Criteria for Selecting Environmental Flows in Estuaries with Application to the Snowy River Estuary

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Abstract: The Snowy River is one of Australia's most important rivers, with a large flow, part of which is diverted for hydro power and inland irrigation. Environmental flows in the riverine reaches have been developed on criteria including provision of a diversity of fish habitats and maintenance of sediment bed forms. The hydrodynamic regime in an estuary is very much more complex than that in a river, with a range of salinity distributions and current patterns possible. Changes to these regimes depend on both river flow and tidal currents, with the governing dimensions of the channels subject to change as a result of tides, floods and coastal processes. Formal consideration of the environmental flows in the estuarine reaches dates back to the 1980s when extensive diversions of the river flow near the head of the estuary were contemplated. These and more recent studies have focused on a requirement to limit the upstream extent of salt wedge penetration and have not paid adequate attention to the range of beneficial uses of the estuary. The strategy proposed here parallels that for the development of criteria for fluvial environmental flows: define the beneficial uses to be preserved, determine the physical factors which directly and indirectly impact these uses and define a flow regime which will protect these uses. To specify conditions over a reach or major estuarine segment the salinity regime provides a compact description and one amenable to measurement, modelling and prediction. Prediction of the regime present in a given case may be made by modelling and/or field study, or more crudely by using one of several classification schemes based upon ratios of dynamic terms in the equations of motion. The procedure is illustrated by preliminary application to the Snowy River, which has been the subject of a field and modelling study. This procedure leads to criteria additional to the maintenance of a minimum flow designed to restrict the upstream penetration of a salt wedge.

Keywords: Decision support system; Tidal inlet; Model; Hydrodynamic model; Environmental flow, Snowy River; Salinity intrusion

1. INTRODUCTION

The term "environmental flow" has been in use for about 20 years to describe a low river flow below which significant changes in the environment will occur. It was generally presumed that such changes would be undesirable. The environmental flow has been defined in many ways in the literature, for example, in the case of the Snowy River in 1988 the brief for the Snowy River Hydrodynamic Study (Department of Water Resources Victoria) used the minimum 7-day average flow causing no long term impact.

Soon after introduction of the term, the concept was widened to consider limiting flow regimes rather than a single flow and to consider impacts on net sediment transport and water quality in addition to the biological environment. More recently, the term has included consideration of flushing of saline drainage and indirect impacts on biota through changes in habitat such as bed form and river snags [Gippel and Stewartson, 1995].

The minimum water use was specified so that water could be used for agriculture, industry or export to other catchments and other commercially valuable uses. The ecologically viable flow was seen to safeguard the ill-defined or poorly understood beneficial uses while giving maximum water resource to the commercially valuable uses. This does not provide a point of decision at which the benefits from all uses may be compared and evaluated. Hence, swings in government policy or community pressures may result in poorly informed decisions which jeopardise key beneficial uses.

Although this concept has proved useful in the fluvial case, the extension to estuarine conditions is difficult for two reasons. First, because the independent action of the tides and coastal processes means that river flow is not the sole determinant of flow conditions. Second, the links between the physical regime and the beneficial uses are generally more complicated. Typically, in the estuarine case, the maximum velocity, mean velocity, mean salinity and salinity range all affect the water quality, sediment transport and the biota. Their temporal and spatial variability will also be important. In the next section of this paper, criteria for estuarine environmental flows are developed by consideration of beneficial uses and the physical factors that impact these uses. These criteria are then applied to the Snowy River estuary, one of Australia's largest rivers with great economic and conservation values.

2. CRITERIA FOR ESTUARINE ENVIRONMENTAL FLOWS

2.1 Beneficial Uses

The strategy followed here extends that for the development of criteria for fluvial environmental flows: define the beneficial uses to be preserved, determine the physical factors which directly and indirectly impact these uses, define a salinity regime which will protect these uses and determine a river flow which will maintain this regime. Beneficial uses for an estuarine and coastal zone have been considered by the Texas Water Development Board [2001]. They aimed to define the stream inflow quantities and water qualities to produce an "ecologically sound and healthy Estuary", and considered as beneficial uses a number of recreational and commercial fisheries. For each beneficial use the environmental conditions were determined by research programmes. Other commercial uses were not considered in this major study. Existing guidelines for coastal water management in Australia (eg EPA NSW, 2001) set out principles for application to all estuaries in a region. These focus on perceived issues, in the absence of adequately defined thresholds for ecosystem function, and do not address the consequences of different salinity and flow regimes within an estuary and between estuaries. This is now receiving attention within a number of government agencies, where the concept of water sharing between users is the subject of considerable effort.

