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Abstract

Tidal inlets which link a tidal basin to the sea via a constricted entrance are common on the south-east Australian coast. Closure, or even significant constriction, raises water levels but restricts tidal range within the basin, while open entrances provide regular and significant tidal exchange with the ocean. A rapid assessment procedure with minimal data requirements has been shown to be informative for monitoring and a useful component of any Decision Support System set up as part of a management structure. Such a system is presented in this paper. It is based on one permanent water level gauge inside the inlet plus the use of a simple, first-order hydrodynamic model to relate the tide range, mean water level and river flow to the inlet cross sectional area. The method is tested against data from the Snowy River Estuary in south-eastern Australia but would be suitable over a range of estuaries. In addition, the framework presented can also provide a mechanism to explore conditions over the range of expected data, thus allowing better selection of model schematization and runs in estuarine systems where the use of 2 or 3D modeling can be justified.

Keywords

entrance, management, estuary, model, hydrodynamic, simple, application, GeoQUEST

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APPLICATION OF A SIMPLE HYDRODYNAMIC MODEL TO ESTUARY ENTRANCE MANAGEMENT

Errol J. McLean[1] * and Jon B. Hinwood[2]

Tidal inlets which link a tidal basin to the sea via a constricted entrance are common on the south-east Australian coast. Closure, or even significant constriction, raises water levels but restricts tidal range within the basin, while open entrances provide regular and significant tidal exchange with the ocean. A rapid assessment procedure with minimal data requirements has been shown to be informative for monitoring and a useful component of any Decision Support System set up as part of a management structure. Such a system is presented in this paper. It is based on one permanent water level gauge inside the inlet plus the use of a simple, first-order hydrodynamic model to relate the tide range, mean water level and river flow to the inlet cross sectional area. The method is tested against data from the Snowy River Estuary in south-eastern Australia but would be suitable over a range of estuaries. In addition, the framework presented can also provide a mechanism to explore conditions over the range of expected data, thus allowing better selection of model schematization and runs in estuarine systems where the use of 2 or 3D modeling can be justified.

Keywords: estuary, model, decision support, tidal analysis

INTRODUCTION

Tidal inlets which link a barrier estuary to the sea via a constricted entrance are common on the south-east Australian coast. Storm overwash events and longshore sand transport tend to close or restrict these inlets while tidal and flood scouring act to keep them open. Closure, or even significant constriction, raises water levels but restricts tidal range within the basin, while open entrances provide regular and significant tidal exchange with the ocean. To protect assets against flooding and for maintenance of the local ecology of wetlands and channels, there is often pressure to maintain an efficient flow through the restricting barrier. The costs and time delays associated with full hydrodynamic modeling, with a wide range of river flow and entrance conditions, combined often with a paucity of data are constraints on a complete assessment of entrance and tidal conditions. A rapid assessment procedure with minimal data requirements has been shown to be informative for monitoring and a useful component of any Decision Support System set up as part of a management structure (McLean et al, 2003). A simple hydrodynamic model to assist in the development of such a Decision Support System is presented in this paper.

The methodology outlined is based on one permanent water level gauge inside the inlet plus the use of a first-order hydrodynamic model to relate the tide range, mean water level and river flow to the inlet cross sectional area. The method is demonstrated against data from Lake Conjola and the Snowy River Estuary in south-eastern Australia and is suitable for a range of estuaries. It is particularly useful where rapid response is required or data and funding are not adequate to employ more complex hydrodynamic models. In addition, the framework presented can also provide a mechanism to explore conditions over the range of expected data, thus allowing better selection of model schematization and scenarios in estuarine systems where the use of 2 or 3D modeling is necessary.

The paper first describes a DST which has been used in Lake Conjola, a small estuary with low stream inflow, then considers a key component of that DST - the use of the tidal amplitude as a surrogate for entrance area. For estuaries with greater stream inflow a model is required and the EET model is described and its use illustrated by application to the Snowy River estuary.

