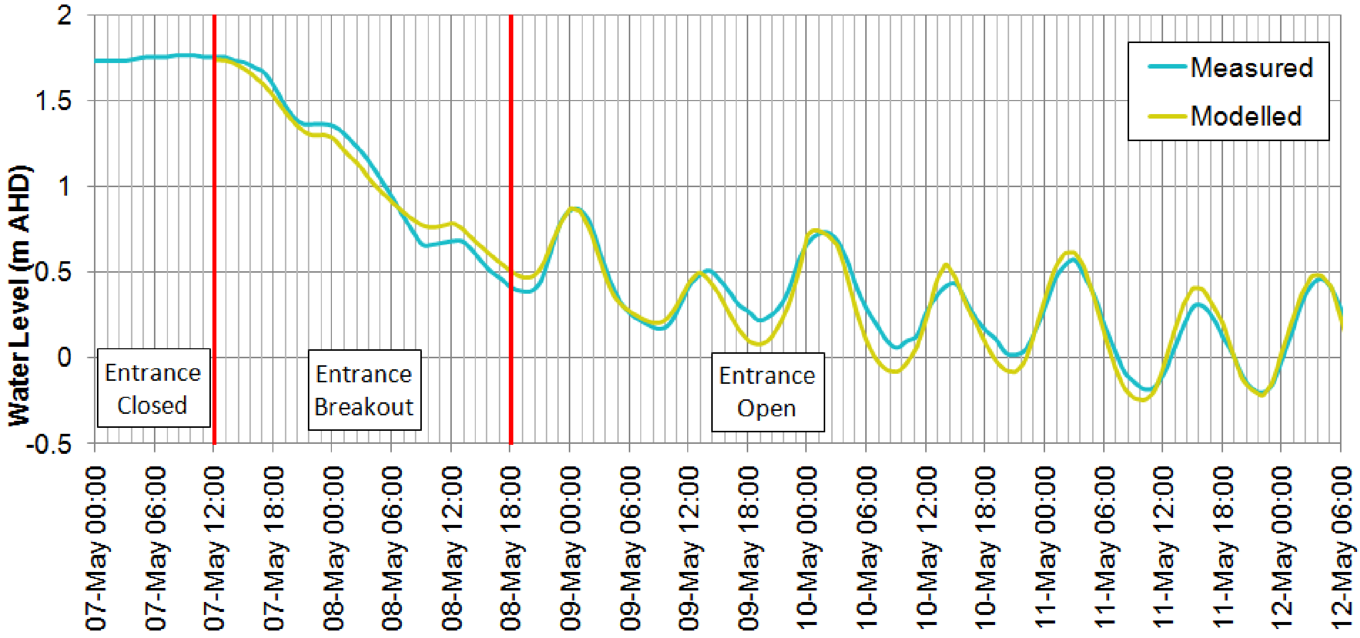

Figure 3 Simulation of Breakout Event (BMT WBM, 2011)

It is important to acknowledge there is no universal sediment transport formulation that performs effectively in a broad range of physical conditions. Accordingly, results from morphological models need to be approached with caution. The application of the morphological model within a flood study context is not intended to define the exact evolution of the entrance channel in terms of definitive erosion and sedimentation zones and the final entrance shape and bathymetry. What is important however is that the models provide for an appropriate representation of the bulk conveyance of the entrance, and simulate the changing capacity as the flood wave propagates through the system. Comparison of pre- and post-breakout bathymetric survey, although typically unavailable within reasonable periods of the event, can provide the opportunity to validate the models in respect to the shape and position of the scoured channel.

Further example results of a typical flood model application of the morphodynamic model are shown in Figure 4. The model simulation results shown are for the Lake Conjola entrance on the NSW South Coast for a 1% AEP event magnitude, providing time series of discharge (flood hydrograph) and water level, and snapshots of the bathymetry and velocity vectors pre- and post-breakout. The hydrograph represents flow through the entrance channel across the major breakout channel. Water level profiles are shown for the ocean tide condition (downstream model boundary), within the entrance channel just upstream of the breakout location, and within the main lake body some 4km upstream of the entrance.

