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A parametric hydrodynamic model of a complex estuary

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1. Introduction

Parametric modelling of an estuary aims to produce cost effective and robust computer models for use by environmental managers. These requirements lead to a different approach to the developments of the last few decades which have emphasised detailed representation of the physics of the estuary.

A scheme of classification of numerical models for the prediction of flow in tidal waters, including estuaries, was given by Hinwood and Wallis [11]. They classified the models into an array according to the number of spatial dimensions, the level of physics represented, and whether the model was eulerian or lagrangian. The spatial dimensions may be three, two (in plan or elevation), one (length) or zero (a single well-mixed box) dimensional. The levels of physics may be as follows:

(i) Hydrodynamic - uses momentum equations and hence can find velocities in new configurations. The energy equation may be used in one dimensional hydrodynamic models.
(ii) Kinematic - uses mass conservation equations and empirical data on velocity profiles and water levels to solve for velocities.
(iii) Transport - uses the convection-diffusion equation and data on velocities to solve for pollutant transport.

Hinwood and Wallis [12] found models of most types, and more have been developed since then. All of the models use finite difference or finite element schemes dividing the estuary into large numbers of elements, all but a couple solving the primitive equations.

A hydrodynamic model must be used for prediction of flow velocities and longitudinal salinity distributions in applications such as substantial upstream diversion of flow or channel modifications or where data are sparse. On the other hand, where the tidal and river flows are known with sufficient accuracy, a kinematic model may be used. In both cases a transport model is then used to compute the pollutant distributions.

The averaging involved in one or zero dimensional models makes them too crude for many applications but frequently there is no need for a three-dimensional model and a two-dimensional (in elevation) model may be used. In such models the computation of flows over many tide cycles requires extensive programming and data preparation and appreciable computer time and power. These cost and time penalties reduce the utility of these models for resource management, planning of data collection, and other interactive tasks where the highest precision is not essential.

To overcome these disadvantages, a parametric hydrodynamic model has been developed and is described in this paper. The application of this model to the Snowy River estuary is discussed.

2. The Parametric Hydrodynamic Model

2.1 Modelling Concept

It is presumed that the flow in the estuary is forced by the river flow and the presence of salt water at the seaward limit. Tidal forcing may also be present. Boundary conditions depend on the flow model adopted for each reach, as discussed below. Data required are the upstream river flows, tidal range and period, channel dimensions, bed and interfacial resistance coefficients, and eddy diffusion coefficients.

2.2 The General Model

The model uses published analytical solutions of specific flow situations to describe the hydrodynamics. These solutions include homogeneous flow, the salt wedge, and some partially mixed flows. While the presently available solutions have been used, the model is modular and improved solutions may be substituted as they become available. For each identified reach of the estuary, an appropriate flow is selected. The solutions are applied to each reach, to build up a set of linked flows describing the whole estuary. The model has been developed for a branched, but not looped channel system, with one point of discharge to the sea.

The analytical solutions have been obtained only for estuarine reaches with very simple geometry, most being restricted to uniform rectangular channels. In order to use the solutions in a real estuary, each reach is divided into a few segments over which the restrictions are adequately met. The solutions are used in a manner analogous to finite element equations over each of the segments.

The flows are assumed to be quasi-steady, with the salt or pollutant concentrations changing with time via the unsteady convection-diffusion equation. This restricts the model to slowly changing forcing, but permits the simulation of changes from an initial salinity distribution following changes in the forcing flows or tides, including response to a flood hydrograph.

The different analytical solutions used are described in the following sections and conditions applied at the junctions are then outlined.

2.3 Kinematic Model For Velocities

For all flow regimes, the kinematic model utilises the continuity equation in the form

$$\frac{\partial Q}{\partial x} + A_s \frac{\partial y}{\partial t} = 0 \qquad (1)$$

where Q is the volumetric discharge, y is the water depth, $A_S(y)$ is the water surface area of the segment, x is the longitudinal coordinate and t is time.

Where a sectionally averaged velocity is required it is given by

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$$V = Q/A \tag{2}$$

where A is the cross-sectional area of the segment. Non-uniform velocity calculations depend on the flow regime in the reach, as described below.

2.4 Hydrodynamic And Transport Models

Models for the different flow regimes considered are given in the following subsections.

