

SALINITY RESPONSE TO ENVIRONMENTAL FLOW RELEASE IN ESTUARIES

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The Snowy River in southern Australia has been impacted by flow diversion since the construction of a dam in the upper catchment, constructed between 1955 and 1967. As part of a monitoring program the effects of two flow releases were studied in 2010 and 2011. The estuarine component of the monitoring and the estuarine modelling phase of the Snowy River Increased Flows Program has been presented. The impact on the estuarine salinity distribution for the selected flow releases is reported and a subsequent modelling exercise outlined. A simple numerical model has been used to simulate about 100 events in a mature barrier estuary, from which a sequence of response types has been identified. The occurrence of each response type has been related to the duration, inflow volume and peak flow rate of the inflow event and to relevant parameters of the estuary. It has been found that the salinity changes may be classified in terms of a dimensionless “estuary flushing parameter” E , which represents the ratio of the direct flushing by the river inflow to the tidal exchange.

Keywords: environmental flows; Snowy River; hydrodynamic model; salinity regime

INTRODUCTION

The recognition that water flowing from catchments to the sea should not be regarded as a “loss”, but rather, an integral component of ecosystem function in rivers and estuaries has been a relatively recent development. To a large extent, this has been driven by increased understanding of the importance of a range of flows to normal riverine function. While environmental flows were initially viewed simplistically as a low river flow, below which significant changes in the environment would occur, it has been lately extended to include a range of critical flows which could be crudely summarized as habitat flows and channel maintenance or geomorphic flows. As their names imply, these are flow levels and durations which exceed threshold levels regarded as critical to ecosystem or geomorphic function. More recently, and perhaps recognizing the difficulties of determining these thresholds, attempts to mimic the pattern of flows in a natural stream have formed the basis of water sharing and catchment storage release programs for regulated streams (reported in Williams, et.al., 2019). This is made simpler where catchment flows are predominantly seasonal due to distinct seasonality in climate and/or snow melt dominating river regimes. Where flows are largely a response to meteorological events, this pattern is difficult to determine and inconvenient to mimic. However, it is an improvement on the more traditional practice of releasing relatively constant flows from dam storages (Gippel, 2001). Gippel offers a review of hydrological techniques and supports attempts to determine hydrological events or flows which are environmentally significant in the spectrum of biological and geomorphological responses. Because of a paucity of data for many streams these techniques often form the basis of “best practice” applications to setting environmental flows for rivers in S.E Australia.

The difficulties in determining environmental flows for rivers are compounded in the estuarine reaches of catchments where additional sets of both flow and ecological response variables are encountered. The introduction of tides and other coastal processes give rise to another set of forcing parameters independent of river flow and the gradients between river flow at one end and marine processes at the other become critical to the distribution of water parameters and biological responses. As a result, temporal and spatial variability is more concentrated over shorter reaches in the estuarine environment, leading to steep ecological gradients and a wider selection of indicator species to consider. McLean and Hinwood (2001) discussed beneficial use criteria for environmental flows and Pierson, et. al., (2002) outlined sets of procedures to establish and monitor environmental flows for general application to estuaries. However, lack of data for many estuaries has meant that “best practice” methods are often used when establishing environmental flows in S.E Australian conditions.

Estuaries are exposed to these river flows which vary naturally and from human intervention. Transient changes of inflow cause changes in the estuarine salinity distribution, which affect the biota, water quality and sedimentation. The few studies of the salinity following river inflow changes have revealed a wide range of response times and some differences in the nature of responses. Several studies have been entirely of field observations (e.g. Nichols 1977, Lepage and Ingram 1988) while a few have utilized one-dimensional numerical models, either transport only (e.g. Officer and Lynch 1981) or simple hydrodynamic and transport models. Many of the studies have really considered only one of the parameters of the flood although there are three – volume, duration and peak flow.