The model scenario shown in Figure 4 is for a heavily shoaled initial condition at the entrance, with an adopted minimum berm height of 1.0m AHD. At this level the entrance is closed, with no tidal interaction as evident in the water level time series profiles. The overtopping of the berm initiates outflow through the entrance in response to catchment inflows. On the initial rising limb of the hydrograph, the entrance remains largely constrained with the lake body and entrance water levels rising commensurately. As catchment inflows increase and induce scour of the entrance, the outflow hydrograph rises rapidly. Under the high flow conditions a significant water level gradient from the Lake to the entrance is generated. Water levels in the lake and entrance channel would continue to fall through the hydrograph recession until the tidal exchange is reinstated through the now scoured (open) entrance.

The results presented show in general terms the simulation of flood behaviour in an ICOLL system for a catchment flood event. There is however a number of significant variables that require consideration in the model configurations with respect to entrance dynamics and their influence on the resulting flood simulations:

- Berm height – perhaps the key variable in the breakout simulations that defines the threshold water level for berm overtopping and initiation of major scour. Highly variable in nature and dependent on both longer term climate patterns and incidence of storm activity.

- Entrance bathymetry – in addition to the main berm barrier itself, the overall entrance bathymetry is a key driver in the model simulations, representing location, alignment and capacity of major flow channels, and the volume and distribution of bed material in the active morphological domain.

- Initial lake levels – this a typical variable within flood studies incorporating significant permanent or temporary storages; however it has implication in the entrance breakout simulation. This relates to the timing of the initial breach in relation to the catchment flood hydrograph, as flow rate and velocity conditions in the entrance channel impacts on the breach initiation and rate of scour.
- Tidal boundary – the magnitude and timing of the tidal boundary and interaction with the catchment inflows that also impact on the scouring pattern and rate.