DECISION SUPPORT TOOL FOR A TIDALLY-DOMINATED ESTUARY

Example of a small catchment case - Lake Conjola

Decision support systems are used to assist environmental managers to make decisions by reducing the number of aspects of a complex system through a set of simplified rules or by simple modeling. These support systems usually comprise a set of analytical and numerical tools that collectively provide a framework for making an assessment (Townend, 2002, Lawrence et al., 2002). Decision Support Tools could be regarded as single components, generally more quantitatively-based;

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incorporated within a broader Decision Framework that would usually contain both qualitative and quantitative information.

McLean et al (2003) described the development of a DST for Lake Conjola, a small barrier estuary located 210 kilometres south of Sydney on the south-eastern coast of Australia. It has a water body area of approximately 4.3 km^2 and a catchment area of 145 km^2. While the lake body is comparatively deep, the constricted entrance and the 3km long entrance channel attenuate the ocean tide to the order of 20% when the entrance is open. The small catchment provides low stream inflow and, except during major floods, the stream inflow has negligible effect on the tides. As described by McLean et al (2003), community concerns relating to local flooding during periods of entrance closure and opposing concerns of conservationists and government agencies regarding drastic interventions such as rock wall training of the entrance had lead to half a dozen studies, reports and management strategies. The final strategy selected was for a "managed natural entrance" where intervention is triggered by entrance constriction past a certain point and intervention strategies are for limited dredging in an attempt to mimic the "natural" stable entrance condition over the longer-term. These activities were supported by the development of a DST outlining the sequence of management steps to be undertaken.

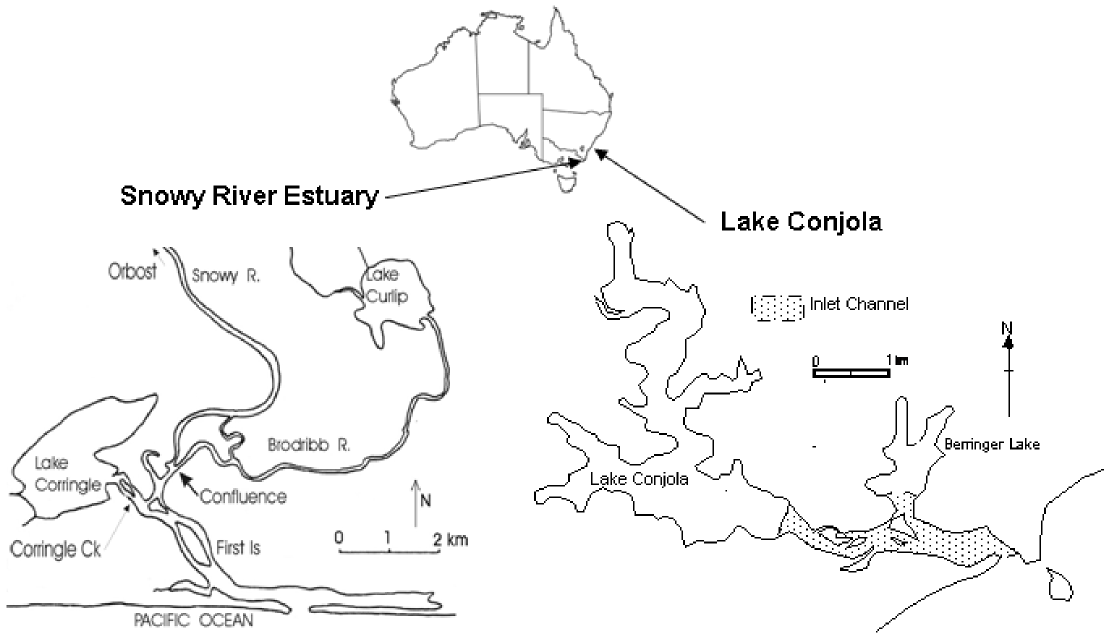

Figure 1 Lake Conjola and the Snowy River estuary

The Lake Conjola case illustrates the case of a small barrier estuary where a digital water level record at 15 minute sample rate is available from a gauge located approximately half way along the inlet channel to the lake. This provided a reliable data set over a number of decades. The data set has been useful to illustrate the time series of relative constriction/condition of the entrance as affected by recorded coastal storms and catchment flows. The water level gauge has also been an obvious monitoring device on which to base the continuous DST.