This paper outlines some of the steps taken in assessing the environmental flow regime for the Snowy River estuary in eastern Victoria, Australia with special reference to the effects on salinity patterns in the estuary.

THE SNOWY RIVER

The estuary chosen is that of the Snowy River (Figure 1.), a typical south-east Australian mature barrier estuary, approaching Pritchard's Coastal Plain Estuary, and hence the findings are expected to apply to other estuaries of this type. The varied channel morphology, river inflow and tidal mixing give rise to a diversity of estuarine salinity and hydrodynamic patterns (Hinwood and McLean, 1999). Ocean tides are semi-diurnal with strong diurnal inequality and microtidal range. The tidal range within the estuary is reduced via frictional attenuation through the constricted mouth. Tidal and salinity intrusion usually extend 10 km from the ocean but can extend as far upstream as Orbost, 24km from the mouth. The much smaller Brodribb River is tidal upstream to Lake Curlip as are Lake Corringale and Corringale Creek, which carry only local runoff. Under low river flows, there is a salt wedge in the upper Snowy above the confluence with the Brodribb, while lower Snowy and the other channels are essentially well mixed. At higher flows, higher than the maximum flows studied here, the salt wedge is washed downstream below the confluence of the Brodribb. Major flood flows wash the salt water out of the estuary.

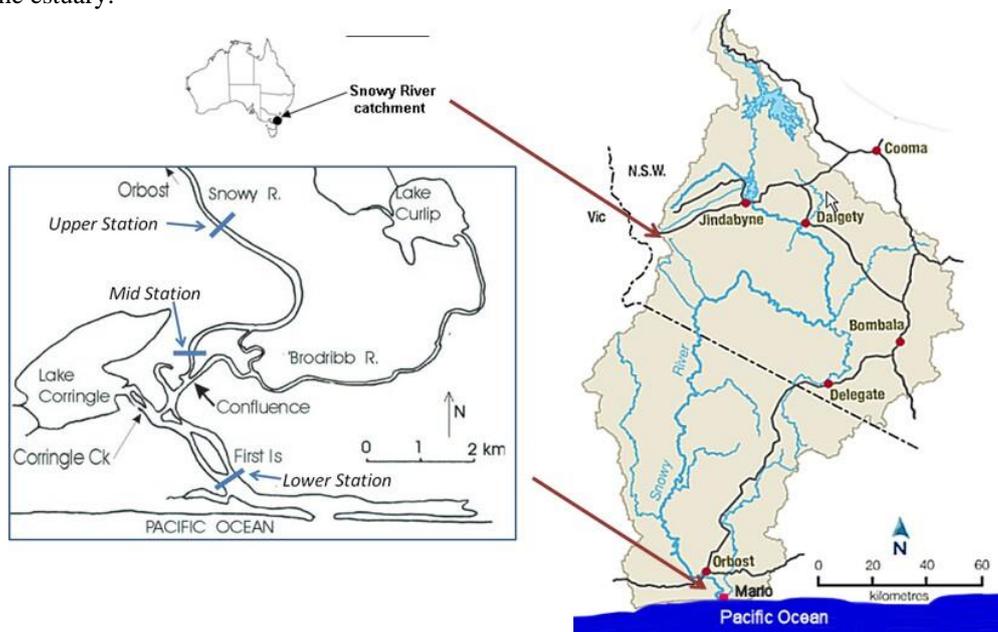


Figure 1. Map of the Snowy River and estuary. The main model stations are indicated by the bars in the estuary diagram.

The Snowy Mountains Scheme (SMS), with Jindabyne dam constructed between 1955 and 1967, diverted a significant fraction of the river's water to irrigation areas outside the Snowy catchment. Since that time, water releases from Jindabyne Dam have not been of sufficient magnitude, frequency or duration to adequately maintain the condition of the channel, including the form and dimensions of the entrance channel, as they existed prior to the Snowy Mountains Scheme. The Snowy River Increased Flows (SRIF) program was established to restore ecological and geomorphic function, mainly to the upper catchment below the dam at Jindabyne, but also to rehabilitate the lower catchment and estuary. This has been mainly through the development of an environmental flows regime to restore flow patterns to an acceptable level within the scope of the available water resources.

