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RESPONSE OF THE SNOWY RIVER ESTUARY TO TWO ENVIRONMENTAL FLOWS

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ABSTRACT: The Snowy River is a major river in south-eastern Australia, discharging to the Tasman Sea via a barrier estuary, with its entrance constricted by marine sands. Since the construction of the Snowy Mountains Scheme, river flows have not been sufficient to maintain the river channel. A program of environmental flow releases (EFR) is returning water to the river to restore the fluvial reaches and is now trialling flow regimes that may also benefit the estuarine reaches. This paper documents the response of the estuarine segments of the Snowy River to two EFRs; the release in 2010 was designed to scour the upper reaches of the Snowy River while the larger 2011 release was intended to extend the scouring downstream. For each release, the effects on the entrance morphology, tides and salinity through the flow peak and recovery are described.

Each EFR caused minor increases in depth and very minor longshore movement of the entrance channel, although each EFR had been preceded by a larger fresh flow that would have scoured the channels. The small increase in fresh water inflow in the 2010 EFR pushed salinity contours seawards and steepened vertical salinity gradients. The larger inflow in the 2011 EFR purged the upper estuary of saltwater. After the peak flow, salinity recovery was rapid in the principal estuarine channels but took weeks where poorly connected wetlands could store fresh flood waters. Critical flows for scouring the entrance and purging salinity are estimated.

Keywords: estuary, Snowy River, tidal inlet, environmental flow, tides, salinity, scour

INTRODUCTION

The Snowy River is one of the largest and most iconic of the rivers of south-eastern Australia. The largest engineering project in Australia's history, the Snowy Mountains Scheme (SMS) was constructed between 1955 and 1967 and 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. Popular dissatisfaction with this situation led to community and political action that resulted in a restoration of part of the diverted water. This restored water is to be returned to the catchment through a regimen of environmental flow releases (EFRs), the first few of which were and are being used to gain an understanding of the response of the river system to EFRs of different duration, water volume and seasonality. This paper describes the responses to two of the EFRs and provides guidance to the system managers on the effects of different EFRs on the conditions in the estuary: its hydrology and hydrodynamics, its salinity regime and its entrance morphology.

The term 'environmental flow' was coined in the late 1970s to define a river flow below which significant changes in the environment will occur. It was generally presumed that such changes would have undesirable impacts on ecosystems. The concept was then progressively widened to consider limiting flow regimes rather than a single flow and to consider impacts on net sediment transport (Konieczki et al. 1997), stream geomorphology (Gippel & Stewardson 1995), water quality and the biological environment (Kimmerer 2002; Drake et al. 2002), including the temporal availability of habitat (Stalnaker et al. 1996). The extension of this concept from fluvial to estuarine conditions is difficult for two reasons. Firstly, the independent actions of the tides and coastal processes mean that river flow is not the sole determinant of flow conditions. Secondly, the links between the physical regime and values are generally more complicated, requiring consideration of the maximum velocity, mean velocity, mean salinity and salinity range on both shock and press time scales.

The range of physical factors and beneficial uses in an estuary, and the balancing of conflicting demands, have been described by many authors (e.g. Alber 2002; Estevez 2002; McLean & Hinwood 2001) but few have then defined a regimen of environmental flows based on these uses. Two early examples are Pierson et al. (2002) who linked processes directly to potential impacts in the Tweed

River in northern New South Wales and the Texas Water Development Board (2001). In the Texas project, targeted research programs were used to link each of the beneficial uses for the different regions of an estuarine and coastal zone to the processes acting, and so were able to define the stream inflow quantities and water qualities to produce an 'ecologically sound and healthy estuary' (Montagna et al. 2002). This approach recognises that different reaches will exhibit significantly different hydraulic, geomorphic and water quality conditions.

Both environmental flows and natural floods are transient events, with the response depending on the flow sequence, the prior state of the estuary, its morphology and geomorphology. Effects are time and location dependent. There have been surprisingly few studies of the response and recovery of an estuary to a flood flow. Most field studies have measured the response of only a limited number of biological, chemical, hydrodynamic or geomorphic parameters. The pioneering study of Nichols (1977) and the later studies of Eyre (Eyre & Twigg 1997; Hossain et al. 2001) and Diez-Minguito et al. (2013) are notable for their scope and careful treatment of the data. Such detailed case studies can provide a basis for management and, more generally, guidance on the processes that must be retained in a model and those of lesser importance that may be approximated or omitted.