2.4.1 Unstratified Flow In reaches of an estuary which are well mixed vertically and laterally, the well established equations of homogeneous channel flow may be used:

(i) In uniform steady flow in a wide channel, the depth, y_O, and the average velocity, V_O, are given by

$$y_o = \left(\frac{q^2 f}{8gS_o}\right)^{1/3} \qquad V_o = \frac{q}{y_o} \tag{3}$$

where q is the discharge per unit breadth, f is the bed friction factor, g is the acceleration of gravity and So is the bed slope. If necessary, the velocity distribution over the depth may be described by a seventh-power law or another boundary layer expression.

Depth-averaged pollutant concentrations, C, are then found from the depth-integrated convection-diffusion equation

$$\frac{\partial C}{\partial t} + V\frac{\partial C}{\partial x} - K\frac{\partial^2 C}{\partial x^2} = 0 \tag{4}$$

where the longitudinal dispersion coefficient, $K = 6V\sqrt{f/8}$. The solution of equation(4) for steady flow is

$$C = C_o\left(1 - e^{x/a}\right) \tag{5}$$

where $a = Ky/V$. Solutions may be superimposed to accommodate multiple sources. Alternatively, equation (4) may be solved by finite differences using velocities and depths from the hydrodynamic solution. Finite difference solution for each segment is required if V is not the same in all segments, which is the usual case.

(ii) In uniform steady flow in a general prismatic channel, expressions equivalent to equation (3) are available for a range of channel shapes (Chow, [2]). Fischer *et al* [4] give expressions for K for channels of arbitrary cross-section and for estuaries in which tidal motion affects the coefficient in the tidally-averaged form of equation (4). Equations (4) and (5) are unaltered in form.

(iii) For a uniform rectangular cross section with linear friction, tidally forced at one or both ends, Ippen and Harleman [14] provide equations which replace equation (3).

(iv) For a tidally forced basin connected to the sea by a short channel, Glenne *et al* [5] provide an equation to replace equation (1).

For all other cases data on water levels must be provided, then equation (1) is used to solve for V as in section 2.2.

2.4.2 Salt Wedge There are several solutions for the form and dimensions of the salt wedge. The model described in section 3 used the equations of Keulegan [15] for the salt wedge length and that of Farmer and Morgan [3] for the interface profile. While these equations are widely used, it is believed that the following equations are slightly more accurate (Hinwood, [9]).

The depth of the salt wedge at the sea, *do*, may be found in terms of the upstream densimetric Froude number, $F_o = V/\sqrt{gD_o\,\Delta\rho/\rho}$:

$$d_o = D_o\left(1 - m F_o^{2/3}\right) \tag{6}$$

where $\Delta\rho/\rho$ is the relative density difference between the layers, and $m = 1$ for uniform flow in the upper layer and no flow in the lower layer, or $m = 0.85$ suggested for boundary layer flow in the upper layer and minor entrainment.

The shape of the interface may be obtained from the following implicit equation (Officer, [17]):

$$\frac{x}{D_o} = \frac{F_o^2 n^2}{3k}\left(1 - \frac{16}{9}n + \frac{19}{18}n^2 - \frac{8}{105}n^3 + \ldots\right) \tag{7}$$

where x is the longitudinal coordinate measured seawards from the toe of the wedge, $n = d/D_0$ is the relative depth of the salt wedge and k is an interfacial friction factor. At the sea, $d = d_0$ and $x = Lw$, the length of the salt wedge.

The velocity distribution in each layer has been assumed uniform in the example of section 3, but could be calculated from boundary layer equations.

Pollutant or salt transport in each layer may be found from equation (5) or by finite difference solution of equation (4). The mean motion of the lower layer due to entrainment has been neglected in deriving equations (6) and (7) but could be estimated using the numerical results of figure 7 of Arita and Jirka [1].

2.4.3 Partially Mixed Regimes Since the relative importance of buoyancy flux and tidally-induced mixing vary along the estuary a single analytical model is not usually adequate. Rattray and Hansen [6,7,18] recognised this. They obtained a sequence of three analytical solutions, each restricted by its own assumptions of geometry and diffusion coefficients for a stratified estuary in which mixing was significant. For application to a particular estuarine regime, they have simplified the two equations and have chosen convenient forms of the momentum and mass diffusion coefficients, as follows:

(i) In Rattray and Hansen [18] they developed similarity solutions for the seaward reach of an estuary of uniform breadth and variable depth, valid for low river inflows.