ENVIRONMENTAL FLOW RELEASES

Hydrodynamic and salinity regimes under different river flow and entrance conditions, previously obtained for the Snowy River estuary have demonstrated the need for datasets with a strategic mix of intensive profiling and longer-term recording. The studies reported here were planned to provide that information for the specific environmental flow releases being evaluated as part of the Snowy River

Increased Flows (SRIF) program. These two EFRs provided an opportunity to compare the influence of two fresh flows of different magnitudes on the Snowy River estuary. A more detailed examination of the two flows is reported elsewhere (McLean & Hinwood, 2015).

Environmental Flow Releases (EFRs) were made over several years to optimize the design of the EFRs primarily to achieve sediment and water quality objectives for the fluvial segments of the Snowy River. Two EFRs were specifically designed, the first to restore ecological function (2010) and the second to scour upper reaches of the river (2011). Prior to, during and following these EFRs, measurements were made of salinity distribution, estuarine water levels and the entrance cross sectional dimensions. The EFR parameters fell within the range of the modelled parameters and hence the data obtained allow a check to be made of the modelling.

Comparison of the salinity response for the two EFRs.

The discharge in each EFR rose rapidly to a peak, held the peak discharge for three days, then fell over the subsequent two weeks, rapidly at first then gradually. Assessment of the effects of each EFR was made difficult by a high antecedent flow and a minor fresh flow three to four weeks after the peak. One difference between the responses is the fact that the tributary and catchment inflows had much less effect on the larger 2011 EFR. In 2011 these inflows were just sufficient to compensate for the attenuation of the peak, which was, as expected, greater for the higher peak flow in 2011. Figure 2 shows the salinity at the upper measurement station for the 2010 and 2011 EFRs and the long profile of salinity over the main channel of the estuary.

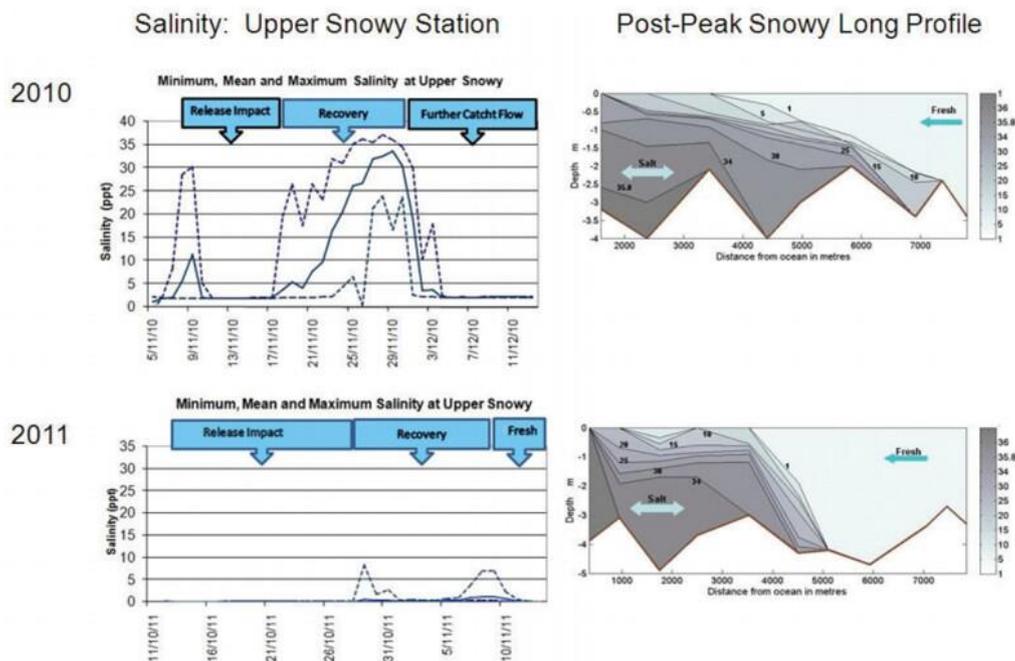


Figure 2. Salinity patterns for the 2010 and 2011 EFRs.