Previous studies of the Snowy River have largely been project driven and generally focused on the fluvial segments. Environmental flow releases to the Snowy River were made in November 2010 and October 2011 and while government studies concentrated on the fluvial segment, the present authors, with some support from government, instigated a monitoring program for the estuarine reaches. The release in 2010 was designed to scour excess sediment and algal film from the bed and banks of the upper reaches of the Snowy River, while the larger 2011 release was intended to be a geomorphic flow to extend the potential for scouring to downstream reaches. This study of the response and recovery of the estuary to the two EFRs had the following objectives:

- Assessment of the beneficial and adverse effects on the physical conditions and the environment for the biota of two EFRs that were likely to form part of future environmental flow management.
- Identification of switches in response in consequence of different EFR magnitudes, for example, purging of saltwater from a reach or significant geomorphic change.
- Provision of datasets against which numerical models can be validated.

This paper addresses the hydrodynamic and geomorphic results of the two EFRs. For each EFR, the effects on the inlet entrance morphology, tidal response and salinity fluctuations were measured at four separate times to cover the flow peak and recovery. The results of these studies are presented in terms of the hydrologic, geomorphic, hydrodynamic and salinity responses to the environmental flows. Following consideration of these shorter–term responses, the long-term response to the post-SMS catchment flow regime has been evaluated.

THE SNOWY RIVER ESTUARY

The Snowy River rises in the Eastern Highlands in south-eastern New South Wales and flows generally southward, entering the Tasman Sea in north-eastern Victoria (Figure 1). For the last 24 km to the coast, the river passes through alluvial flats forming the lower floodplain and associated terraces. The smaller Brodribb River, carrying approximately 10% of the Snowy discharge, flows via the tidal Lake Curlip joining the Snowy River approximately 4 km from the sea. Closer to the sea, the tidal Lake Corringle is linked to the Snowy River by Corringle Creek and carries only local drainage.

The coast at the mouth of the Snowy River is aligned east to west with wave exposure ranging from east through south to west. Because of the limitations of fetch, extreme storm waves are likely to result from south-easterly storms; however, the dominant longshore transport is from west to east. The estuary is a barrier type, with the entrance constricted by the barrier of marine sands, opening to a deeper and wider drowned river channel. Fluvial sediments extend along the length of the estuary bed and contemporary

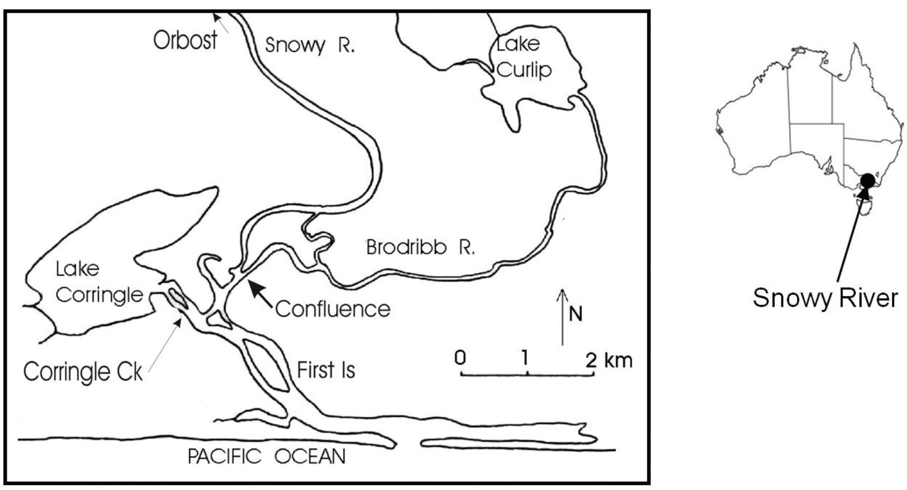

Figure 1: Location of the Snowy River and estuary.

Figure 2: The Snowy River entrance in 2011

marine sands are limited to the flood tidal delta near the mouth (Figure 2).

The entrance is formed and maintained by a combination of catchment and tidal flows with other coastal processes impacting through wave action and longshore transport, largely tending to constrict the entrance. Entrance condition, therefore, is closely related to the balance between these opposing actions and is responsive to subtle changes in this balance. This has important consequences for the internal estuarine tidal and salinity regimes.