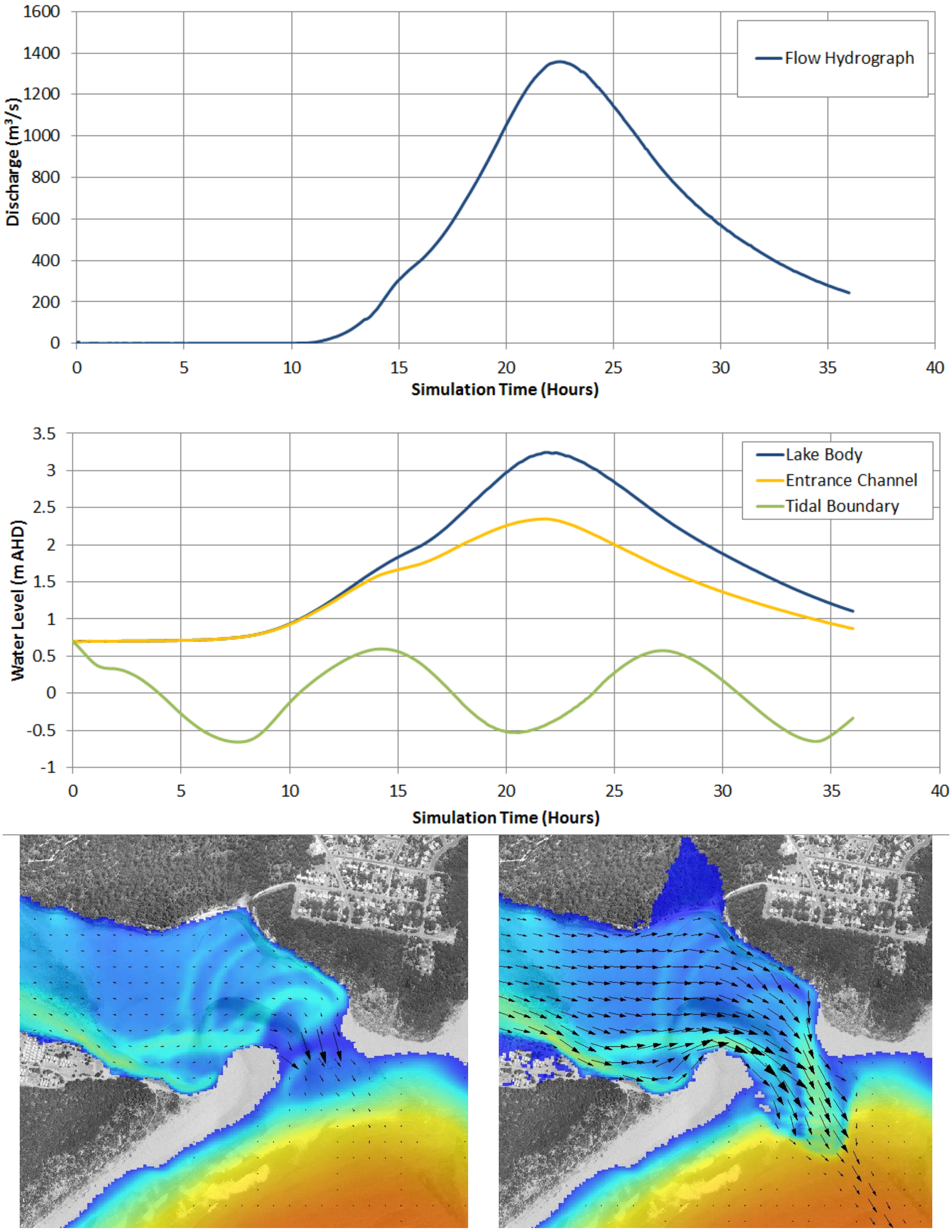

Figure 4 Simulation of Breakout Event (BMT WBM, 2012)

Ultimately, the application of the morphodynamic model is to simulate the breach behaviour and the resulting impact on simulated flood conditions. To this end, the breach modelling aims to represent:

- Initial scour and relative timing to main hydrologic drivers (catchment inflows, tidal conditions);
- Changing conveyance through the simulated event period; and
- Final shape of the entrance channel and connectivity to ocean for tidal exchange.

An example comparison of initial and final cross section shape through the entrance channel as shown in Figure 5 provides an appreciation of the change in the overall entrance conveyance through the simulation. Viewed as a time series of cross sectional area (below a nominal 2m AHD) as the scoured channel develops, the changing capacity of the entrance channel through the flood simulation is evident. With respect to fixed bed modelling approaches, the adoption of a constrained (shoaled) entrance throughout the simulation may result in conservative estimates of flood levels. Conversely, a fixed scoured entrance may result in non-conservative flood level estimation. The opportunity therefore exists to utilise entrance breakout modelling to determine a more representative flood condition.