While the peak flow profile data provide an insight to the whole Snowy channel at high water, the temperature/salinity loggers provide a record over time at a single point. This information has been used to show the mean salinity and the salinity range which would be experienced by a sessile organism. Selected records were processed to summarise the mean, maximum and minimum salinities at key locations from a point just before the flow release peak and during the salinity 'recovery'. The variation in impact between the two EFRs can be illustrated by comparing the salinity record for the upper layer of water at the Upper Snowy station for the 2010 and 2011 releases (Figure 2.). There was a larger displacement of the saline water in 2011, corresponding with the larger freshwater volume in the release. In particular, the Upper Snowy gauge exhibited a complete washout of the brackish water and a longer period of freshwater than did the 2010 release.

The vertical profiles of salinity, obtained on a high tide on each trip in 2011, provide a detailed picture of the salinity pattern (Figure 3). The profiles have been incorporated into longitudinal sections with interpolated salinity contours.

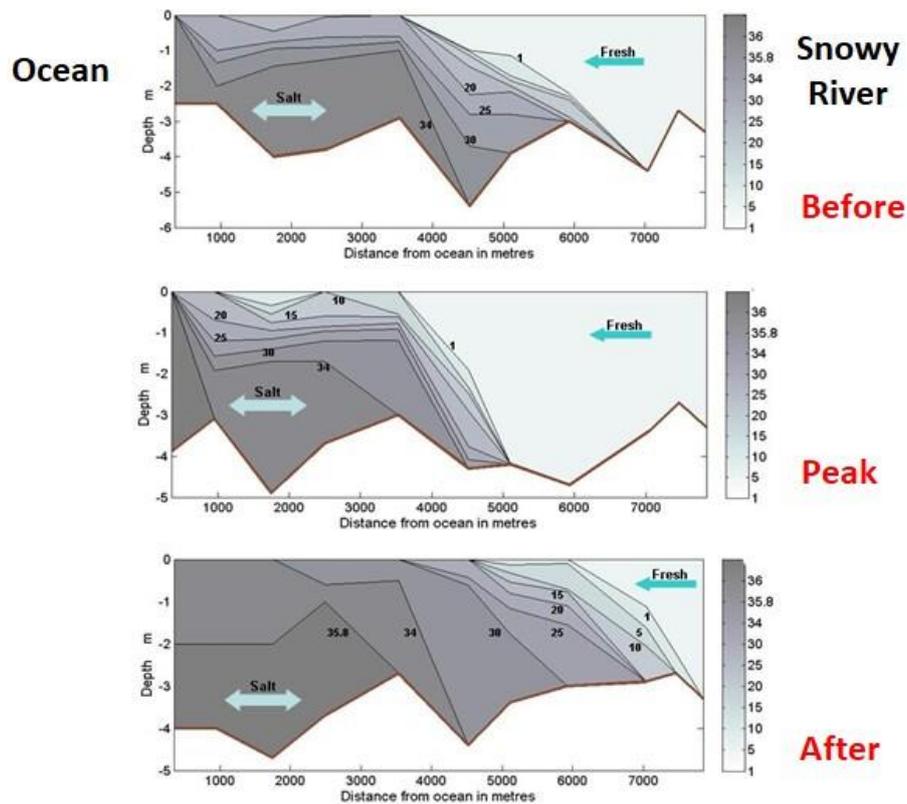


Figure 3. Long profile salinities for the 2011 EFR at stages of the flow release.