While rainfall is distributed through the year, it is heaviest from May to December, in particular in September and October. The driest months are January to March. From 1965, the runoff from about 15% of the catchment has been captured by the Snowy Mountains Scheme and diverted out of the catchment, reducing typical and dry weather flows and the spring season snow-melt. While freshes (minor flows from the catchment) and floods due to rainfall events are of short duration, with a rapid rise and slow recession, the snow-melt high flows are typically of much longer duration.

Most previous studies of the hydrodynamics and salinity of the Snowy River estuary have been restricted in geographical or temporal extent and frequently have not documented the environmental conditions at the time of measurement. Three published studies did obtain fairly comprehensive data, although for limited ranges of river flows and entrance conditions. The first of these was the compilation of James (1989), who brought together the river discharge statistics, previous observations of salinity, and tide and cross-section surveys to provide a basis for the selection of a minimum environmental flow. The second was the set of 24-hour temperature/salinity/velocity (T/S/V) cross-sections of Hinwood and McLean (1999) measured in a low river flow. These two studies and a dozen unpublished studies made by students and staff of Monash University Department of Mechanical Engineering found that, under low river flow, the water in the lower estuary was close to seawater at all depths, the upper estuarine segment was sharply stratified for several kilometres, and the Brodribb was well mixed or slightly stratified over its length with a salinity typically 5–15 psu. Under moderate to high flows the salt wedge was washed out of the Upper Snowy and the Brodribb became much fresher. These studies showed that the salinity changes were crudely related to river flow but did not relate them to tidal range or entrance state. The third study was made to provide calibration and operational data for the modelling of selected environmental flow scenarios and included some vertical profiles and some T/S/V records, reported later by Arrowsmith and Hinwood (2011). These more comprehensive data are still limited by lack of hydrographic surveys during the three months of data collection.

Reviewing the available data on the very different hydrodynamic and salinity regimes under different river flow and entrance conditions has demonstrated the need for datasets with a strategic mix of intensive profiling and longer-term recording, and which include several bathymetric surveys. 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.

THE ENVIRONMENTAL FLOW RELEASES

Background

In the late 1990s, the New South Wales and Victorian state governments and the Australian Government agreed to return water to the Snowy River via the SRIF program.

Two spring EFRs have been delivered — a peak discharge of 3080 ML/d in 2010 and a release of 12,000 ML/d at Jindabyne in the spring of 2011, monitored by McLean and Hinwood (2011, 2012). Since then, EFRs of about 10,000 ML/d have been made in September 2012 and 2013 but have not been monitored in the estuary.

Before the SMS, the discharge of the Snowy River below Jindabyne included both rainfall and snow-melt that typically exhibited a strong season signal (Pendlebury et al. 1996; Morton et al. 2010). The spring snow-melt recession lasted for several months, and could be regarded as a press disturbance to the estuary. Snow-melt in spring from the upper parts of the catchment formed the bulk of this increased discharge, raising the base flow discharge to above 1000ML/d for six months of the year. Higher rainfall and minor snow-melt meant flows typically increased during winter, producing a second, smaller peak in July. Low flows occurred through late summer and autumn with the lowest flows in March–April. The river flows resulting from catchment rainfall typically had a rapid rise and a recession lasting for several weeks pre the SMS. The reintroduction of a spring snow-melt signal has been identified as a key component of the SRIFs to the Snowy River.

The first of the two EFRs studied was made over the period 2–12 November 2010. This simulated a spring snow-melt and comprised an additional 16.6 gigalitres, with a maximum discharge rate of 3,080 ML/d, released over four days. About a year later, the second snow-melt release was made over the period 5–24 October 2011. This release had a total of 84 gigalitres with a maximum discharge rate of 12,000 ML/d over three days. The aims of this release were similar to the 2010 EFR and included the creation of a better-defined channel between Jindabyne and the Delegate River, but added the possibility of geomorphic action further downstream.

These two EFRs provided an opportunity to compare the influence of two fresh flows of different magnitudes on the Snowy River estuary.