The beneficial uses commonly present in an estuary and some of the physical factors affecting them are indicated in Table 1. This is a restricted list and is intended to be indicative only.

The physical factors are point measures with temporal variability covered by the range variables. Spatial patterns are also very important and are considered later in this section. The water quality variable is in some sense an aggregated measure, and is itself determined by physical factors such as the velocity and salinity patterns within the estuary.

Table 1. Beneficial uses of estuarine waters and physical conditions required for them (y - yes, n - no)

Beneficial Use	Salinity		Velocity		Water Quality
	Mean	Range	Minimum	Range	
Recreational fishing	(y)	n	(y)	y	y
Recreational boating	n	n	n	(y)	y
Swimming	n	n	(y)	y	y
Tourism	n	n	y	n	(y)
Bank vegetation	y	y	(y)	y	y
Bank stability	(y)	(y)	n	y	(y)
Estuarine ecosystems	y	y	y	y	y
Estuarine wetlands & ecosystems	y	y	y	y	y
Commercial port	n	n	n	(y)	y
Passage of sediment	n	n	y	y	n
Passage of flood flows	n	n	n	y	n
Water extraction for agriculture	y	y	(y)	n	y
Water extraction for other uses	y	y	(y)	n	y

2.2 Spatial Patterns – Estuarine Salinity Regimes

In an estuary, the salinity, velocity and water quality, and all the quantities which depend on them, vary widely over the depth and from place to place through the tide cycle and with variations in the river flow. Most beneficial uses will be affected by these variations, hence a full specification of conditions at a point would state the tidal or diurnal mean and range under a representative set of conditions such as dry weather inflow, fresh and flood inflows. It is then necessary to condense the information obtained for a range of spatial points, time instants and hydrodynamic conditions.

The first description uses a classification of salinity regimes while the second uses selected salinity distributions, eg the longitudinal distributions under dry weather flow and those under median flow. The second description is applied to the Snowy River in the next section. The salinity regime provides a compact description amenable to measurement, modelling and prediction. In a narrow estuary the principal salinity regimes are sharply stratified/salt wedge, partially mixed and well mixed [Pritchard, 1956]. Prediction of the regime present in a given case may be made by modelling and/or field study, or more crudely by using one of several classification schemes based upon ratios of dynamic terms in the equations of motion. A simple but widely applicable method is that of Ippen and Harleman [1966]. It uses the ratio G/J, defined as follows, to classify salinity profiles.

G = rate of tidal energy dissipation
J = potential energy input to the estuary

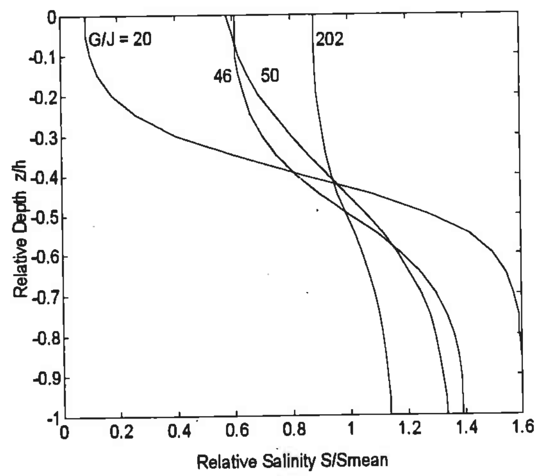

Figure 1. Vertical salinity distribution for a range of G/J [after Ippen and Harleman, 1961].

These parameters are known functions of the estuary dimensions, hydraulic roughness, stream inflow and tidal range. As shown in figure 1, for G/J < 40 the flow is sharply stratified with little vertical mixing and salinity intrusion dominated by density effects. At the other extreme, for G/J > 100 the flow approaches vertical homogeneity and is dominated by mixing. Estuarine salinity and flow patterns in wide embayments or lagoons may differ and require additional classification parameters, such as the ratio of wind mixing to tidal mixing, but these extensions are readily added to the present scheme. With a knowledge of the salinity stratification the estuary type described above may be selected, providing a comprehensive indication of the overall salinity distribution and the velocity patterns throughout the reach experiencing this regime.

2.3 Assessment of Environmental Flows and Other Management Options

To apply the knowledge of the estuary to the maintenance of the beneficial uses requires two steps. The first is consideration of which salinity regimes meet the conditions in table 1 (or the more complete velocity, salinity and water quality conditions which may be developed for any given beneficial use). The second step is the assessment of which river inflow, and other management options will provide the required regimes.