The DST was required to be easily accessed and used in a practical sense to manage the estuary entrance. The DST uses the tidal amplitude as a surrogate for the entrance area of the tidal inlet. The tidal amplitude in the estuary (M2) is tracked over time, as described in the next section. The trend of entrance area reducing successively triggers alerts culminating in advice to intervene and open the constricted entrance, as shown in figure 2. The DST was developed to provide guidance to management but through use of the internet it has proved very valuable in advising the local community and reducing conflicts.

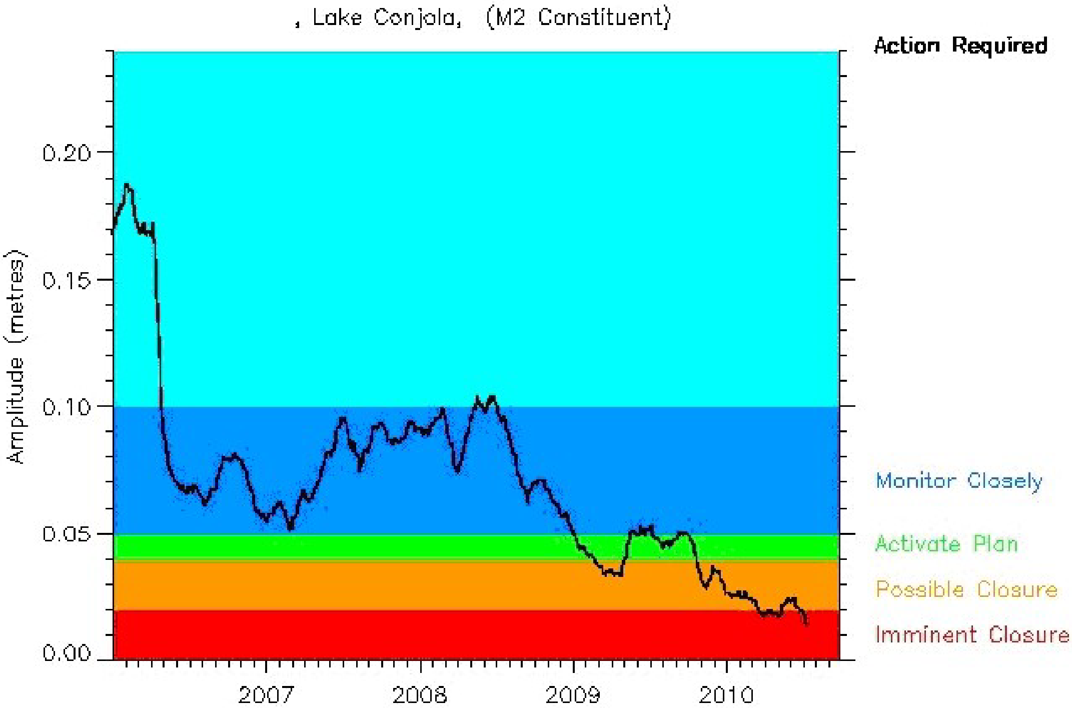

Figure 2 Screen capture of the DST display for Lake Conjola (Source: Manly Hydraulics Laboratory, NSW http://www.mhl.nsw.gov.au/www/lconj.htmlx)

Use of tidal amplitude

The existence of a long-term water level record has allows the deconstruction of the time series and extraction of a tidal constituent as a surrogate measure for entrance condition as explained in the following section.

