Impact of Flow Reduction on Australian Estuarine Habitats

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Abstract: Australian rainfall can be highly variable and many Australian estuaries lack a seasonal pattern of freshwater flow. As a consequence, the saline structure of Australian estuaries can be highly variable as a consequence of climatic fluctuations in temporal rainfall patterns. It is during drought periods that estuaries experience the most intense intrusions of salt water from the ocean. Developments adjacent to coastal river systems impose demands for fresh water that can have significant consequences for freshwater inflows to estuaries, particularly during drought. A new approach to quantify the impact of changes to freshwater flows to estuaries in highly variable climates has been developed. The approach combines numerical simulation of estuarine saline structure with a risk assessment of changing salinity on estuarine biota. This approach has been applied to the Richmond River estuary in northern New South Wales and includes 50 year simulations of saline structure with appropriate verification against measured field data. A preliminary estuarine ecosystem risk analysis has shown that it is extreme droughts that are crucial in determining the threat to estuarine freshwater biota. This contribution describes the hydrological and estuary modelling techniques in detail; their application to the assessment of ecosystem risk; and, recent developments and application.

Keywords: Environmental Flows; Estuary; Estuarine Habitat; Drought; Salt Water Intrusion; Climate change

1. INTRODUCTION

In this paper, techniques are described which were developed to assess the impact of reduced freshwater flow on the aquatic ecology of the Richmond River estuary in northern New South Wales. The entire investigation is reported in Peirson et al. [1999] with a focussed description on the management aspects presented in Peirson et al. [2001a].

An estuary is the part of a river that is affected by tides, in which the fresh water of the river mixes with the salt water of the sea. Estuaries are important and productive regions, fostering an abundance and diversity of wildlife, as well as offering recreational and commercial values.

Alteration to the freshwater flow of rivers, through impoundment and extraction can damage aquatic habitats. It has been recognised in recent years that the competing users of this water must also allow water to flow in rivers to maintain aquatic ecosystems (so called *environmental flows*). To our knowledge, the unique needs of Australian estuaries have not previously been considered in detail.

The freshwater flows in the rivers of coastal south-eastern Australia do not follow a consistent annual pattern. In particular, the length and intensity of drought periods can vary greatly. During periods of high freshwater inflow from the estuary catchment, salt water can be flushed from the estuary. During sustained periods of low freshwater inflow, saline waters penetrate greater distances from the ocean towards the tidal limits of the estuary either as density currents or as a result of tidal mixing. This process can severely limit the habitat available to freshwater biota during long droughts.

If fresh water extractions from an estuary below its tidal limits are sufficiently high, the ingress of salt water along the arms of an estuary during periods of extended drought may be substantially increased. This may damage freshwater vegetation and substantially reduce the habitat of freshwater fish and other organisms.

Because saline structure of an estuary is dependent on the rainfall and other antecedent conditions, analyses cannot be undertaken by assuming steady flow where freshwater flows do not follow a consistent annual pattern. For reliable assessments of estuarine saline structure, historical analyses must be undertaken.

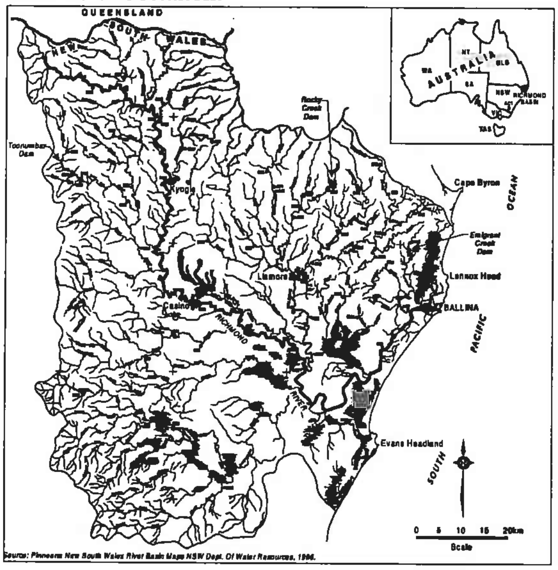

Figure 1. The Richmond River Catchment.

Initial investigations were focussed on the Richmond River catchment shown in Figure 1. The river entrance is near Ballina with the major tributaries being Bungawalbin Creek and Wilsons River. Farmers extract water from the Richmond River, Wilsons River and Bungawalbin Creek upstream of the Richmond-Bungawalbin junction under drought conditions.

