A Conceptual Framework for a Physical – Economic Model of Tidal Inlet Flooding

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Abstract: Small tidal inlets which link a tidal basin to the sea via a constricted entrance are common on the NSW south coast and elsewhere around the Australian coastline. Storm overwash events and longshore sand transport tend to close these inlets while tidal and flood scouring act to keep them open. Closure, or even significant constriction, raises water levels within the basin while open entrances introduce tidal and coastal factors into the modelling of flood levels. Costs or losses may be incurred by the inundation of assets, such as infrastructure with definable values, or by intangible losses such as damage to ecosystems. Opening an entrance may reduce some costs but increase others. The costs associated with full hydrodynamic modelling, with a wide range of river flow and entrance conditions, are a constraint on assessment of potential flood damages. A rapid assessment procedure is outlined. This methodology permits coverage of a range of estuaries and conditions allowing a more detailed assessment of catchments which include a higher damage or risk factor. The framework presented comprises a first-order hydrodynamic model, a cost database, and data on storm and flood return periods. It can provide an "optimum" solution considering only the tangible costs, but is better regarded as a decision support system which comprises cost and benefit information for the wide range of conditions considered.

Keywords: Decision support system; Tidal inlet; Numerical model; Hydrodynamic model; Flooding; Estuary

1. INTRODUCTION

The coastal zone is the focus of recent increases in population and infrastructure with consequent exposure of assets to flood damage. Flooding in coastal catchments provides a unique set of problems for the manager. In conventional flood modelling of non-estuarine areas, an important parameter is the flood gradient. With flooding in estuary areas, the flood gradient is usually small and flood levels depend more on other variables such as floodwater storage in the estuarine/lake areas and the efficiency of drainage through the inlet area. The actual flood hydrograph is often controlled by backwater and storage effects. This is compounded by the dynamic boundary condition resulting from tidal forcing and an entrance subject to change by coastal processes. In such cases the use of conventional flood modelling is not capable of providing a solution to the problem of estimating flood levels and flood damage potential, especially for "smaller" storm events, as discussed below.

While the 1% and probable maximum flood levels are widely used for design purposes and floodplain zonings [NCCOE, 1992], many coastal floodplains have an historical level of infrastructure and assets such as agricultural land located at lower levels. These require management decisions for floods extending over a wide range of catchment events and entrance conditions.

This paper offers a different and more cost-effective approach to a first-order assessment of flood costs/infrastructure damage throughout the estuarine region of a catchment via a modelling approach that uses the main variables affecting flood levels. Flood levels are strongly affected by the closure or restriction of tidal inlets by the action of coastal processes. Entrance closure by sedimentation is one of the more important management problems for the small barrier estuaries along the southern coast of NSW. Less severe sedimentation restricts the entrance and modifies the tidal characteristics within the estuary, increasing the elevation of high water. Studies of estuaries have shown the importance of floods and coastal storms in determining entrance conditions [eg Walker et al, 1997; Elwany et al, 1998; McLean and Hinwood, 1999]. The interaction of entrance condition with flooding levels has not been examined to the same extent.

Flood damage assessment in the floodplain segments of catchments currently employs a range of methodologies including mapping of previous flood levels and simulation of 1% or probable maximum flood (PMF) levels through detailed hydraulic modelling. GIS mapping has been increasingly used to delineate flood affected areas, while the estimation of damage costs is usually completed using depth/damage curves constructed for the infrastructure on the floodplain. Where the lower catchment includes a coastal lake or estuary, it is necessary to model floods with both open (including tidal flows and coastal storm surge) or closed (with elevated lake levels) estuary conditions as the downstream boundary condition. Inclusion of this dynamic boundary condition introduces the need for a full hydrodynamic model. Thus, the estuary entrance condition introduces another parameter in flood assessment and this component increases in significance through the estuarine reach of the catchment.

Given that infrastructure development is often concentrated in this section of the catchment, it would be illustrative to obtain detailed information on the effects of entrance restriction on the absolute level and persistence of flooding associated with storms with high return frequency and relatively lower inundation levels. This would allow more informed decision making with regard to the potential for relocation or removal of infrastructure and modification of activities to lessen flood costs and allow a more natural entrance regime to dominate estuary management strategies. On a more systematic level, there is a need to develop a methodology to allow a cheap and rapid assessment of a number of coastal catchments which would highlight those catchments where the costs of low-level flooding are relatively high, allowing better direction of resources to those areas.

The next section briefly reviews the costs of estuarine flooding to demonstrate the link between flood level and cost. Sections 3 and 4 outline the hydrodynamic model which is used to predict flood levels for a given inlet and river flow, and to indicate the trend of inlet scouring or sedimentation. The return periods of flood and storm events are likely to be correlated, and relatively sophisticated analyses are needed to prepare reliable conditional and joint probability statistics; these methods have been described elsewhere [Higgins and Hinwood, 1999]. Using these components, the framework for a Decision Support System is developed in section 5.