The impacts of the two spring environmental water releases on the Snowy River estuary were similar in basic effects, but the effects varied in magnitude corresponding to the different flow volumes, where the 2011 release was an order of magnitude larger than that in 2010. The effects on the salinity regime in the estuary were significant, with the increased volume of the 2011 EFR causing a markedly larger displacement of saline water in the estuary. Maximum displacement occurred around the peak of the flow releases. Recovery to pre-release salinities was similar in time frame with bottom and mid-depth salinities recovering at the same rate.

While the monitoring of the two EFRs revealed the fundamental characteristics of the shock/recovery patterns for the estuary, the need to explore the salinity regime over the range of both future EFR and natural flows for the estuary has necessitated the inclusion of modelling to the study. The occurrence of natural flows before and after the measured EFRs has also affected the monitoring results to some degree. The use of model simulations permits the examination of a range of flow events where both the catchment flow characteristics and the entrance conditions may be simulated separate from natural flows. This is especially important for the Snowy River estuary as the tributary flows will be negligible during most EFR releases down the main Snowy River channel.

THE MODEL STUDY

The numerical model, a one-dimensional parametric model (Hinwood and McLean 1996), was used to compute salinities in the estuary. The model has been verified for the Snowy River under a number of steady river inflows (Hinwood and McLean, 1996) and for several other N.S.W. and Victorian river estuaries. Model tests consisted of establishing salinities under two typical tidal and average river flows, then applying an additional pulse of water over several tide cycles. Four series of model scenarios were simulated: 2 pulse volumes, W , (7.8, 15.6 GL) each with two tidal amplitudes (0.6, 0.25m), the former corresponding to a wide open entrance and the latter to a constricted entrance (Table 1.). Each series comprised about 20 model runs with the same pulse volume but durations, T_p , ranging from 3 to 300 semi-diurnal tide cycles.

Pulse	Added volume ML	Catcht. inflow ML/d	Duration T_p tides	Tidal ampl. m
1	7,800	352 to 5288	3 to 155	0.6
2	15,600	352 to 5288	6 to 310	0.6
1A	7.800	353 to 5288	3 to 140	0.25
2A	15,600	353 to 5288	6 70 280	0.25

Model Results

The response to Pulse 1 of duration 4 tide cycles is shown for the three main channel locations in Figure 4. The inflow is shown by the black line and the salinity change resulting on the main Snowy River channel is shown by values at successive high and low tide values. The plot shows only 30 tide cycles. The ambient salinity and tidal variations for each of the stations is shown to the left of the pulse. The pulse impacts over time are clearly seen with most variation both tidally and in magnitude at the middle station. The recovery extends over the 30 tides, here without reaching the ambient salinity levels.

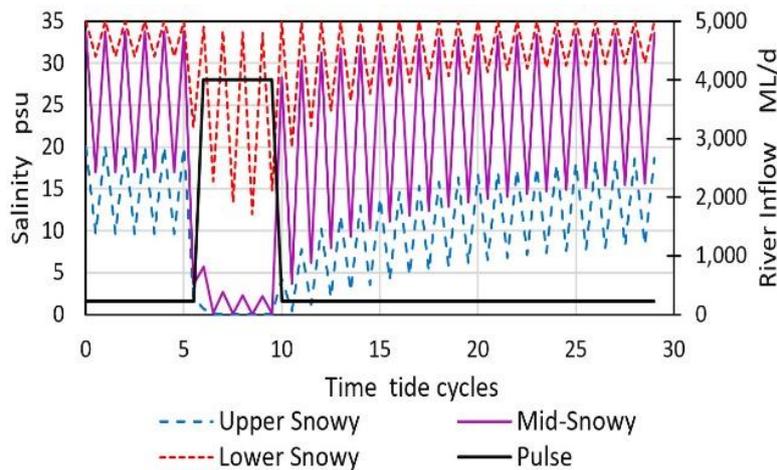


Figure 4. Inflow hydrograph for Pulse 1 of duration 4 tide cycles, with salinity histories at 3 sites along the Snowy River channel (high and low tide values).