The primary objective of this investigation was to assess the risks to the aquatic ecology as a result of changing extraction rates. Risk was assessed by:

1. determining the changing saline structure of the Richmond River based on varied rates of extraction of water from the estuary for irrigation; and,
2. identifying and assessing potential impact for representative estuarine aquatic ecology that are sensitive to salinity.

2. THE MODEL SYSTEM

An integrated numerical model of the estuary was developed, verified and used to undertake 58 year simulations of estuary behaviour (1940 to 1997). The integrated system was capable of reproducing the changes in longitudinal distribution of salinity in response to changing freshwater inflows and climatic conditions. The model consisted of three components which are described in turn.

2.1 Catchment Model

The AWBM model [Boughton 1993, Boughton and Carrol 1993] has been used to generate the daily freshwater inflows to the estuary from recorded rainfalls. This model was selected because it was developed in Australia and has been calibrated on a large number of catchments in Eastern Australia. For this investigation, it was used as an eight parameter model so that the baseflow due to antecedent rainfall could be determined.

AWBM is a saturated overland flow model which allows for variable source areas of surface runoff in different storms and in different periods of a given storm. Both surface runoff and baseflow components are defined. During periods of rainfall, AWBM simulates the recharge of shallow groundwater stores as well as determining surface runoff as the excess over a separate baseflow recharge. After the passing of storms, the model simulates discharge from the shallow groundwater stores, again determining surface runoff as the excess over the baseflow recharge. The baseflow storage enables dry weather discharges to be determined in terms of a daily recession constant.

Data required by AWBM are temporal precipitation and evaporation rates as well as suitable streamflow data for calibration and verification.

Approximately 60 years of reliable streamflow records were available on four representative subcatchments within the study area: the Richmond River at Casino, the Wilsons River at Eltham, Leycester Creek at Rock Valley and Myrtle Creek at Rappville. Using daily rainfall records from local stations, a mean daily rainfall depth was determined using the Thiessen method whilst a mean daily evaporation rate was derived from monthly evaporation data from Alstonville.

An AWBM model was created for each of these catchments and calibrated using the available streamflow data over the period 1990-1991 to determine optimum values for the capacities and distribution of surface stores, daily surface recession constant and baseflow parameters (baseflow index and daily recession constant). The calibration period (1990-91) was chosen as it included two floods and a prolonged drought. It was found that it was possible to tune the model to obtain good representation of either the larger flow events or the period of low freshwater flow but not both. The periods of primary interest to this investigation were sustained dry periods, so it was decided to focus model calibration on periods of low freshwater flow. A representative model calibration is shown in Figure 2.

It can be observed that the hydrograph recession rates are not always identical and the model has been tuned to reproduce an average behaviour during periods of low rainfall. Similar behaviour was observed for all model catchments.

The catchment models were verified for the period of low rainfall during 1994. This period was of particular significance as several water quality surveys of the Richmond River were conducted in that year and the data from these surveys was then used to calibrate the salt dispersion model.

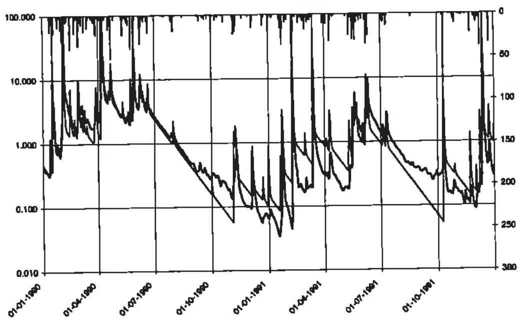

Figure 2. AWBM Model Calibration for the Wilsons River at Eltham. Histograms from top indicate catchment rainfall, the heavy line indicates recorded streamflow and the lighter line indicates AWBM estimates. The scales are rainfall depth on the catchment where 1mm of rainfall=$2.5m^3.s^{-1}$

For the ungauged catchments, two methods were used to estimate runoff. The model values for the calibrated and verified catchments were used to estimate appropriate values for other catchments of similar size and slope in close proximity. In the coastal, swampy catchments, values from Boughton [1993] were used to configure the model.

Once this process was complete, freshwater flows from all catchments were generated for the period 1940 to 1997 as inputs to the hydrodynamic and salt transport models.

2.2 Hydrodynamic Model

The numerical models to simulate estuary behaviour are two components of the Resource Management Associates (RMA) suite. Both components have used an identical one-dimensional mesh using appropriate junctions where necessary.