2. COSTS OF FLOODING

The value or utility of many assets which may be located in the coastal zone is reduced by flooding. The following examples are indicative of the direct losses for infrastructure, agriculture and personal property:

Infrastructure – roads: Roads can function under minor infrequent flooding, but are unusable when fully flooded. Roads are damaged by foundation failure following even partial flooding.

Infrastructure – bridges: Bridges can function under very minor flooding but may be damaged by debris or wave action over the deck.

Infrastructure – sewerage treatment works: Cannot function when the outfall is backed up, leading to contaminated overflows. Permanent damage from backing up or minor flooding is usually not costly unless electrical equipment of pumping stations is inundated.

Agriculture –grazing: Temporary loss of function during flooding.

Agriculture – market gardens: Loss of crops and possible degradation of land from even minor flooding.

Domestic and commercial – caravan parks and camp grounds: Minor loss of useable area but generally low restoration costs.

Domestic and commercial – shops and schools: When flooding is a common occurrence, disruption is temporary and not costly, otherwise damage is high. Once floor level is exceeded by still water level or wave crests damage is significant.

Domestic and commercial – housing: health hazard commences at relatively low water levels as does minor disruption. Once floor level is exceeded by still water level or wave crests damage and social disruption are significant.

Indirect losses include the following:

- Allocating land to less remunerative uses,
- Additional costs to the community to assist owners of flooded assets,
- Costs of diversion of traffic,
- Public health costs.

Estimates of these costs can be made but exact figures are generally unknown.

Even more difficult to quantify are indirect costs which include the following:

- Loss of amenity to residents,
- Damage to natural ecosystems,
- Costs to the larger region or state in loss of earnings and tax revenues

These indirect costs are often the focus for current estuarine management strategies which are designed to maximise ecological integrity. The direct infrastructure flooding costs are often seen as preventing the implementation of more "natural" management techniques. There is a perceived need for a more complete risk assessment of low-lying infrastructure in order to provide a more informed debate on the future of such assets.

Most of these costs of a given asset are incurred from the time that the water level rises above a threshold level and increase in a discontinuous fashion as the water level increases. They involve a cost per incident and another cost proportional to the duration of flooding. The simplest analytical model of this scheme is:

$$L(y_m) = \sum_i \{a_i + b_i\, t_i (y - y_{oi})\} \qquad y_{oi} \le y_m \quad (1)$$

Where the summation is over all assets i = 1, 2, 3, .. for which $y_{oi} \le y_m$

$L(y_m)$ = cost or loss incurred in a single flood reaching a level y_m

y = water level

y_o = water level at threshold of damage for an asset

a, b = constants for each asset

t = duration of inundation for an asset during a single flood

Typically small groups of similar assets are located at slightly different levels, so that the cost-stage rating may be approximated by a smooth curve. Inclusion of time-related costs is difficult due to lack of data and is treated in an ad hoc fashion by putting all of the costs into the initial cost. In this simplification,

$$L(y_m) \approx \sum_i a_i \approx f(y_m) \qquad y_{oi} \le y_m\,. \quad (2)$$

A more complete model would predict an upper asymptote to the costs when the asset is unable to function or in need of complete replacement, but such severe flooding is not relevant, as explained below.

As an indication, y_o would be 100mm below floor level for buildings and bridges and perhaps 300mm below ground level for market gardens and roads, but this would be highly dependent on soil type and drainage. The initial cost, a_i, would be very low for grazing land and camping areas, equal to the repair costs for buildings and roads, and at least the total value of market garden crops. The b_i would be the annual value of the asset (less the part of that value already counted in the initial cost) plus the indirect costs incurred.

Severe flooding implies a very unusual sequence of events with financial and political implications that will necessitate the opening or enlarging of the entrance, or else extreme physical factors such as a major storm which would lead to natural enlargement. For these reasons severe flooding is not considered in this paper. Hence flooding of the low damage assets plus only a few non-grazing/camping assets need be considered. For the first few of the latter assets the initial cost will be significant and individual estimates are warranted.

Given an economic evaluation of the a_i and b_i values and an assessment of the y_{oi} values for assets at risk, the cost of any flooding incident may be obtained if y and t_i are given. Determination of these quantities utilises the modelling described in the following sections.

3. ENTRANCE HYDRODYNAMICS

Many previous studies of estuarine entrances have identified a “regime state” to which the entrance is supposed to evolve, and about which it may oscillate under changing inflow, tidal and inlet conditions. The regime formulae which have been developed for the design of stable estuary entrances (reviewed in Hume and Herdendorf, 1993) assume a steady state entrance condition as the design state. Many of the barrier entrances of the East Coast of USA display this regime behavior. There the local wave climate and the resultant longshore sediment transport are moderate and the river flow component is usually regarded as minor and hence the tidal flux through the inlet is the dominating forcing function [O'Brien, 1931]. This concept does not apply to intermittently opening estuaries which may change gradually while open but switch from open to closed states, without either state providing a long term norm.