THE ESTUARY MONITORING

Aims

Both natural and flow release events provide a shock to the ambient conditions in the estuary. The response of the estuary to these increased flows and the nature and timing of the recovery period determine the essential characteristics that permit the location of the estuary within the available hydrologic and geomorphic classifications. There are obvious interactions and feedbacks between the geomorphology, the hydrodynamics and, subsequently, the ecology of any estuary.

The aims of this study were to document and assess the physical impacts of two EFRs of different magnitude and duration, with the second release being significantly larger and longer than the first. The response and recovery characteristics are considered under the headings of hydrologic, geomorphic, hydrodynamic and salinity responses. Specific objectives included obtaining general criteria for the occurrence of geomorphic changes to the entrance and for the washout of the saline wedge and the timing of its recovery.

Methods

The discharges in the Snowy River at Jarrahmond and the Brodribb River at Sardine Creek were obtained from the Victorian Government for both years. Snowyhydro provided the details of the EFR in 2010 while information for 2011 was supplied by the New South Wales Office of Water. Meteorological data for Orbost over the period were obtained from the Bureau of Meteorology and wave data for the nearby Lakes Entrance were obtained from Gippsland Ports.

The data collection on each EFR was conducted on four field trips, each of three or four days duration, at approximately two-week intervals. The trips were timed to

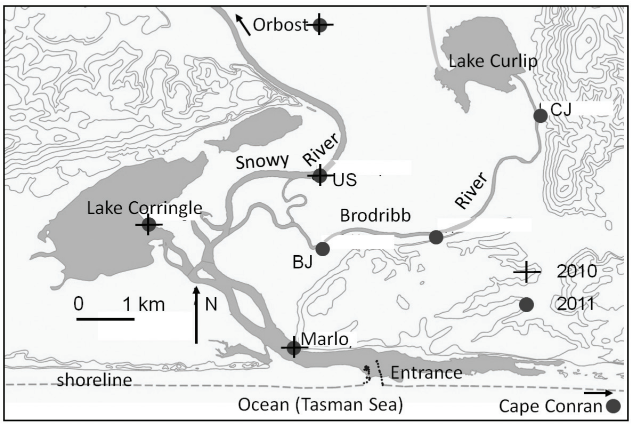

Figure 3: The Snowy River estuary, showing the tide/temperature/salinity recording stations, October–November 2011 (Orbost, Corringle and Cape Conran tide/temperature only). BJ Brodribb Jetty; CJ Curlip Jetty; US Upper Snowy.


Figure 4: Tide board and recorder on Cape Conran Jetty.

obtain one set of data before the arrival of the flow release peak, one right at the end of the peak flow and two to characterise the recovery of the estuarine salinity regime. Tide and salinity loggers were deployed at stations along the Snowy (and Brodribb River in 2011) channels (Figure 3) and additional tide loggers were installed at Orbost, Lake Corringle and Cape Conran (Figure 4). Salinity profiles were taken at a high tide on each field trip (for locations see Figure 5). Detailed soundings were made of the entrance channel and its plan form was surveyed.

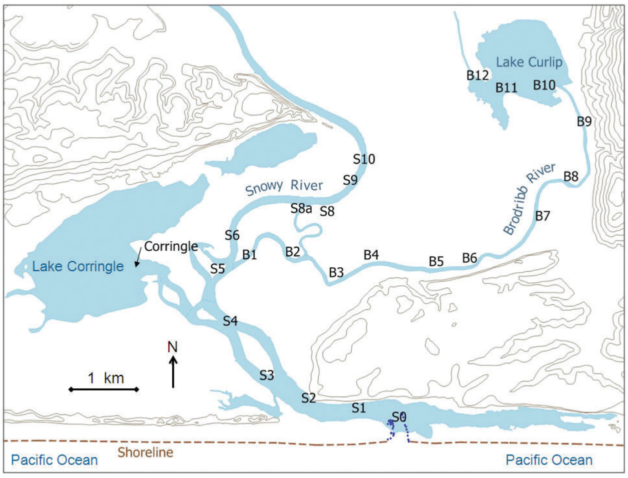

Figure 5: Salinity profiling stations in the Snowy River estuary during October–November 2011. Stations B1 to B12 were not monitored during the 2010 flow release.

Field activities to measure the physical effects on the estuary, measured during the four data collection trips, are listed in Appendix A.

Preliminary profiling in Lake Corringle revealed vertical salinity differences were insignificant, so profiling was not undertaken in Corringle during the other long profile surveys. The profiles on each trip were consolidated into a single longitudinal section with salinity contours that illustrate the general vertical and longitudinal patterns.