The estuarine flows have been simulated using the finite element model *RMA-2*. When restricted to one-dimensional elements, this model simulates unsteady free-surface flow in prismatic channels. The key equations in the solution are:

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}\right)-\frac{\partial}{\partial x}\left(\varepsilon_{xx}\frac{\partial u}{\partial x}\right)+\frac{\partial p}{\partial x}-\Gamma_x=0 \qquad (1)$$

a *momentum* equation in which t is time, x is distance along the estuary, ρ is the water density, p is pressure, ε_{xx} is a turbulent exchange coefficient and Γ_x are the local surface boundary stresses, and,

$$\frac{\partial(uA)}{\partial x}+\frac{\partial A}{\partial h}\frac{\partial h}{\partial t}=0 \qquad (2)$$

a *continuity* equation where A is the cross-sectional area and h is the depth.

Within the Richmond system, cross-sectional area varies gradually and the convective accelerations are not strong. Consequently, the model was insensitive to changes in ε_{xx}.

Wind forcing was neglected and the primary fluid boundary stresses are due to bed friction (represented by Manning's n, more details can be found in King, 1998), thus:

$$\Gamma_x=-\frac{\rho g|u|n^2}{uh^{1/3}} \qquad (3)$$

The model geometry was established from a 1980 hydrographic survey of the river. Representative estuary cross-sections have be determined using the techniques developed for the Tamar estuary by Nittim and Peirson [1987]. In this model, each cross-section is represented by the mean width at mid-tide and a mean hydraulic depth. This allows a simple representation of the estuary cross-sections to be adopted whilst preserving the internal volume of the estuary and the phase speed of the tide along the channel.

The mesh developed for this investigation is shown with annotation in Figure 3. Boundary conditions have been applied to this mesh to represent the ocean and freshwater inputs to the model for the major tributaries. For those catchment inputs located at the upstream boundaries of the RMA model, freshwater inputs were defined as upstream boundary flow hydrographs. The remaining AWBM catchment inputs were input as element inflows at the appropriate locations.

The hydrodynamic model was calibrated against a tidal gauging obtained on 3 November 1994 with a 0.25hr model time step and configured with the recorded freshwater inflows at the tidal limits and the recorded tide at the ocean boundary. The total length of the Richmond River estuary is approximately 110km and during the gauging, measurements were made at approximately 10 points within the system. The model was calibrated by varying the roughness along the tidal channel. At the conclusion of the calibration process:

- recorded tidal ranges were replicated to within 0.1m for a ocean tide range of 1.5m;
- total tidal prisms were replicated to within 12% where the total prism was greater than 2×10^6m3; and,
- tidal lags through the system were reproduced to within 30 minutes with a lag at the tidal limits of up to 6 hours.

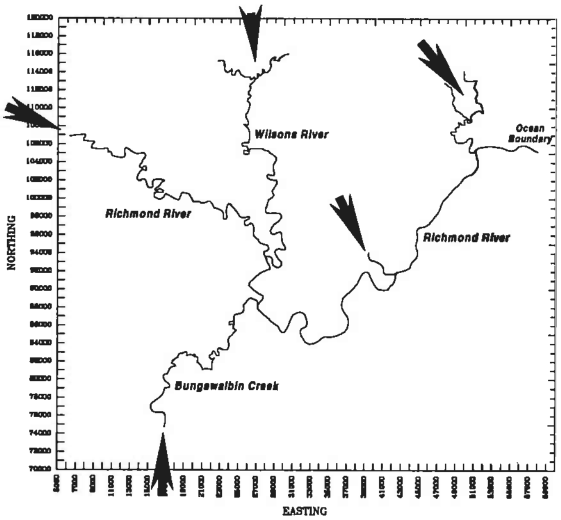

Figure 3. Finite element mesh for the Richmond River investigation. Arrows indicate locations of significant freshwater input.

2.3 Salt Dispersion Model

Salt dispersion within the estuary has been simulated in the companion water quality model RMA-11 (King, 1999). Salt transport is simulated using the flows computed by RMA-2 with diffusivities used to simulate salt dispersion being specified for RMA-11. RMA-11 is capable of simulating more complex water quality interactions if required. The equation solved is a one-dimensional form of the advection-diffusion equation:

$$A\frac{\partial S}{\partial t}+Au\frac{\partial S}{\partial x}-\frac{\partial}{\partial x}\left(D_{xx}A\frac{\partial S}{\partial x}\right)=0 \qquad (4)$$

where S is the salinity and D_{xx} is a turbulent diffusivity. The boundary conditions applied were 35psu at the ocean boundary and 0psu for all freshwater inflows.