The south eastern and south western coasts of Australia are characterised by high energy waves and a narrow, steep shelf with limited sediment availability dependent on the direction and size of local or regional storm waves. Entrance conditions for small barrier estuaries on these coasts are, therefore, quite sensitive to both coastal storm and fluvial events [McLean and Hinwood, 1999] with tidal flows providing the background energy and coastal processes producing gradual entrance change following these larger perturbations. Thus prediction of the trend of these estuaries towards opening or closure requires prediction of their response to both tidal and river flows, and consideration of the probability of occurrence of flood flows or coastal storms within a given time horizon.

4. ENTRANCE MODELLING

The scheme outlined in this paper is based on a simple hydrodynamic model. The model, which is described in McLean and Hinwood [2000], uses the equations of mass and energy conservation to predict the water level in a tidal basin which receives fluvial inflow. The dimensions of the basin, the ocean tide and the magnitude of the river flow are specified. The model then simulates a sequence of tides and from the simulations obtains the tidal statistics within the basin and the velocity statistics in the inlet contraction. For the purposes of evaluation of losses caused by flooding, the extreme water level at high tide and its duration are of significance. For determining the likely future behavior of the inlet – further constriction or scouring – the maximum flood and ebb velocities through the inlet are the key parameters obtained from the model.

The model, fitted with a graphical user interface and basic output plotting, has been packaged as the Estuary Entrance Tool (EET). The EET presents the equilibrium solutions under the given tidal and river flow conditions, and does not directly simulate the transition of the estuary from one state to another. Instead it provides the basis for answering "what if" questions such as:

- What if we get another onshore storm?
- What flood run off is required to enlarge the entrance to the point where it will be self maintaining?
- If no severe weather is experienced, is the entrance likely to shoal?

The model is simplified by assuming that the parameters may be lumped with a constant basin plan area (A_b) and inlet throat area (A_0) and the tide within the basin is characterised by single value (η_b). The inlet resistance is made up of two terms, the frictional resistance in the inlet channel and an inlet/outlet loss which depends on the maximum velocity in the inlet throat. These may be lumped into a single (dimensionless) head loss coefficient through the entrance throat, c. Deposition of sediment in the inlet channel will cause an increase in the value of c for a given inlet, conversely, scouring by floods will cause a decrease in c. Only one other independent parameter is required, a river flow parameter, Q, being the ratio of river flow (Q_f) to the nominal tidal inflow:

$$Q = \frac{Q_f \, T}{4 a_o \, A_b} \qquad (3)$$

where a_o is the tidal amplitude in the sea. and T is the tidal period.

The statistical parameters output by this model are the tidal attenuation and phase, the superelevation of the mean basin water level and the maximum flood and ebb velocities in the inlet. From this set two parameters are obtained for the present use. The first of these is the maximum ebb current velocity, u_m . A value of u_m below a threshold [O'Brien, 1931] indicates conditions where any sediment deposited in the inlet will not be scoured, and hence the inlet cross section will be reduced. A value larger than the threshold indicates a scouring or stable inlet.

The second parameter is the maximum water level during the tide cycle, which is directly used in assessing flood damage. Figure 1 shows the extreme tide level for a wide range of river discharge and entrance resistance parameters. The Scour Threshold line is based on the O'Brien criterion for a self maintaining tidal entrance. To the right of this line the trend is towards closure and to the left towards opening. Closure will cause a rapid rise in water level and a sharp rise in losses. Complete closure is not depicted on this diagram. Solutions have been evaluated for a very wide range of each of these parameters.

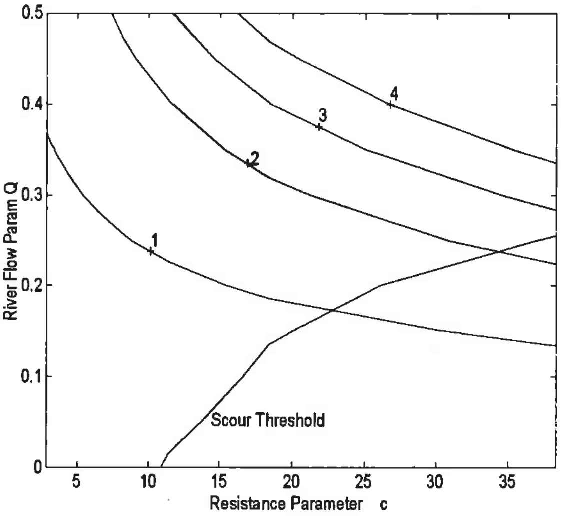

Figure 1. Contours of maximum water level (non-dimensionalised using tidal amplitude) vs River Flow and Entrance Resistance parameters.