For the Lake Conjola DST, the tidal amplitude is found by tidal analysis of the record from the estuary, using a moving window following the method of Hinwood and McLean (2001) and the same procedure is proposed as a generally applicable technique. In this analysis, a time window is chosen and the water level data within the window are analysed to determine the amplitude and phase of the leading tidal constituents. The window is then advanced by one day and the analysis repeated, until a complete time series of the leading constituents has been computed. Selection of the length of the time window is a compromise between accuracy and resolution of the rapid changes of flow and entrance area typical of these small estuaries; the tidal constants obtained are not intended for hydrographic or similar uses. A window of a few days length would enable changes to be followed in time, but is too short to enable reliable determination of the harmonic constants. On the south-eastern coast of Australia at least 4 constituents are required: M2, S2, O1, K1. Following Rayleigh's criterion (Godin, 1972), two constituents can be distinguished if the time window is longer than the reciprocal of the difference between their frequencies. Although subjective, this is quite a robust criterion, permitting visual separation of the constituents on a spectral plot in the absence of significant noise. For the 4 constituents above it requires a window 14 days in length, while adding the N2 would increase this to 28 days. A much shorter window is feasible to identify the relative magnitudes of the semi-diurnal and diurnal tidal species (Godin, 1972).

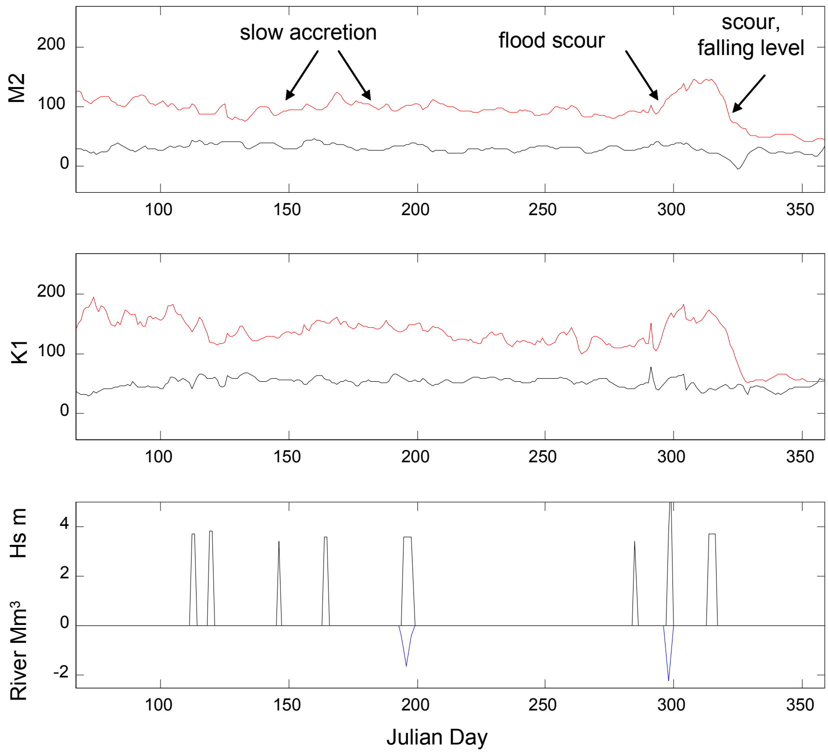

Figure 3 Selected plot of tidal constituents related to entrance conditions, Lake Conjola
a), b) Upper line is amplitude (mm), lower line is phase (degrees)

The nearest tide gauge to Lake Conjola that is representative of the ocean tide is at Jervis Bay. A series of experiments with different numbers of constituents showed that use of the five tidal constituents M2, S2, N2, K1, and O1 was needed to obtain relatively stable estimates of the tidal constants. The analysis used a 14-day window which was confirmed by trial as the minimum that gave stable values of the coefficients, although being less than the value given by the Rayleigh criterion. The use of the 14-day window means that an event causing a water level anomaly starts to influence the computations 7 days before its occurrence and there are still effects of the pre-storm conditions up to 7 days after its occurrence. Thus stable values of the pre-storm conditions must be taken at least 7 days before the occurrence of the storm. The data window uses a short cosine taper and the constants are determined using a least squares fit.

Tidal harmonic analyses with a moving window have been performed on the water level records obtained for both Lake Conjola and Jervis Bay. The computed amplitude and phase constants have been plotted in figure 3 against the date of the central day within the 14-day window, using the Julian day as the measure of time.