For each model run the minimum salinity has been graphed vs pulse duration in Figure 5. Separate model runs for a given pulse volume are depicted as markers along a line for each pulse. As expected, pulses with a longer duration result in a higher minimum salinity, i.e. a lesser reduction in salinity for a given pulse volume. The zero values of minimum salinity for very short pulses indicate purging of some reaches of the estuary by the freshwater.

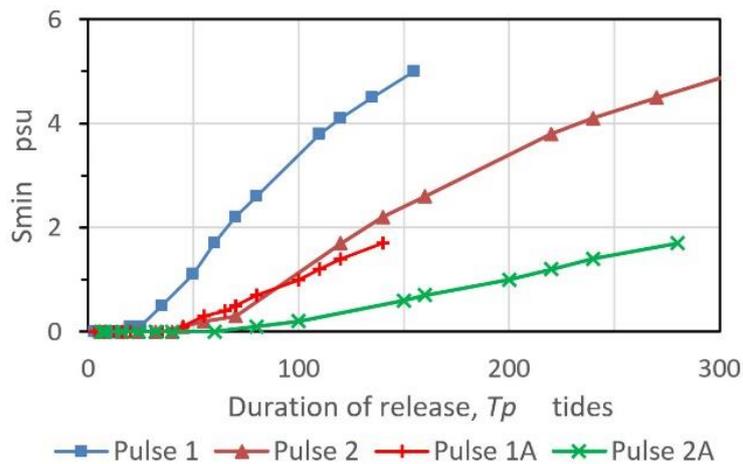


Figure 5. Salinity at Upper Snowy for all pulses.

Similar diagrams were constructed for other segments of the estuary. However, while illustrating the different responses depending on the location and connectivity down the estuary, there is a need to systematize these results as extrapolation and interpretation between these results is difficult in this raw form.

Model Data Reduction

The relevant variables and dimensionless parameters that describe the estuary and the forcing are the tidal period, T_t , the tidal prism P and the volume of water in the estuary at mean tide, W , and the river inflow, Q , being the sum of the base flow, Q_b , and the flood inflow. The flood inflow is specified in terms of its duration, T_p , and added volume, V , such that

$$Q = V/T_p + Q_{base} \quad (1)$$

A useful scale when considering flow and salinity changes is the average residence time, T_r , which is the average of the times for which water particles will remain in the estuary. Both the river inflows and tide determine the hydraulic regime within an estuary and hence determine the residence time (Oliveira and Baptista, 1997). For steady flow conditions the residence time is given by equation (2) (Officer & Lynch, 1981):

$$T_r = V_f/Q \quad (2)$$

where V_f is the volume of fresh water within the estuary and Q is the rate of river inflow, which is assumed constant.

The response may be related to parameters formed from these variables as shown in equation (3):

$$S' = \frac{(S_{min,x} - S_{base})}{S_{base}} = f \left(\frac{W}{QT_r}, \frac{W}{Q_{base}T_r}, \frac{W}{QT_p}, \frac{T_p}{T_r}, \frac{T_p}{T_t}, \dots \right) \quad (3)$$

From fairly extensive trials, we have found that the principal terms are the first four terms on the right side of equation (3). The first of these is a new grouping which we have called the estuary flushing parameter, $E = W/QT_r$. The estuary flushing parameter represents the ratio of the direct flushing by the river inflow to the tidal exchange. A small value of E indicates that river flow is dominant while a large value indicates that tidal exchange is dominant. The second term is the value of E for the base flow alone or, equivalently, a negligible pulse flow or one with a very large value of T_p .