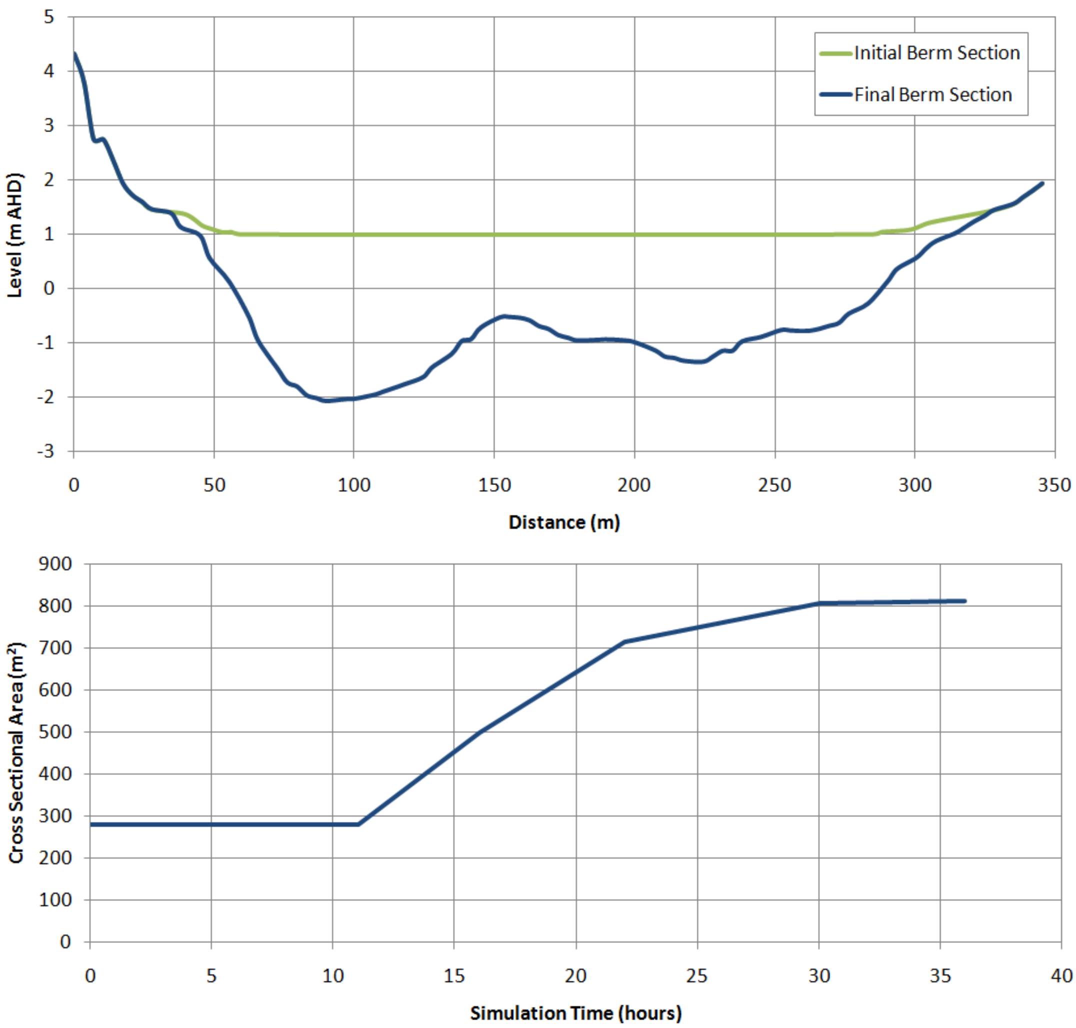

Figure 5 Changing Entrance Cross Section Properties (Shape and Area)

The use of morphological models to simulate entrance dynamics also has potential application for floodplain management beyond the typical simulation of major flood events. Such applications include the simulation of longer periods of erosion and sedimentation to investigate opening and closing characteristics of the entrance, and assessment of entrance management procedures.

The presence of significant low-lying development around many of our ICOLL systems, has seen an increasing focus on low-level persistent flooding, largely occurring in times of closure. The uncertainty around potential climate change impacts has increased this focus on low-level flooding with the likely future scenario of more frequent inundation.

Figure 6 shows an example time series of water level in an ICOLL system following a breakout event, with a gradual re-establishment of the entrance berm (noting the weakening of the tidal signal) and subsequent closure within a relatively short time frame. For communities at low-level flood risk during periods of closure, the rapid progression to re-closure following a breakout event is problematic, and often the source of considerable angst if associated with perceived ineffective entrance management policies.