As shown in Figure 3, tide and salinity loggers were installed at eight data collection stations before the flow release and maintained over the collection period. Tide and salinity recorders were installed at Marlo Jetty (the principal tide station) and at Upper Snowy at the confluence with the Little Snowy River, while tide and temperature loggers were deployed at Orbost and at the mouth of Lake Corringle, as in November 2010. In 2011 the study was expanded to cover the estuarine reaches of the Brodribb River, so additional tide and salinity loggers were installed in the Brodribb River at the boat ramp jetty, upstream of the Marlo Road bridge, and at the Lake Curlip Jetty. A tide logger was installed at Cape Conran. The water levels were tied to Australian Height Datum (AHD) by Real Time Kinematic (RTK) survey.

The entrance surveys included low-tide waterline mapping and a hydrographic survey of the areas below low-tide level. The hydrographic survey was performed using a survey-quality echo sounder with Differential Global Positioning System (DGPS). The mapping of the channel boundaries and spot heights at intertidal scarps and bank crests was undertaken using an RTK survey system, linked to the VicCORs survey network. These data were used to define cross-sectional areas but were too sparse for contouring. Temporary tide boards were installed on the estuary and at the seaward ends of the entrance channel during these surveys and were set to AHD by RTK survey.

RESULTS

Hydrologic response

River inflows and water levels in 2010. The hydrologic response investigated comprises the hydrograph of the EFR as it enters the estuary and the response of the water level at the upstream tidal limit. The antecedent conditions strongly affect the hydrographic and other physical responses, and are outlined here for each EFR.

The discharges of the Snowy and Brodribb Rivers in 2010 are shown in Figure 6 (log scale). The two curves are similar, with the Brodribb flow typically 5%–10% of that in the Snowy. These flows show a sequence of very short duration flood peaks, then about a week of rapid recession, followed by weeks of gradual recession. The environmental release created the final peak in the Snowy, which lasted about three days, in contrast to the typical storm runoff peaks of one day.

Two freshes of about 20,000 ML/D occurred in the first half of the year, the data from the first of these being mentioned in Water Technology (2010). A more sustained period of high flows occurred in late July and early August but only peaked at 9800 ML/D. Closer to the environmental release, another fresh peaked at 7620 ML/D on 17 October

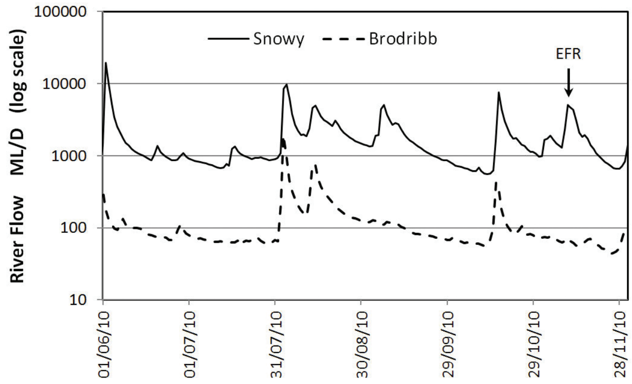

Figure 6: River flows in the Snowy River at Jarrahmond and the Brodribb River at Sardine Creek, 2010.

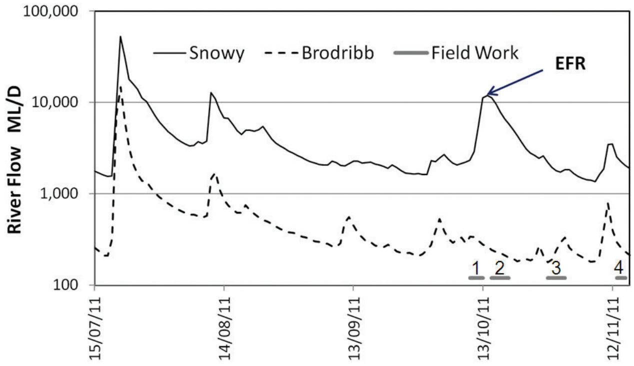

Figure 8: River discharges July–December 2011: Snowy River discharge at Jarrahmond showing the environmental flow; Brodribb River at Sardine Creek.