Considering the third term on the right in equation (3), QT_p is the total volume of fresh water inflow over the flood duration, T_p and W is the total volume of water in the estuary. Thus W/QT_p is a measure of the dilution of the estuary water during a flood, neglecting exchange with the ocean. The latter condition means that this parameter is expected to be important for short duration inflows, where $T_p < T_r$ and for small estuaries. The fourth term, T_p/T_r , is the ratio of the fresh inflow duration to the response time of the estuary. Most authors (e.g. Cifuentes et al, 1990, Loder and Reichard, 1981, Officer and Lynch, 1981) have regarded the relative magnitudes of pollutant inflow duration and residence time as important but have not systematically considered their role or region of influence. This ratio is expected to be significant when $T_p \leq T_r$. The fifth term, T_p/T_t , where T_t is the tidal period, is likely to be significant only for very short pulses when $T_p \leq T_t$; this case was not considered here.

DISCUSSION

The results, as in Fig. 5, were replotted in non-dimensional form against each of the possible parameters on the right side of equation (3). The only parameter which achieved consistent relationships over the range of pulses, flow conditions and locations was the estuary flushing parameter, E . The minimum salinity for each case, S_{min} , has been normalized with respect to the base flow, S_{base} , as in equation 3. The salinity-time results have been systematized by plotting the normalised salinity against the parameter $E=W/Q*T_r$ for five representative locations shown in Fig.6. The first three locations are for the main trunk of the Snowy estuary at Upper, Middle and Lower stations while the two other stations are for tributary lakes. Lake Curlip is upstream on the tributary Brodribb River. Lake Corringle is on Corringle Creek which joins the lower Snowy River to a large tidal lake and has a very small fluvial catchment with water exchange dominated by tidal flows from the main Snowy channel.