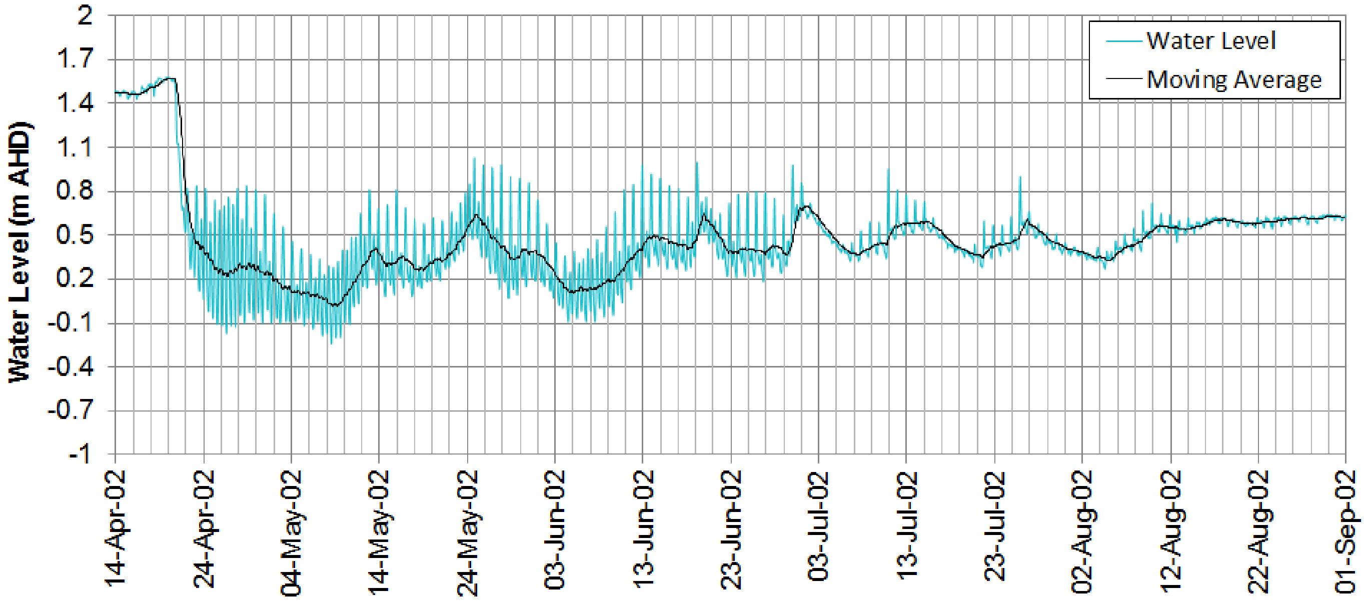

Figure 6 Water Level Trace to Entrance Closure Following Breakout

Ocean waves can re-form a sand bar or berm across the entrance following breakout, however the time for this process to occur is a function of the preceding wave climate and the degree of breakout achieved (i.e. a large flood will scour the entrance more substantially than a breakout that results from natural or artificial breakouts that are initiated when lake water levels are lower).

To establish the success of intervention programs to open an entrance, one of the key factors is the period the entrance remains open. We may see more frequent use of morphological models to optimise entrance management procedures. One such application is the investigation of manual breakouts. Entrance modelling may be applied as a tool to assess the effectiveness of manual breakouts and possibly to optimising the breakout procedures with consideration of:

- Width, depth and length of pilot channels;
- Alignment relative to flow channel;
- Trigger levels for intervention; and
- Influence of climatic conditions.

For many existing low-lying developments, the increased frequency of inundation from potential climate change impacts may potentially render the existing land use impractical, thereby requiring consideration in the floodplain management process of future adaptation strategies. The viability of entrance management techniques such as artificial openings will be under increased scrutiny from these communities. Modelling results may serve as a useful community consultation aid to explore and demonstrate the likely outcomes of “what if” options.

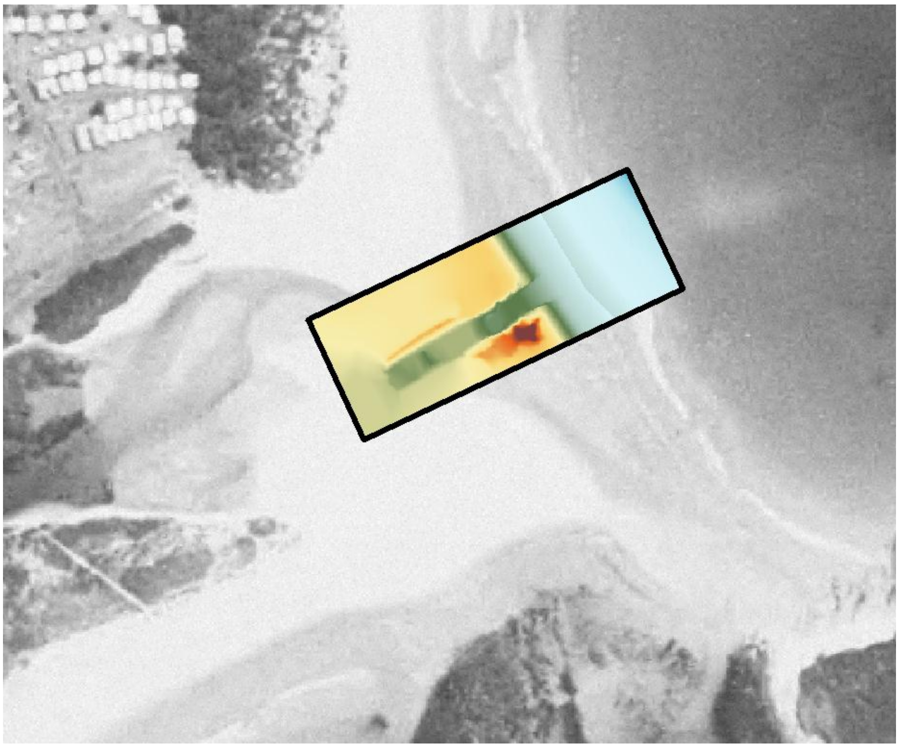

Figure 7 Testing Pilot Channel Configurations (BMT WBM, 2010)

CONSIDERATIONS FOR MODELLING

Application of morphological models in flood studies increases the complexity of the analysis, however can add significant value to the project through better representation of flood conditions. This increased complexity does come at a cost with further time investment in additional data requirements, considerations for model configuration, appreciation of limitations and interpretation of results.