2010, but was well into its gradual recession before the environmental flow, as shown in Figure 6.

The EFR was released from water stored in Jindabyne Dam in the Upper Snowy River catchment. Figure 7 shows the flow in the Snowy River just below Jindabyne Dam and the flow at Jarrahmond, about 9 km above the tidal limit. At Jarrahmond, the Jindabyne release was augmented by tributary and catchment inflows of about the same magnitude as the EFR.

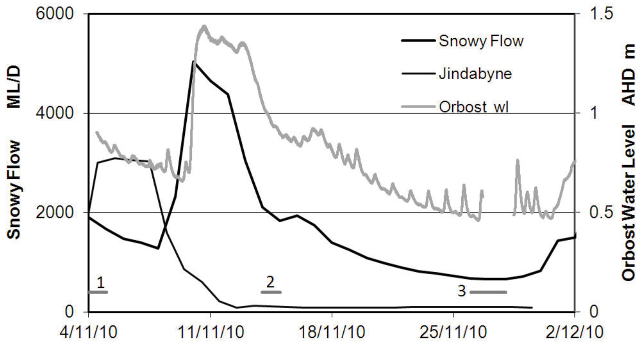

Figure 7: Flow in the Snowy River at Jarrahmond and Jindabyne, and water level at Orbost for November 2010 (several days of water level record were lost due to instrument malfunction).

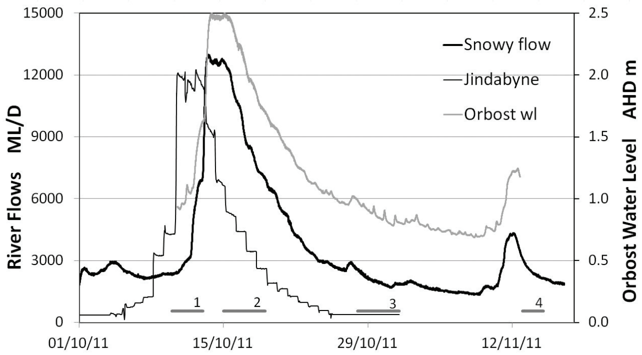

Figure 9: Flow in the Snowy River at Jarrahmond and Jindabyne, water level at Orbost for November 2011 river discharges showing the environmental flow and field trip dates October–November 2011.

The other curve in Figure 7 shows the direct response of the water level at Orbost, at the tidal limit. The Orbost water level lagged Jarrahmond by about one day on average. Tidal action near the tidal limit was dominated by the 24-hour constituents and in turn they were largely suppressed by the peak flow.

River inflows and water levels in 2011. The discharges of the Snowy and Brodribb Rivers for July–November 2011 are shown in Figures 8 and 9. The two sites display similar hydrologic patterns through time and, similar to 2010, the Brodribb River discharge was typically 5%–10% of that in the Snowy River. The data in Figure 8 show several flood peaks of very short duration, with a rapid rise, followed by weeks of gradual recession, as was found in 2010. A flood of 53,000 ML/d occurred in the Snowy River on 21 July 2011 and the Brodribb peaked at about 15,000 ML/d due to unusually heavy coastal rainfall coming from an east coast low pressure cell, situated to the south-east of the study area. A fresh of 12,900 ML/d occurred in the Snowy River on 11 August 2011. Another minor fresh occurred after the EFR on the 11 November 2011 (just before Trip 4).

The peak flow in the EFR lasted about three days (Figure 9) and was thus more like the snow-melt flows. As in 2010, the Orbost water level closely matched the Jarrahmond discharge hydrograph with an average of a one-day lag. This time, tidal effects were fully suppressed by the peak flow.

Comparison of 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.

The mean water level in the Upper Snowy estuary responded first, with the levels at low tide rising ahead of the EFR peak. The rise in water levels in the other reaches lagged by from twelve hours to three days, presumably due to the Upper Snowy station being sited on the Snowy River, which had to pass the inflow in a relatively narrow channel while further downstream the flow divided, flowing down the lower Snowy River and running upstream into the Brodribb River then into Lake Corringle. The inflow then had to fill the latter channels as the water level rose, reducing the rate of rise downstream. Despite their different magnitudes, the hydrologic characteristics of each EFR were very similar. These characteristics include the time of travel, duration of peak flow, rate of recession, and lag between river flow and water level changes at the tidal limit.