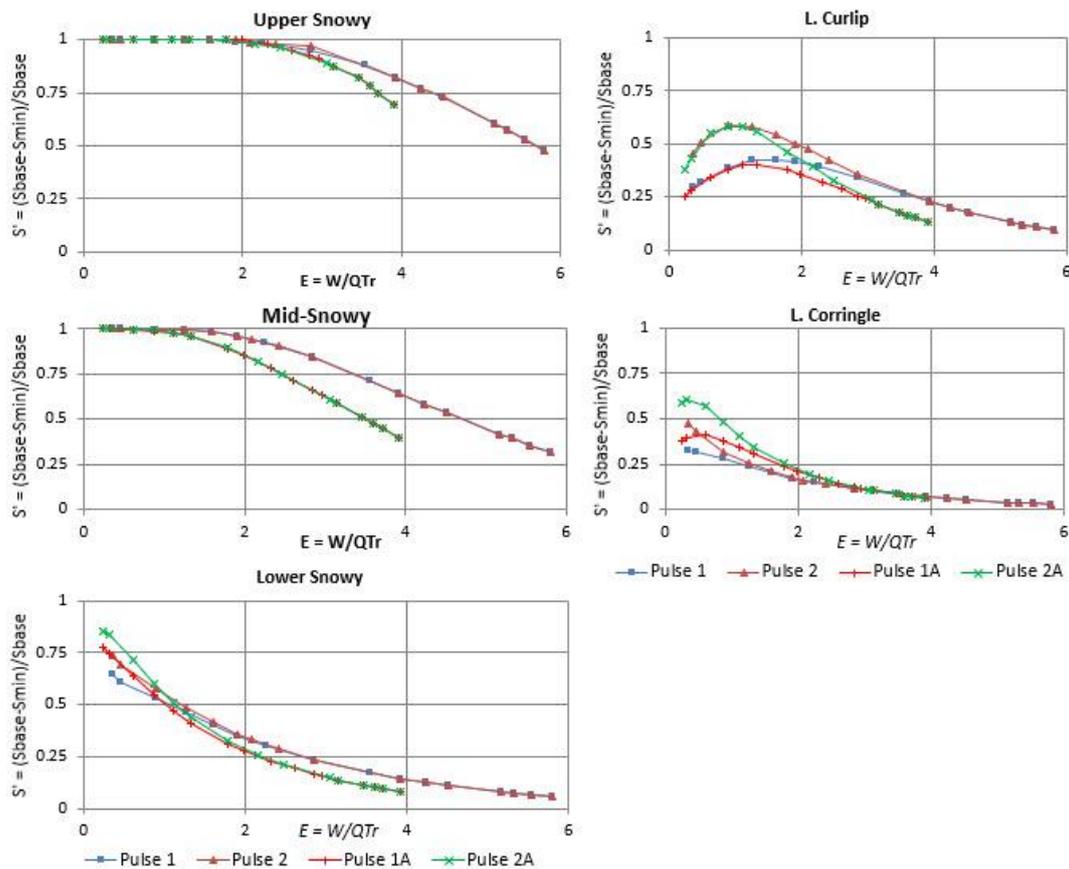


Figure 6. Minimum salinity (normalised by S_{base}) as a function of estuary flushing parameter, E . Left hand plots are for main Snowy River channel, right hand plots are for tributaries

... In Fig. 6, in all reaches the spread of the results has been greatly reduced and the data in each reach have collapsed from a separate line for each of the 4 pulses to a pair of lines. These lines now show broadly the same form in all reaches. The general form of the curves is a rapid rise in normalized salinity to a maximum (corresponding to a minimum value of S_{min}). The normalized salinity then falls gradually to zero (corresponding to no effect of the fresh) as E increases. For short pulses, in the Upper and Mid-Snowy sections, the minimum salinity was fresh water as the pulse completely flushed the brackish estuarine water seawards. For longer pulses with correspondingly lower Q and larger E values only Upper Snowy section was completely flushed. The two tributary sections are affected by a pulse with a time delay as the fresh water is transported upstream to them by tidal exchange and dispersion.

The curves in Fig. 6 show that the normalized minimum salinity also depends on two other parameters, one at small values of E ($E \leq 1$) and one at large values of E ($E > 1$). This is particularly clear for the Lake Curlip results where, with $E \leq 1$, the results depend on both E and the fresh volume and hence on W/QT_p . However, for $E > 1$ the curves switch and instead depend on E and $W/Q_{base}T_r$ (but note that W and Q_{base} were not varied in these model runs). Curves at the other stations show the same behaviour if less completely.

CONCLUSIONS

Recent advances in the development of environmental flow regimes have incorporated the idea that flow releases should attempt to mimic the natural pattern of stream discharge before regulation, but with reduced flows. Determining the impact of these reduced flows on the receiving waters is an important component in the development of any EFR method. Monitoring of individual trial releases has been shown to be of benefit for particular release levels but further exploration through the use of models, simulating releases over a range of volumes and durations, is a useful method to evaluate effective flow levels where specific objectives and outcomes are required. This is especially important for the estuarine reaches of the system where salinity distribution will have an important role in the ecological function of these terrestrial/marine transition environments. Selection of model input data

should cover the expected range of both EFRs and the natural flows to be expected under a regulated regime, especially where climate change will alter the frequency and magnitude of flows in the near future. Intelligent use of these models will depend partly on the model scenarios selected and the data reduction of the model results.

In this paper we have demonstrated a method of predicting the effects of freshwater pulse flows that has general applicability. The method uses a simple salinity transport model, but requires modelling of each estuary. This is to be expected as the simulation of a flood hydrograph – a natural pulse - requires individual modelling due to unique plan form, inflow distribution and tidal patterns.

We have shown that the normalised salinity depends principally on a new parameter, E . For $E < 1$ an additional parameter is required. The normalised salinity deficit has been found to effectively collate the salinity changes. The consistency of the $S'-E$ plots enables interpolation and limited extrapolation, reducing modelling effort.

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