The computational times required for the long-term simulations required that a model time step of a least a day be used. Consequently, calibration of the water quality model using a short time step that incorporates tidal motions would be inappropriate. RMA-11 calibration has been undertaken in comparison with the salinity structure observations obtained during 1994 on a time step of one day. The ocean boundary level at the downstream end of the model was represented by a constant tailwater held at approximately the high tide level.

Field measurements had shown (Eyre and Twigg, 1997), that the estuary does not exhibit strong vertical stratification except during periods of strong freshwater inflow. As periods of low freshwater inflow are of primary interest during this investigation, the model system used has neglected stratification effects. The well-mixed state indicates that boundary friction resulting from tidal flow is the dominant process determining mixing during periods of low flow in the Richmond system.

Because tidal excursions were not simulated explicitly, tidal mixing was simulated by using higher dispersion coefficients with a fixed tailwater level at the river mouth (0.79mAHD). The calibration of the model has been undertaken using a varying dispersion coefficient to account for the changing geometry and tidal flushing of the system. Following Elder [1959], we have used:

$$D=\alpha U_{max,tidal}h \qquad (5)$$

where $U_{max,tidal}$ is the maximum tidal velocity occurring in a given reach (determined from the hydrodynamic calibration), h is the mean hydraulic depth and α is a coefficient. A single value of α=15 has been used for the entire model with diffusivities ranging from approximately 4.5m2s-1 at the headwaters to 42 m2s-1 at the mouth. This has been calibrated to achieve the best match between the model and the observed longitudinal salinity structure during 1994. The progression of salt along the estuary during 1994 in the model is shown in Figure 4.

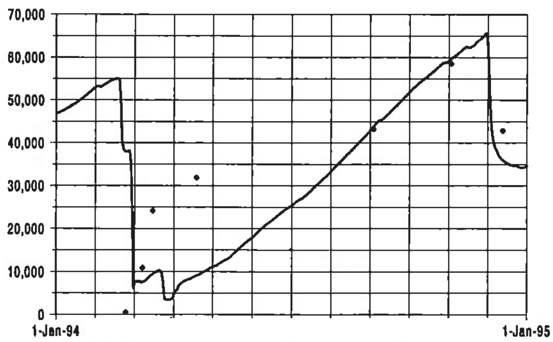

Figure 4. Comparison of measured and modelled saline excursions in the Richmond River during 1994. *Top panel*: Mean rainfall (mm). *Middle panel*: Mean flow depth (mm). *Lower panel*: measured position upstream of the mouth of the 0.2psu isohaline is indicated by the diamonds and the model result by the solid line.

It can be observed that salt intrusion after fresh events is underestimated by the model. This is a consequence of the stratified behaviour of the estuary. Density currents associated with the more dense ocean waters penetrate along the bed to transport saline waters upstream. Such behaviour can be represented by more sophisticated stratified flow models (for example, King 1993) but is beyond the capability of the simple model used here.

Once the estuary becomes vertically homogenous, the diffusion of salt from the ocean is adequately represented. However, it proved impossible to reproduce the measured spacing of the isohalines in the model. This may be a consequence of the effects of saline density currents following major fresh events on the estuary or interactions with adjacent groundwater systems, swamps and wetlands.

Higher salinities (>10psu) are generally restricted to the most downstream reaches of the estuary where irrigation is less likely. Consequently, it was decided to calibrate the model to reproduce the rate of upstream movement of the 0.5psu isohaline. It is to be noted that, at 0.5psu, model response to the small fresh event in late 1994 is quite good although the seaward excursion is approximately 5km too high.

3. APPLICATION

Representative modelled salt distributions for existing and a proposed future scenario over the assessment period are shown in Figure 5. These highlight the strong fluctuations in isohaline position along the estuary on time scales of months to years.

Simulations of proposed changes to freshwater extraction from the headwaters of the estuary were undertaken for a number of extraction and climatic scenarios. Notably, it was shown that increasing current extraction rates by a factor of 5 could result in salt diffusion to the estuary tidal limits during droughts approximately every 5 to 10 years.