In the first step of evaluating which regimes are required knowledge is often limited and conflicts between requirements of uses arise. For example, maintenance of a recreational fishery for marine species will require a mean salinity close to that of sea water with a low range and clear water of high purity; just how saline and how pure is generally not known. A well mixed or partially mixed estuary would provide only a limited volume of habitat of suitable salinity, whereas an estuary with a salt wedge extending upstream from the entrance would provide a long wedge of sea water into which food detritus would settle from the upper brackish layer. The upstream tip of the salt wedge provides known fishing spots in the Snowy River.

Maintenance of a recreational fishery for estuarine species, on the other hand requires salinities between fresh and sea water - ideally with a longitudinal gradient from sea water to fresh - with wide tidal and seasonal ranges and generally lower water quality being tolerated by most species.

Management options for an estuary may include:

- *Changes in river inflows,* including reduced flows because of upstream extraction, changed probabilities of flows due to changes in catchment land use or releases from storages;
- *Changes in entrance restriction,* due to shoaling, dredging or training works, and affecting tidal and salt water penetration;

- *Changes in tidal basin,* and hence in water exchange and salt water penetration, due to reclamation of wetlands, construction of canal estates or conversion of tidal wetlands to freshwater wetlands.

Prediction of future or possible conditions within the estuary is essential to enable assessment of the impacts of the different management options on the beneficial uses. Description of future or possible conditions in the estuary requires modelling and then classification of the computed flows and salinity distributions.

3. APPLICATION TO THE SNOWY RIVER ESTUARY

3.1 General Description

The Snowy River drains a catchment of 13,700 km^2 of largely uninhabited, forested gorge country in the Great Dividing Range of south eastern New South Wales. Over the last 24 km to the coast the river passes through rich alluvial flats where it is joined by the smaller Brodribb River via the tidal Lake Curlip and by Corringle Creek – Lake Corringle. The two lakes are connected to the main estuary by a system of branching channels. This complex geometry results in a number of identifiable reaches each with its own morphodynamic and salinity regime.

In 1965 the Snowy Mountains Scheme (SMS) commenced diversion of water from a small but productive portion of the catchment, modifying the statistical distribution of discharges, particularly low flows. Development proposals for the region and an awareness of the extent of the impacts of the SMS have led to improved determinations of the environmental flows for the fluvial sections of the Snowy River and to recommendations to change the regime of water releases from the SMS [Snowy Water Inquiry, 1999]. Formal consideration of the environmental flows in the estuarine reaches date back to the 1980s when extensive diversions of the river flow near the head of the estuary were contemplated. These studies focused on a requirement to limit the upstream extent of salt wedge penetration and hence concentrated on low flows.

3.2 Beneficial uses

The present beneficial uses of the Snowy River Estuary are:

- Recreational fishing (marine and estuarine).
- Recreational boating (small motor boats).
- Swimming, usually very near the sea.
- Tourism, camping and a few holiday cottages and motel units.
- Bank vegetation - primarily for bank stability.
- Estuarine ecosystems – little attention, focus has been on wetlands and fish habitat.
- Estuarine wetlands - state-wide issue of degradation.
- Commercial port - unimportant with only 2 or 3 small fishing boats.
- Passage of sediment - there is a large intermittent fluvial supply and a large longshore marine sand transport.
- Passage of flood flows, some overbank flooding usual.
- Water extraction for agriculture - licensed extraction at several locations.
- Water extraction for other uses - not important.

This list may be regarded as a subset of the possible uses for the rivers and coastal waters of the region listed in EPA Victoria [1988] or comparable policy documents from other state or Commonwealth governments.

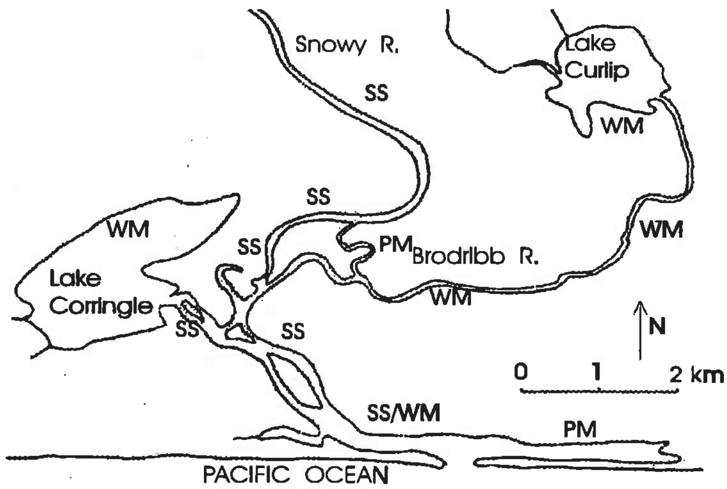

Figure 2. Snowy River salinity zones. SS sharply stratified; PM partially mixed; WM well mixed.