(ii) In Hansen [6] they developed solutions for the central reach of an estuary in which there is a nearly constant salinity difference from top to bottom along the reach.

(iii) In Hansen and Rattray [7] they generalised the method of (i) and obtained solutions for the central and for the inner (upstream) reaches, subject to particular functional forms for the variations of the breadth, river flow and the diffusion coefficients.

2.4.4 Surface Plumes Studies of surface plume flow over stationary underlayers are being developed for use in the model. Extensions of the present model will utilise slightly modified forms of the solutions of Stolzenbach and

Harleman [19]; more recent reviews return to this work while complaining about its assumptions.

2.5 Selection Of Regime For Each Reach

While the most comprehensive scheme of classification of estuarine flow regimes is that of Hansen and Rattray [8], it is impractical to apply in modelling since it requires advance knowledge of the downstream stratification and the flow of the entrained salt water. The scheme of Ippen and Harleman [14] is readily applied and is used here as the principal criterion. It uses the parameter G/J, which may be interpreted as the ratio of the tidal energy available for mixing to the energy required to mix the fresh water over the depth. Based on an inspection of their figure 1, the following criteria have been adopted:

$$\begin{aligned} G/J &< 30 && \text{sharply stratified} \\ 30 < G/J &< 100 && \text{partially mixed} \\ 100 &< G/J && \text{well mixed.} \end{aligned} \tag{8}$$

Once a sharply stratified flow is indicated it is tested to confirm the presence of a salt wedge by checking the densimetric Froude number at the upstream end of the reach and the (approximate) length of the salt wedge:

$$F_0 < 1 \quad \text{and} \quad Lw > 1 \tag{9}$$

If a wedge is not indicated, a surface plume is assumed and similar tests to equations (9) are made. If a surface plume is not indicated a two-layer exchange flow is assumed.

2.6 Treatment of Junctions between Reaches

At junctions of reaches, mass and energy conservation rules are applied. The water levels of each reach at a junction are made the same. For low speed flows or where the speed in each reach is the same, this is equivalent to conservation of energy. This assumption does not generally restrict the applicability of the model.

The sums of the fresh water and salt water inflows to the junction are made equal to zero. If more than one reach at a junction is stratified, the salinities of the bottom waters are made the same in each reach, and equal to the maximum at the junction. A corresponding condition is applied to the surface waters.

2.7 Computational Procedure

To establish a model, a file of segment dimensions and coefficients within each reach is created. A file of reaches made up of these segments is then defined and the expected flow regime is entered for each reach. The selection of both reaches and segments is critical to the efficient operation of the model. Selection is based on "natural" divisions considering both hydrodynamics and geomorphology (McLean and Hinwood, [16]). The ordering of the file of reaches defines the sequence of computation, which is up the main stream from the sea in the cases studied to date.

Computations are started by entering the forcing river flows and sea level data to calculate the sectional-average velocities. The first pass of the main computations solves for the salinity distributions using the expected regimes. For this step the junction relations are defined; for the example in section 3 this was done for each junction individually but the process has been made part of the model software. At the end of this step, the regimes are reassigned if necessary, and the computations repeated. Time is advanced and the sequence repeated as required.

The kinematic and transport models use first order forward time differences and upwind spatial differences. A test based on Courant number and another on rate of change of variables are applied to check that conditions for accurate solution are met and, if not, execution is terminated.

2.8 Attributes Of The Model

The attributes of the model have been discussed in Hinwood and McLean [10], but in summary are as follows:

- The model is able to obtain salinity values within each estuarine segment with sufficient accuracy for assessment of water use and ecological impact.
- The output is at temporal and physical scales compatible with data generated by other disciplines and can be readily integrated into multidisciplinary studies.
- The model may be run interactively on a basic personal computer.
- The initial segmentation and setting of limits of validity are critical and require expert input.
- After its establishment the model may be run by managers and others not expert in modelling or hydrodynamics.
- The model is robust and includes traps to prevent use outside its range of validity.