Geomorphic response

Entrance changes in response to fresh flows have been noted for many years but published studies are few. Arrowsmith and Hinwood (2011) conducted a three-month model simulation of the Snowy River estuary, during which a natural fresh flow occurred. The model study included full 3D hydrodynamic and morphological modelling of the estuary, with simulation of coastal wave action. During this period, river inflows were gauged and water level data were collected in the estuary and an initial Lidar survey was available. This study showed that minor scouring occurred during the small fresh flows but, more significantly, the entrance resistance changed with the river flow.

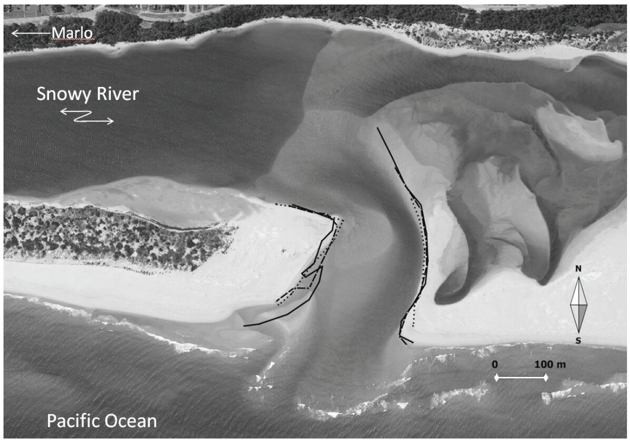

Figure 10: Entrance channel boundaries in the Snowy River estuary, November 2010. Dotted line: Trip 1; dashed line: Trip 2; solid line: Trip 3.

While environmental flows can be designed to scour estuary entrances as well as provide upstream geomorphic channel change, these outcomes will be conditional on the entrance state at the time of the water release. For both the 2010 and 2011 flow releases, natural catchment flows of at least similar magnitude to the EFRs had preceded the flow releases, thus producing entrance dimensions capable of accepting the increased flows without substantial change or scour.

The results for the two flows are summarised in the following sections. A companion paper (Hinwood & McLean 2014) used simple models to examine the tidal and river flow contributions to sediment transport in the entrance and depicted the changes and longer-term trends.