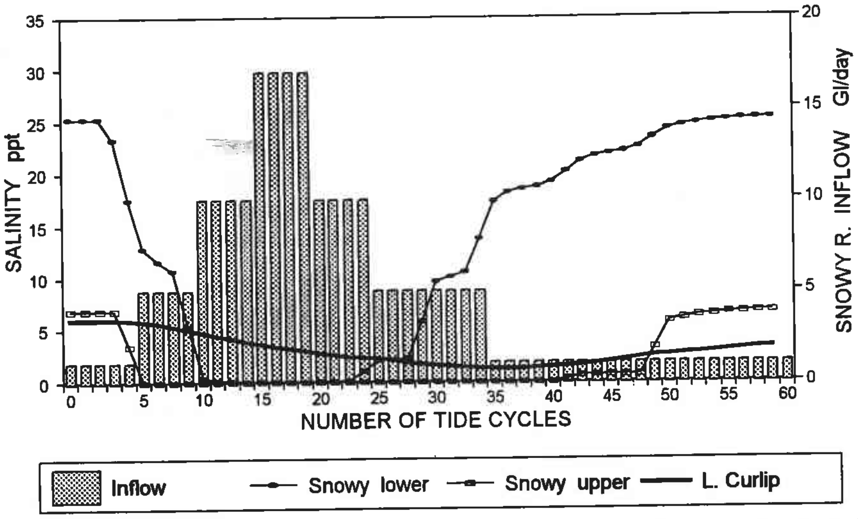

Figure 3 Salinity variation (tidal average) at selected points during the passage of a fresh inflow.

3.3 Estuarine regimes

The estuarine regimes in the Snowy River Estuary shown in Figure 2 have been determined using a simple model [Hinwood and McLean, 1996] which computes tidal flows kinematically and mixing and intrusion of saline water dynamically. Data to set up, calibrate and verify the model were obtained from published data and the study reported in Hinwood and McLean [1999].

Under dry weather conditions the Snowy River above its confluence with the Brodribb is strongly stratified containing a salt wedge. The waters of Lake Curlip and most of the Brodribb River are well mixed and brackish. Corringle Creek, the lower Brodribb River and the Snowy between the Brodribb and Marlo are sharply stratified near slack high water and partially mixed at other times, with the Snowy below Marlo being predominantly saline with a fresh surface plume during the ebb tide. Figure 3 illustrates the differences in the salinity regime in the Snowy River channels in response to two a transient high river inflow.

Model results shown in figure 4 demonstrate that under minor fresh conditions the salt wedge is pushed 3 or 4 kilometers downstream and the upper reaches of the Snowy, Lake Curlip and the Brodribb become fresh. The tidal lakes remain relatively fresh for a couple of weeks after the passage of a flood and the recovery of salinity in the river channels. The magnitude and duration of the response in the different reaches is clearly evident.

3.4 Criteria for the Snowy River Estuary

The consideration of the requirements to maintain the salinity regimes to preserve the beneficial uses leads to consideration of possible constraints on the dimensions of the entrance and on river inflows, particularly low river flows. The difficulties of resolving the conflicting requirements of the different beneficial uses are well illustrated by consideration of different management options for the entrance. To permit passage of floods and fluvial sediments and entry of sea water under normal flows the entrance should remain open. Conceptually this could be by natural means or artificially assisted by dredging or the use of training walls, entrance breakwaters and some dredging. The artificially assisted options may adversely impact the present tourism operations, but may enable other tourism activities and would benefit the commercial boating users. The enlarged entrance section, necessary for the passage of flood waters would result in greater penetration of sea water, reduction of the estuarine habitat and loss of fresh water for agriculture within the estuary. On the other hand, natural opening of the entrance requires the maintenance of flood flows with return periods of 5-20 years (the need for less frequent very large events is not established but cannot be ruled out).

To maintain the low salinity brackish wetland areas, upstream penetration of sea water in a salt wedge or partially mixed regime must be restricted. Similar requirements are set by the need to ensure fresh water in the Snowy near its tidal limit (near Orbost). These requirements could be met by provision of a minimum stream inflow coupled with maintaining the entrance opening within a specified range - too large admits too much salt water, too small raises mean water levels and increases salt penetration upstream. Alternatively, the requirements could be met more artificially by control of channel depths and cross-sectional areas and river flows. To ensure that the present fresh water extractions from the estuarine Snowy River above the Brodribb remain fresh, a salt wedge regime must be retained there. Water quality in the lower estuary depends almost exclusively on tidal exchange and hence is highly dependent on the entrance opening.