Coupled with the already high demands on flood studies in assessing multiple design scenarios and sensitivity testing, the modelling introduces more variables and hence further uncertainties potentially requiring sensitivity testing. Nevertheless, as the modelling is required to address increasingly complex and integrated natural resource management issues, the evolution of the models (software and hardware) will continue to improve the modelling of important processes.

Some of the key considerations in terms of model inputs and system representation when applying dynamic entrance modelling to flood studies are presented below.

Initial conditions

The key bathymetric features to represent in the model is the entrance berm geometry (height, width. location), the size and alignment of the main entrance channel flow paths, and location and geometry of major system shoals. Largely this is a definition of the entrance channel capacity, the physical obstructions to flood flow and volume and distribution of sediment source.

ICOLL systems can be very dynamic, with movement of sand affected by waves, tides, wind and catchment discharges which can cause notable changes over relatively short periods, such as during a storm. These processes mobilise sand from the bed and transport it from one area to another, resulting in areas of erosion and accretion.

The initial bathymetry is perhaps the most sensitive input variable in relation to impact on simulated flood behaviour. This is reflected in the general adoption of various states of closure dependent on modelled flood mechanism e.g. closed entrance condition for catchment flood simulation and open entrance for ocean flood. However, within these general open/closed classification, there is significant potential for variation.

When the ocean entrance is closed, the beach berm can build naturally to over 2 metres above mean sea level given an extended period of suitable climatic conditions and no intervention. A similar extreme in modelling an ocean flood event with an open condition could utilise the extensive scour resulting from a major flood event, e.g. 1% AEP.

Between these extremes, though possible but unlikely to have been experienced in recorded history, lie what may be considered a typical condition based on previous experiences. Historical survey and aerial photographs provide for snapshots of conditions at a given time, but the key question is how representative these conditions are given the broad range of expected variability?

Both the potential extremes and typical conditions are influenced by:

- Natural climate variability and storm incidence – ICOLLs are named thus so given the cyclic (albeit random) nature of open and closed periods and various degrees of shoaling in between.
- Management practices – artificial openings, dredging or the construction of groynes or breakwaters will also alter the way that sand is transported within the study area.
- Climate change – though general impacts of climate change on coastal entrances are widely acknowledged, the timing and magnitude of effects in relation to specific system response is unknown.

All of these factors play some part in defining “representative conditions” to adopt in establishing design flood conditions.

Constraints

The morphological model domains need to incorporate where appropriate the constraints on erosion and sedimentation regimes. In much the same way that a levee bank or flood wall constrains the passage of flood flows, the presence of natural and artificial controls provide horizontal and vertical constraints on sand movements.

These constraints can be represented in a number ways including complete or partial control on lateral channel migration, limits on vertical erosion and reduced erodibility. Some examples of common features requiring representation in the models include:

- Permanent structures such as groynes, rock walls and revetments;
- Natural bed rock controls either exposed, submerged or at depth beneath sand bed layers (see Figure 8) ;
- Heightening and stabilisation of dunes reducing opportunity for washovers and breakthrough in flooding events (see Figure 9); and
- Different material types defining spatial distribution of sediment properties.

Figure 8 Rock Platform at Burrill Lake Entrance

Figure 9 Dune Stabilisation at Narrabeen Lagoon Entrance

Natural and Artificial Triggers

The timing of the breach event relative to the main hydrological drivers (catchment inflow and tidal condition) can have a significant influence on the flood behaviour. In typical estuarine flood studies, consideration is given to the coincident timing of peaks and or/lows in the flow hydrograph and tidal profile. Intuitively, coincident peaks would provide for peak water levels, whilst peak velocities may be attained combining a peak and low to generate a higher hydraulic gradient.