3. Application To The Snowy River Estuary

3.1 Model Schematisation

The general model discussed above was set up for the Snowy River Estuary, selecting reaches and flow regimes from field data. The model was developed to provide an interactive tool to enable planners to gain maximum information from the data collected in a field study of the Snowy River estuary (Hinwood *et al*, [13]). The estuary, shown in figure 1, is complex with two tidal lakes, tidal lagoons and three stream inflows. Under low to moderate flow conditions there is a salt wedge in the upper Snowy River, while the Brodribb River and Corringle Creek are well mixed except near slack water. There is a weak surface plume in the lower Snowy river but this was approximated as a well mixed reach in the model.

Field data on bathymetry and sediments were used to identify significant geomorphological boundaries in the estuary. These were then assessed for their hydrodynamic significance by reference to longitudinal profiling of salinity and temperature under varying fluvial flows into the estuary. It was observed that, noticeable changes in estuarine configuration usually coincide with changes in the processes operating in adjacent reaches. For example, the transition between the flood-tidal delta (segment q) and the mud basin (segment o) and the separation between the latter and the shallower upstream tidal channel are obvious segment boundaries where the magnitude of model flows will reflect real processes within the estuary. These locations were selected as reach boundaries and, in the case of major morphological and hydrodynamic change, location in the model segmentation for change to a different analytical solution.

While some hydrodynamic changes were coincidental with geomorphic change, others show considerable locational variation and are not reflected by

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dramatic dimensional or sedimentological change. For example, the upstream limit of salt incursion in the salt wedge (segments e to a) must be treated as a model variable with segment boundaries selected, in this case, on purely dimensional grounds. While, at the micro-level, circulation patterns in individual segments may be complex, e.g. the pattern of influx of tidal water into and across Lake Corringle, other factors, such as local wind stirring of the very shallow lake, allow it to be treated as a single segment with homogeneous properties in a model of this scale.

Selection of estuarine segments reflecting real and observable estuarine characteristics permits sensible assessment of model results, especially with reference to the suitability of regimes selected for each reach (see section 2.4). Appropriate identification of process boundaries, both sharp and transitional, in the estuary is essential for models of this type.

3.2 Model Calibration

The model was calibrated by adjusting the friction factor in the salt wedge reaches and dispersion coefficients until agreement was obtained between predicted and measured salinities. The final values of the coefficients did not differ appreciably from the values given in section 2 and the references cited there and, as both high and low water salinities were matched, there are grounds for cpnfidence in the model. Figure 2 shows the match of depth-mean salinities at high water for a verification run, made following calibration based on data from a different field trip. Again the agreement is good. The bottom figure shows the measured and simulated density differences at high tide; note that in this version of the model only the upper Snowy River Estuary is modelled as a salt wedge reach.

The model runs in less than 0.2 secs/tide cycle on an IBM 486DX, making it attractive to explore the consequences of a wide range of management options.

4. Conclusions

Most estuaries display a range of salinity regimes simultaneously at different locations. The extent of salt intrusion into such an estuary may be modelled relatively simply and very economically by the use of a parametric model.

Equations are given for several estuarine flow regimes including well-mixed flow and the salt wedge. The modelling method has been applied to the estuary of the Snowy River to predict depth-mean salinities and the upstream salt wedge profile and length.