Geomorphologists regard the last 50 years in Australia as relatively wet in comparison with the first 50 years of the past century. To investigate impacts of extreme dry weather periods upon salt intrusion, an additional analysis was undertaken for the year of 1902 – the driest year on record. The model system was used to simulate the period 1901-1902 and it was found that the landward excursion of salt during 1902 was not substantially greater than other dry events during the period 1940 to 1997 and it was concluded that the hydrological analysis undertaken for 1940 to 1997 is representative of the preceding 50 years.

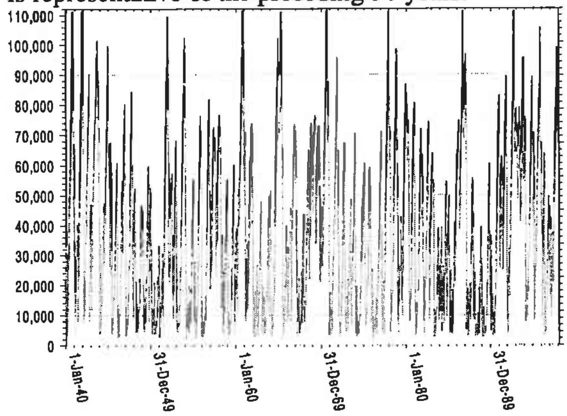

Figure 5. Intrusion of the 0.2psu isohaline to the Richmond River for the period 1 January 1940 to 31 December 1997. The grey line indicates intrusion under existing conditions and the black line indicates the additional intrusion due to increased water usage near the tidal limit.

Water loss via evaporation or evapo-transpiration by aquatic and riparian vegetation was not incorporated in these simulations. Approximate calculations indicated that direct evaporation was of similar magnitude to extractions for irrigation. These factors may require further consideration.

An assessment of risk to representative aquatic biota (vegetation, fish and platypus) was undertaken using the results of the numerical modelling with a risk index reflecting:

1. salt impact on a variety of representative biota;
2. the degree of risk to the selected representative biota; and,
3. identified high conservation areas.

In Peirson et al. [1999], simple statistics were compared in the form shown in Figure 6. Using this approach, levels of risk were established for the different arms of the Richmond River system

However, our knowledge is quite poor in relation to estuarine biota response to changes in salinity. Whilst salinity thresholds have been identified for a range of biota, they rarely include the consideration of medium to long-term chronic effects, or specifications for the time of exposure. With most toxicants, the effect on plants and animals is dependent on both concentration and time of exposure. More recently, Bishop et al. [2001] have investigated the impact of different release regimes from the Emigrant Creek dam in north-eastern NSW on estuarine ecosystems and have modelled salinity-versus-exposure 'signature' for the area of major biological change along the estuary. It remains difficult to know whether the biological change was caused by a low concentration for an extended time period (for example, 0.5 psu salinity for > 30% of the time) or a high concentration for a short period (for example, 5 psu for ~5% of the time).

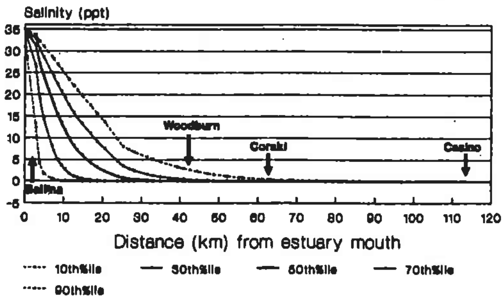

Figure 6. Salinity distributions in the Richmond River: existing condition

Based on these techniques, Peirson et al. [2001b] have developed a more general methodology for the assessment of environmental flows to estuaries based on a checklist of potential ecological impacts of reduced freshwater flows on the saline structure, mixing and water quality of Australian estuaries.

4. CONCLUSIONS

The dependency of saline intrusion to estuaries on antecedent flows makes purely statistical descriptions of freshwater flow inputs inadequate to predict variability in estuarine fresh and saltwater habitats.

In this contribution, we have described a system of hydrological, hydraulic and salt transport numerical models to determine temporal patterns of saline intrusion over a 58 year period. Careful calibration (and verification, where possible) against available field data is essential at each step. By utilising rainfall records from earlier periods, we were able to examine the potential significance of climatic impacts over a much longer period.

Recent work has examined the relationship between the spatial distribution of some estuarine species with modelled saline distributions but investigations to determine the vulnerability of species to different intensities and durations of exposure will be required. A more general and systematic methodology has been developed to enable the environmental flow requirements of Australian estuaries to be assessed.

5. ACKNOWLEDGEMENTS

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