In simulating the breach dynamics, the prescription of the critical conditions is less clear. Significant testing of various combinations of boundary condition may be required to assess the morphological response and subsequent impacts on design flood conditions. This variability in coincident timing of catchment flows and tidal conditions, and influence on entrance dynamics, reflects the randomness of the natural system.

Decisions to initiate an entrance opening at a prescribed water level (artificial trigger) are generally linked to an adopted entrance management framework, with levels tied to reducing exposure of low-lying property to low-level persistent flooding and as emergency procedure to expected major flooding. The simulation of an artificial breakout at a prescribed level is relatively straight forward, given known berm conditions

Rapid changes in conditions once a trigger level has been reached may prevent the opportunity for an artificial breakout given required mobilisation times or dangerous conditions. Accordingly, simulation of design flood conditions should not rely on an artificial breakout at prescriptive trigger levels.

Climate Change

Consideration of potential climate change influences are now well ingrained in the flood study process. However, these are largely limited to provision of sea level rise allowances at coastal water level boundaries and rainfall intensity increases in the rainfall-runoff modelling process.

Over longer periods, broad scale changes can affect the context within which waves and tides transport sand. For example, sea level rise since the end of the last glacial period is responsible for the ongoing movement of the flood tide delta into many estuaries. Similarly, the sea level rise expected over the next century will also alter sand movement. Changes in entrance berm processes is likely from the predicted sea level rise and changes to coastal storm intensity, expected to typically result in a net upward and landward shift in berm profiles at the entrance.

The most simplistic representation of sea level rise impacts is the adoption of equivalent rises in general shoaling levels and berm crest heights. Accordingly, the berm level of a closed entrance scenario for the year 2100 is expected to be almost 1m higher than present conditions. This scenario would have significant ramifications for low-lying property already at flood risk at current entrance levels.

Changes of entrance configurations in response to climate change impacts however are much more complex and wider reaching than simple elevations in entrance berm levels. Longer term beach changes and shoreline recession may occur over several years, and directly impact on the long term stability of the entrance. Advanced models (Patterson, 2010; Huxley, 2010) for shoreline recession and berm response due to sea level rise enable better representation of future entrance geometry to incorporate into model simulations of future planning horizons.

CONCLUSIONS

The development of morphological routines within the TUFLOW hydrodynamic model software and subsequent application in a range of hydrodynamic studies of ICOLLs, have demonstrated the influence that entrance dynamics can have on flood behaviour of these systems.

Morphodynamic modelling within the flood study context makes for an increasingly complex analysis, however does provide the opportunity for better process representation and understanding of physical influence of the entrance configuration on design flood conditions. This can add value to ICOLL flood studies through:

- Determination of representative design flood conditions integrating scouring processes;
- Overcoming some limitations in traditional approaches which lend themselves to overly conservative or non-conservative assumptions in establishing design flood conditions;
- Enabling rigorous testing of entrance management options leading to improved management practices;
- Incorporation of potential climate change impacts on physical configuration of entrance compartments and subsequent change in morphological response to flood events; and

- Providing effective simulation results that can be interpreted by the community and incorporate what is seen in reality.

The software and refinement of its application continues to be developed through projects and research initiatives within BMT WBM.

REFERENCES

BMT WBM (2011) *Lake Cathie / Lake Innes Estuary Hydrodynamic Model Development and Investigation*, Prepared for Port Macquarie-Hastings Council.

BMT WBM (2012) *Lake Conjola Floodplain Risk Management Study*, in preparation for Shoalhaven City Council.

BMT WBM (2010) *Tabourie Entrance Intervention Project*, Prepared for Shoalhaven City Council

Huxley, C. (2010). *Quantification of the Physical Impacts of Climate Change on Beach Shoreline Response*, Master of Philosophy, School of Engineering, Civil Engineering University of Queensland.

New South Wales Government, (2009). *New South Wales Sea Level Rise Policy Statement*. NSW State Government.

NSW Department of Environment Climate Change & Water, (2010). *Flood risk management guide, incorporating sea level rise benchmarks in flood risk assessments*. NSW State Government.

Patterson, D., (2010). Modelling Short to Geological Time-Scale Coastline Response to Climate Change along the Central East Coast of Australia, *Proceedings of the 1st Practical Responses to Climate Change National Conference*, 29 September – 1 October 2010, Melbourne.