Summary

The Lake Conjola DST is a currently operational tool used by the local estuary manager (Shoalhaven City Council) to signal the need for intervention to maintain tidal flows and reduce flooding risk for low-lying local settlements. Uncertaincies still exist because of two main omissions from the DST. The external coastal storms, when coincident with elevated regional sea levels forced by warm-core eddies in the East Australian Current, appear to be the principal cause of substantial entrance constriction. These are not able to be accurately predicted and, thus, management strategies are restricted to an essentially reactive set of actions. The other key omission is the inability of the present DST to predict the likely entrance trajectory by tidal and catchment flows after the constricting storm events. The value of the DST is that it provides a lead-time allowing funding, survey and a detailed assessment of the scope of works needed to be undertaken before actual closure. The future inclusion of a modeling system, simulating tidal and riverine interactions, to support the Lake Conjola DST would significantly increase the ability to predict the likely trajectory of the entrance.

ENTRANCE MODELLING

A simple hydrodynamic model previously 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 model follows Escoffier (1940) van der Kreeke (1967) and others by treating the estuary as a single cell and the entrance channel as another cell. The assumptions made in models of this kind have been reviewed by Mehta and Ozsoy (1978) and Mehta and Joshi (1988).

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. From the simulations the model computes 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 is determined. To estimate 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.

The model, developed in MATLAB with a graphic user interface and file output, has been called the Estuary Entrance Tool (EET). The model gives 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 may be used by the estuary manager to observe the likely trajectory of the entrance condition in response to changes in the main forcing parameters (e.g. coastal storms, flood flows from the catchment). In combination with monitoring of an established tide gauge, the likelihood of the entrance shoaling under tidal flows can also be estimated.

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). Resistance through the inlet is compromised 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* (equation 1). Constriction through sediment deposition in the inlet channel will cause an increase in the value of *c*, while scouring by fluvial flows will cause a decrease in *c* through enlargement of the inlet dimensions.

$$c = \frac{8 a_o A_b^2 C}{g T^2 A_o^2} \qquad (1)$$

The other independent parameter required, a river flow parameter, *Q*, is derived from the ratio of river flow (Q_f) to the nominal tidal inflow (equation 2)

$$Q = \frac{Q_f T}{4 a_o A_b} \qquad (2)$$

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

The statistical parameters output are the tidal amplitude and phase, the elevation of the mean basin water level and the maximum flood and ebb velocities through the inlet. When run under command line the model outputs are normalised variables given in terms of c and Q. Using the graphic interface the actual variables are displayed graphically as functions of entrance area and river discharge. The first parameter (figure 4a) is the tidal amplitude within the estuary, which is directly useful for estimation of flushing efficiency as well as impact on the ecology of estuarine wetlands. The second parameter (figure 4b) is the mean water level during the tide cycle. It is relevant when considering local flooding and becomes very important near closure when considering the ability of the hydraulic gradient to maintain the outflow from the tidal basin to maintain the entrance. The third parameter is the maximum water level during the tide cycle, which is directly used in assessing flood levels in the estuarine basin. The fourth parameter is the maximum ebb current velocity, u_m . A value of u_m below a threshold (O'Brien, 1931) indicates conditions where sediment deposited in the inlet will not be scoured, and the inlet cross section will be reduced. A value larger than the threshold indicates a scouring or stable inlet according to O'Brien's criterion. More recent versions of the model (Hinwood et al, 2003) include several tidal constituents, sloping sides on channel and basin and a simple sediment scour and deposition procedure (Wilson et al, 2010). The extended models still meet the criteria of being robust and fast so could be applied in a DST.