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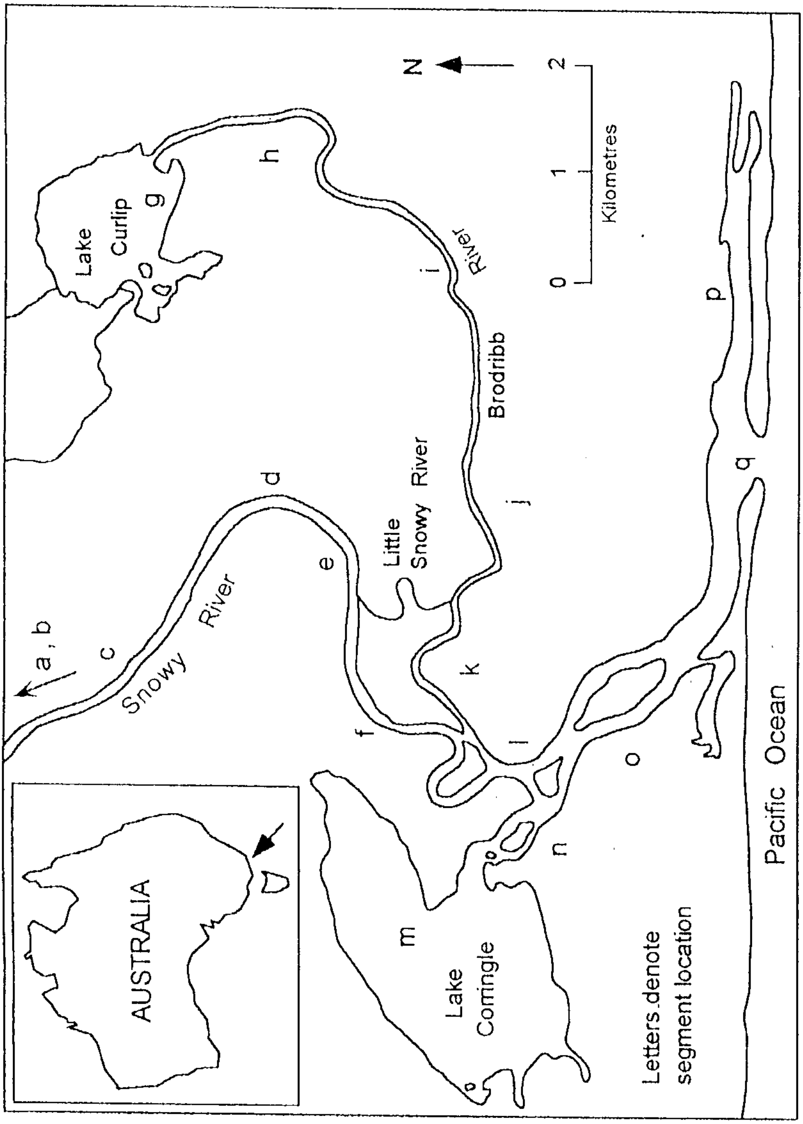

Figure 1 Snowy River Estuary showing computational segments

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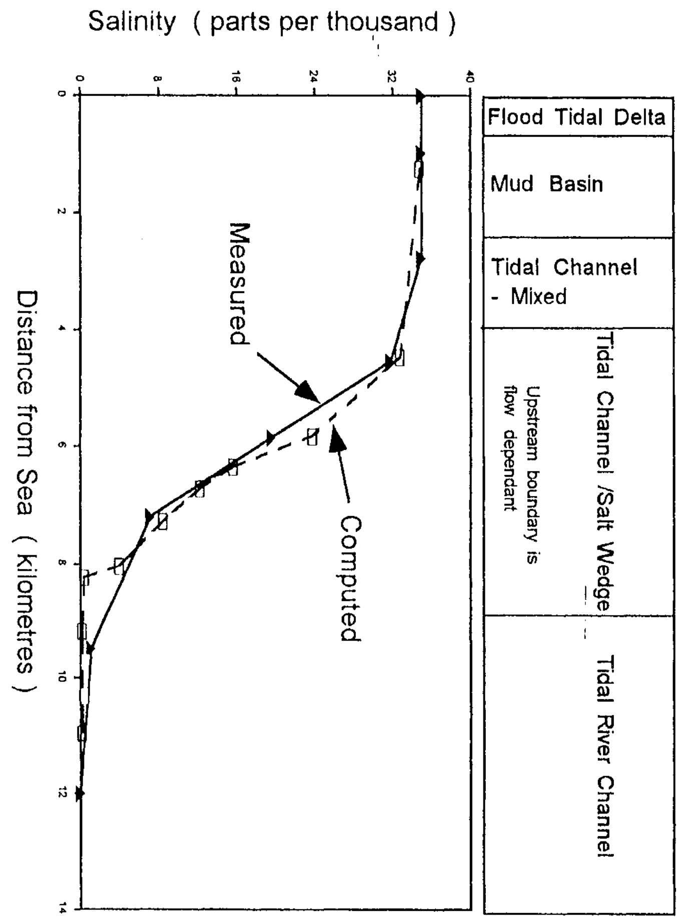

Figure 2 Longitudinal profile of depth-mean salinity for independent verification data set