Figure 1 shows the extreme water level for a range of river discharge and entrance resistance values. Through equation (1) the tide levels may be related to the initial cost of flooding of assets, so that the diagram may be rescaled with the contours corresponding to the total initial costs, $\sum a_i$. The same diagram, but with different scaling then provides the multiplier for the cost term resulting from the duration of flooding. On this rescaled diagram the contour value for the curves represent the values of the sum of the b_i values for the assets with $y_{oi} \le y_m$.

5. FRAMEWORK FOR ESTIMATING THE COST OF FLOODING

The framework proposed is shown schematically in Figure 2. A database of all potentially flood prone assets is prepared. From this database are obtained the cost-stage function, L(y), and the risk of incurring intangible costs such as ecosystem damage. The output to the Decision Support System is the list of assets at risk for each flood level. The EET is then used to simulate the hydrodynamic conditions under a range of flood and entrance conditions. From these model runs the maximum waterlevels for each set of conditions may be found as a function of the two non-dimensional parameters, Q and c. A direct output of the Decision Support System is the trend of the entrance to close or to scour. Using the cost data, the model output (Figure 1) may be rescaled with contours of cost rather than water level. Then using data on flood and storm return periods, the probabilities of the conditions tested may be evaluated, and hence the probability of each flood level determined. By multiplying these probabilities by the cost incurred at each flood level, the probable costs for any management option may be assessed – these options of course include not intervening. The tangible costs form part of the Decision Support System.

The function of the Decision Support System is not to seek exact answers (not even in a statistical sense) but to enable the probable entrance scenario and probable flooding scenarios to be identified and investigated, and hence ballpark costs and relative costs of “do nothing” or “open the entrance” options to be compared.

6. CONCLUSIONS

The framework of a Decision Support System to assist estuary managers in selecting from the “do nothing” or various intervention options has been presented. Decision support rather than an executive or optimum-seeking strategy has been chosen because of the limited data available for most small estuaries and because of the importance of unquantifiable costs of some of the important beneficial uses.

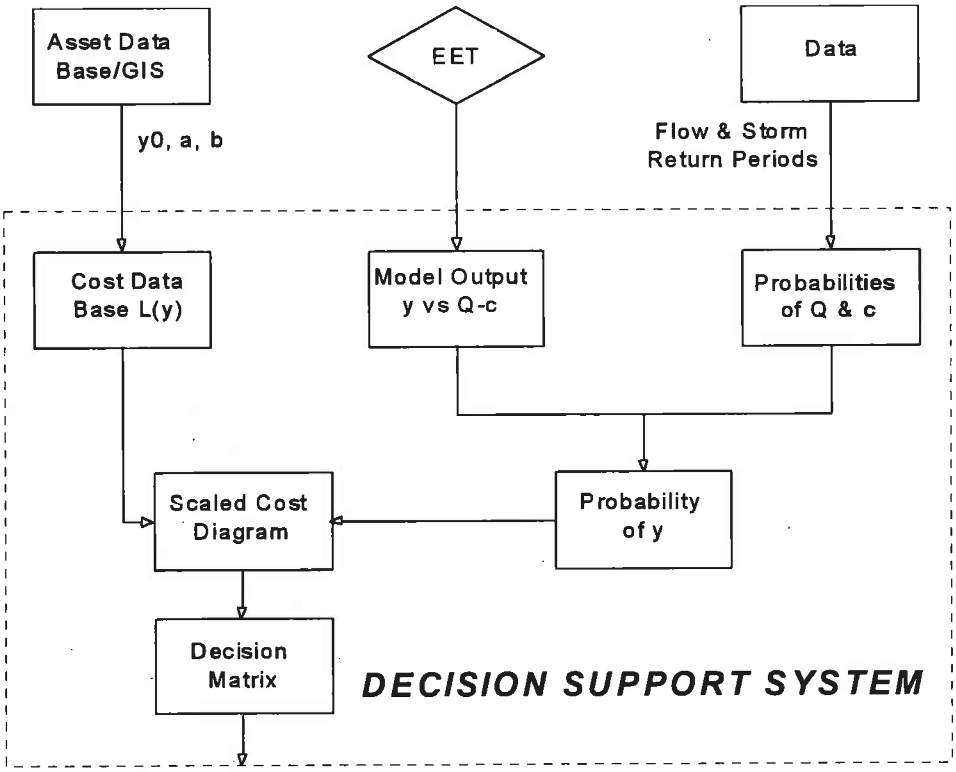

Figure 2. Framework for estuarine flood management Decision Support System.

The structure is modular, permitting upgrades as experience of use or data warrant, and is based on a core dynamic model, reflecting the causal processes. The model permits trends to be identified, explained and predicted.

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