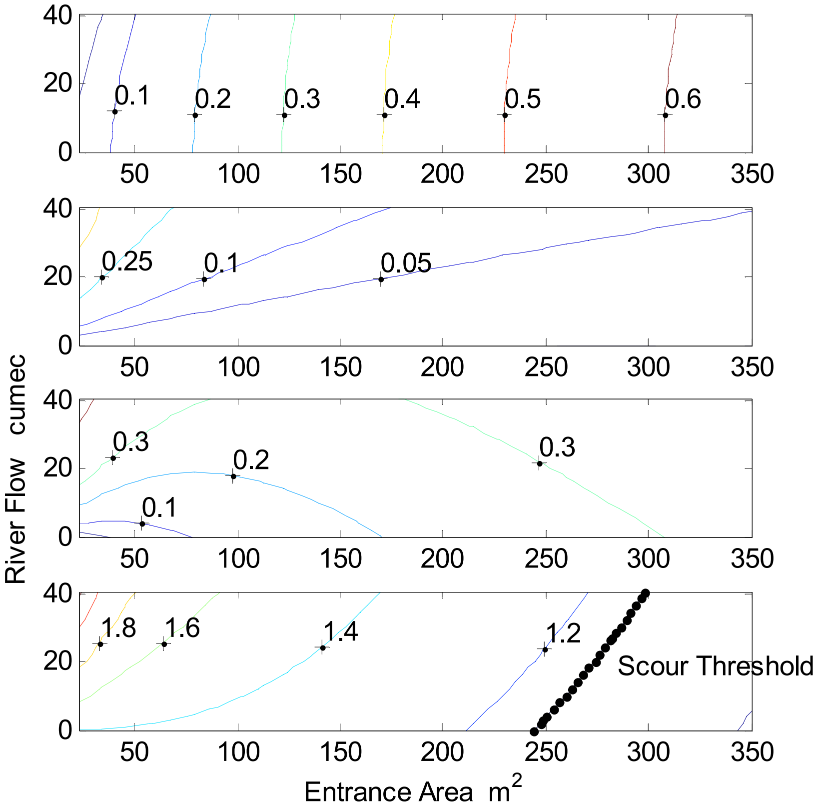

Figure 4 Contours of a) Tidal amplitude, b) Mean tidal level, c) Maximum water level, d) Maximum ebb velocity - non-scouring to right of line. Parameters based on Snowy River late September 2008

APPLICATION TO THE SNOWY RIVER ESTUARY

The Snowy River provides a good test of the concept, with two influent rivers, two large tidal lakes and an entrance prone to large variations. In common with most of the estuaries in south-eastern Australia, it is data poor with very few surveys and limited tidal data. No continuous water level record similar to Lake Conjola is available, making the use of a combination of hydrodynamic modeling and the establishment of a continuous water level gauge essential components of any monitoring or predictive DST. The few entrance surveys that were available fortunately spanned a wide range of flows and were supplemented by photographs which enabled the transition loss coefficient to be estimated from hydraulics texts. The model predictions for 3 of these cases are shown in table 1. The good agreement between model and measurement confirms that the simplifications inherent in the two cell model are adequate for this purpose.

Table 1 comparison of model and measured tidal attenuation

River Inflow	Entrance Area	Tidal Amplitude/Ocean Amplitude		Tidal lag hr:min	
ML/d	m^2	Measured	Model	Measured	Model
320	70	0.123	0.148	2:53	2.52
7,330	230	0.585	0.585	1:50	1:58
10,600	190	0.316	0.316	2:08	2:12

In general data on the entrance dimensions and loss coefficients will not be available. To demonstrate the model capability under these circumstances, the most complete data sets available were used to generate predictions. These are the 2008 and 2009 sets which comprised data from 6 tide recorders in the estuary and one in the ocean, river inflows, and photographs and cross-sections of the inlet channel each gathered over 4 days of record. The 2009 ocean tide, river flow and bathymetry data were used in the EET model to predict the estuary tide. The model was then calibrated by correcting the entrance loss coefficient to give the correct tidal range. The model was then run using the 2008 ocean tide, river flow and bathymetry data and correctly predicted the tidal range, as shown in Table 2. This test confirms that the model can be used to match the tidal range and hence find the entrance area. Improved matching may be achieved by comparing tidal phase and mean water level in addition to tidal range, although water level is more sensitive to river flow effects.