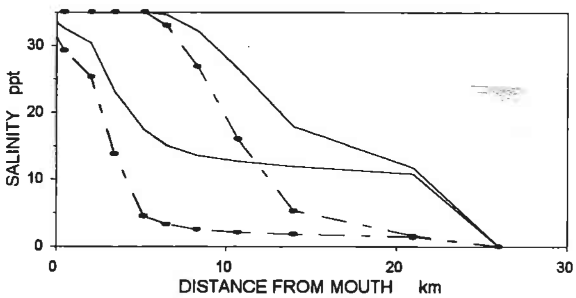

Figure 4. Longitudinal salinity profiles at high and low water under dry weather (solid line) and fresh flow conditions (broken line).

Considering all of these and the other beneficial uses, it is evident that the existing salinity regimes provide conditions suitable for the existing beneficial uses - hardly surprising! These salinity regimes may be maintained naturally by sequences of river flows which are not too different from the present, although there is clearly some latitude. This latitude may be determined by numerical modelling.

If relocations of uses to other segments of the estuary or if significant interventions such as training walls and/or dredging are permitted, then the river flows required to preserve beneficial uses may be made quite different to the present flows. The possibility of such changes depends on establishing that the required salinity regimes (and other requirements from Table 1) will occur in a reach of the estuary, by use of modelling. As with all options, there will be capital and ongoing costs associated with both the natural and the artificial options.

This qualitative discussion indicates the resolution process to establish a combination of river flows and entrance and channel management plans which will support the selected beneficial options. The additional complexity introduced by tidal and coastal processes is evident.

4. CONCLUSIONS

Conditions in an estuary depend on river flows, tidal flows and coastal processes. The roles of flood flows in maintaining entrance geometry, low flows in maintaining salinity regime and tidal flushing in maintaining water quality have been described.

A framework for the determination of an environmental flow regime for an estuary has been given, based on the following steps:

- Determination of the beneficial uses
- Examination of the flow and water quality requirements to maintain the beneficial uses
- Determination of the salinity regimes to meet the flow and water quality requirements
- Determination of constraints on river inflows.
- Consideration of other management options, if flow requirements cannot be met.

The hydrodynamic component of this decision scheme has been demonstrated to be adequately developed and validated for the Snowy River estuary. This provides the appropriate basis for the development of quantitative criteria for the assessment of all beneficial uses. In particular, the flow and salinity information provides a scientifically sound grounding for the ecological studies necessary to quantify the requirements for sustainable ecosystems.

5. REFERENCES

EPA NSW, Water Quality and River Flow Interim Objectives, http://www.epa.nsw.gov.au/ieo 26 July 2001.

EPAVictoria, State Environment Protection Policy – Waters of Victoria, *Victoria Government Gazette*, No. S13, 23 p, 26 February 1988.

Gippel, C.J. and M.J. Stewartson, Development of an environmental flow management strategy for the Thompson River, Victoria, Australia, *Regulated Rivers Research and Management*, Vol. 10, 121-135, 1995.

Hinwood, J.B. and E.J. McLean, A parametric hydrodynamic model of a complex estuary, *Proceedings of the 6th Envirosoft Conference (Envirosoft '96)*, Como, Italy, published Computational Mechanics Ltd., Southampton, 277-286, 1996.

Hinwood, J.B. and E.J. McLean, The Snowy River: A mature barrier estuary, *Proceedings of the Royal Society of Victoria*, vol. 111(2), 215-228, 1999.

Ippen, A.T. and D.R.F. Harleman, *One Dimensional Analysis of Salinity Intrusion in Estuaries*, Technical Bulletin 5, Committee on Tidal Hydraulics, Corps of Engineers, U.S. Army, 1961, or Ippen, A. T. ed., *Estuary and Coastline Hydrodynamics*, McGraw-Hill, 1966.

Pritchard, D. W. The Dynamic Structure of a Coastal Plain Estuary, *Journal of Marine Research*, 15:33-42, 1956.

Snowy Water Inquiry, 1999. Final Report, Snowy Water Inquiry, Sydney.

Texas Water Development Board, Environmental target flows, 02/03/2001, 12p, http://204.64.0.99/sbl/sanantoniobay-guadalupe/guadalupe_target_flo , 2001.