Table 2 Use of model with limited data availability - entrance area found by trial

Case	Tidal amplitude m		Tidal lag hr:min	
	Measured	Model	Measured	Model
A	0.260	0.259	2:10	2.00
B	0.253	0.252	2:40	2:04
C	0.124	0.118	2:42	2:08

POTENTIAL DECISION SUPPORT TOOL STRUCTURE FOR THE SNOWY RIVER ESTUARY

In the scheme presented below, the hydrodynamic model is the EET, described above. To determine the entrance area on a given day, the EET may be run under a control program, changing the assumed entrance area until the predicted tidal range and mean water level match those measured in the estuary, as demonstrated in the previous section. For the DST, we have chosen instead to perform a set of several hundred runs of the EET and store the resultant outputs. These outputs may then be rapidly searched to determine the area. The objective is to determine the entrance area, Ao. A time trajectory of this area will show a trend towards closure or stability of the entrance. Real time data from the estuary are combined with a record of antecedent entrance dimensions and with manually input information on coastal storm events and dredging to enable realistic estimation to be made of the entrance area. The DST would be run each day, providing output to the umbrella decision support system and storing output for use on subsequent days.

A schematic diagram of the DST is given in figure 5. First the model is run for a wide range of parameter values and the results stored, as shown on the right of figure 5. To run the DST, hourly tide elevations and daily river flows are input, as shown on the left of the figure. Then the hourly tidal data are used to obtain estimates of the mean sea level (MSL) and amplitude of the leading tidal constituent (M2 assumed here), as described in a previous section. The calculated MSL and M2 values, the river flow,Q , and the previous entrance area, together with the manual input are fed into a constraint matrix which sets bounds on the permissable change in Ao. The stored model runs are then searched for solutions with the given inflow, MSL and tide. The solution obtained for Ao is checked against the constraints and either accepted or a new solution is sought with the parameters altered within their probable error bands.

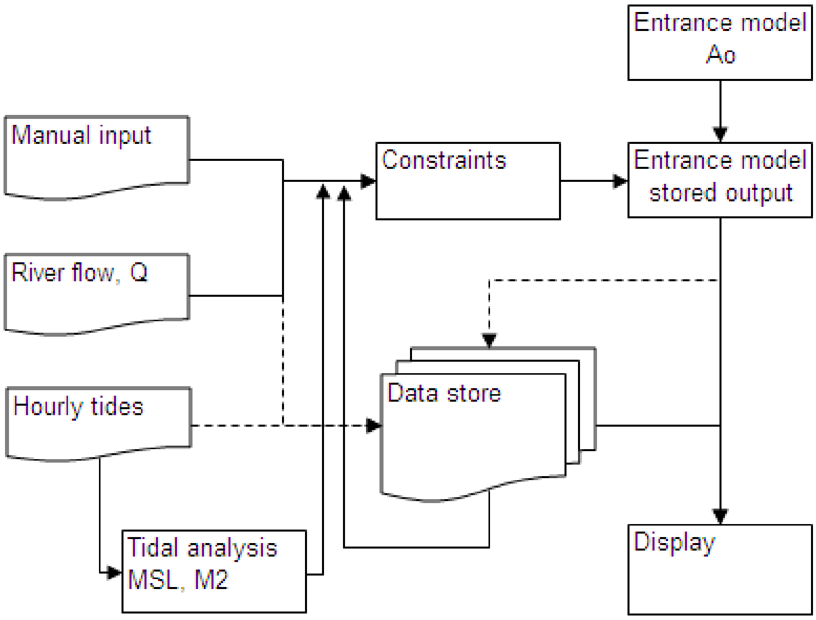

Figure 5 Schematic diagram of the DST for an estuary controlled by both tide and river flow

CONCLUSIONS

While monitoring of entrance condition in small barrier estuaries with minimal fluvial inputs can be readily achieved through the interrogation and data transformation of tide gauge water level records, this is not achievable in estuaries with greater catchment flows. Experimentation in the Snowy River Estuary has shown the practicality of using tide gauge data in conjunction with a simple parameterised hydrodynamic model to estimate both the inlet channel dimensions and the likely trajectory of the entrance condition. Such decision support frameworks are essential where management of estuarine entrances is limited by time and cost restraints. Such tools are therefore widely applicable to estuarine systems where inlet dimensions vary and constriction and periodic entrance closure is perceived to be a problem.

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