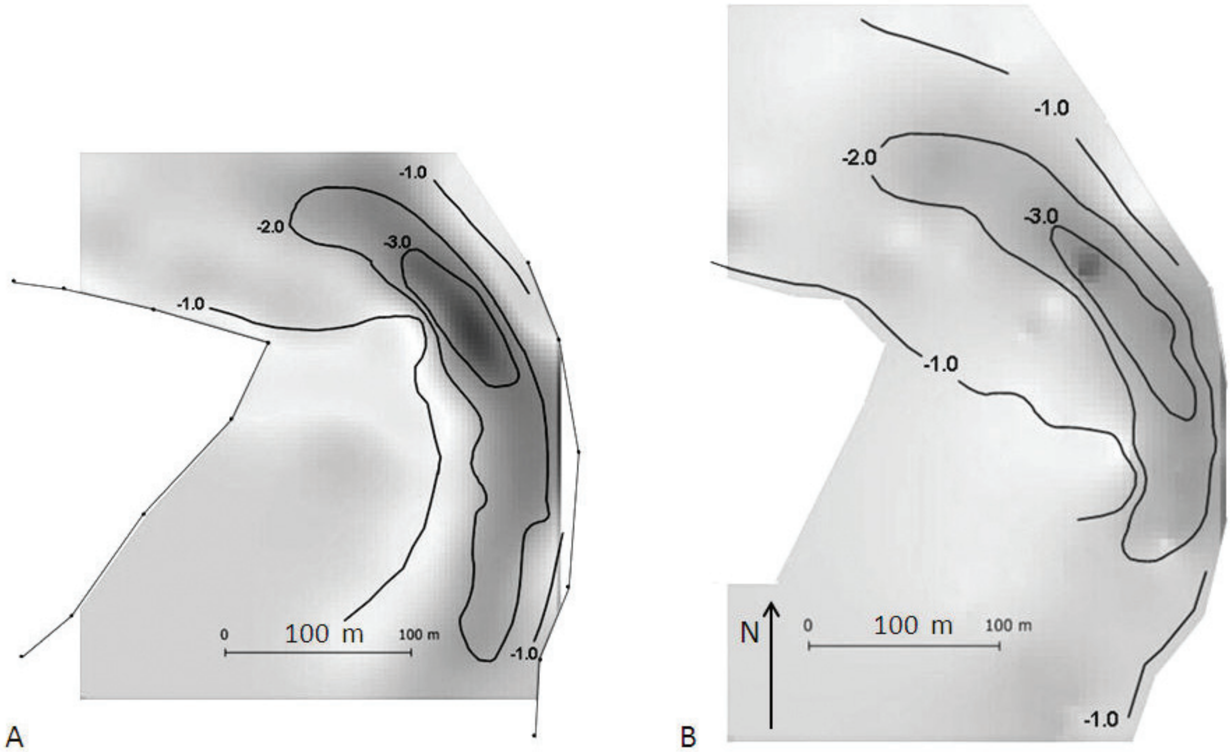

Figure 11: Hydrographic survey of the Snowy River entrance: A: below 0.0 AHD, 4 November 2010; B: 16 November. Depth contours m AHD.

Entrance morphology 2010. The mapped waterlines (or wetted edge) of the entrance channel are shown in Figure 10. Neither the eastern nor the western boundary changed much over the period. The largest change was the advance of the shoreline on the western side near the ocean between Trip 2 and Trip 3. This was caused mainly by the strengthening of the reattachment of an offshore sandbar.

Figure 11 shows the hydrographic survey results for Trip 1 (4 November 2010) and Trip 2 (16 November 2010), before and just following the peak environmental flow. The contours are quite similar, but the seaward section of the entrance had been modified by ocean wave action and was slightly shallower for the second trip. The survey of Trip 3 (27 November 2010) was similar to that of Trip 2.

The pre-existing enlarged entrance cross-section resulted in relatively small increases in ebb flows through the entrance, and the changes in entrance morphology were very small. Despite this, the increase in amplitude of the M2 constituent, described under Response of the Hydrodynamic Regime, showed that the flow resistance of the entrance was decreased. The reduction was due in part to the small increase in cross-sectional area and probably to reduction of bed form resistance, as described below.

Entrance morphology 2011. The mapped waterlines of the entrance channel in October 2011 are shown in Figure 12. Neither the eastern nor the western boundary changed much between the first and second trips. Between the second and third trips, an overwash event built up the inner end of the western shoreline and longshore transport built up the outer end of the eastern shore.

At the start of the EFR, the entrance dimensions were still quite large, following a major catchment inflow in July when the entrance was scoured. The contours for the three surveys are quite similar in basic pattern (Figure 13), indicating that the initial entrance capacity was large enough to accommodate the EFR without substantial change. Between Trips 1 and 2 there was some elongation of the channel towards the ocean, and its form became more streamlined as a result of the increased flow through the entrance. The cross-sectional areas below the -1-m AHD level changed only slightly, but the shoreline at about 0-m AHD at the estuary end and mid-way along the channel widened. On Trip 2 it was noticed that some of the bars near the western shore were lowered and more streamlined. Thus the cross-sectional areas available for flow did increase, particularly for conditions near HW when the tide in the entrance was flooding. By Trip 3, on 29 October, the entrance had been modified on the western side by a significant overwash deposit from a coastal storm on 25 October that narrowed the entrance slightly.

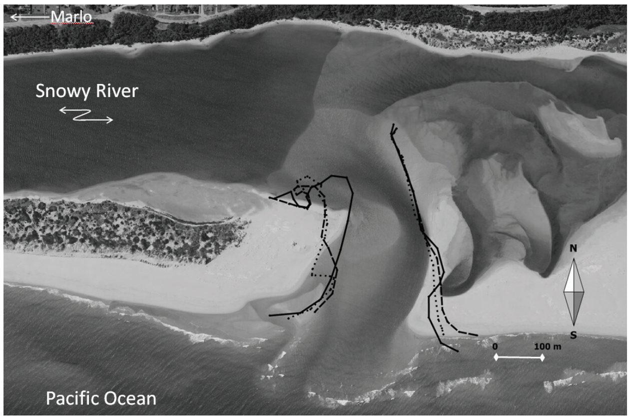

Figure 12: Entrance channel boundaries in the Snowy River estuary, October 2011. Dotted line: Trip 1; dashed line: Trip 2; solid line: Trip 3.

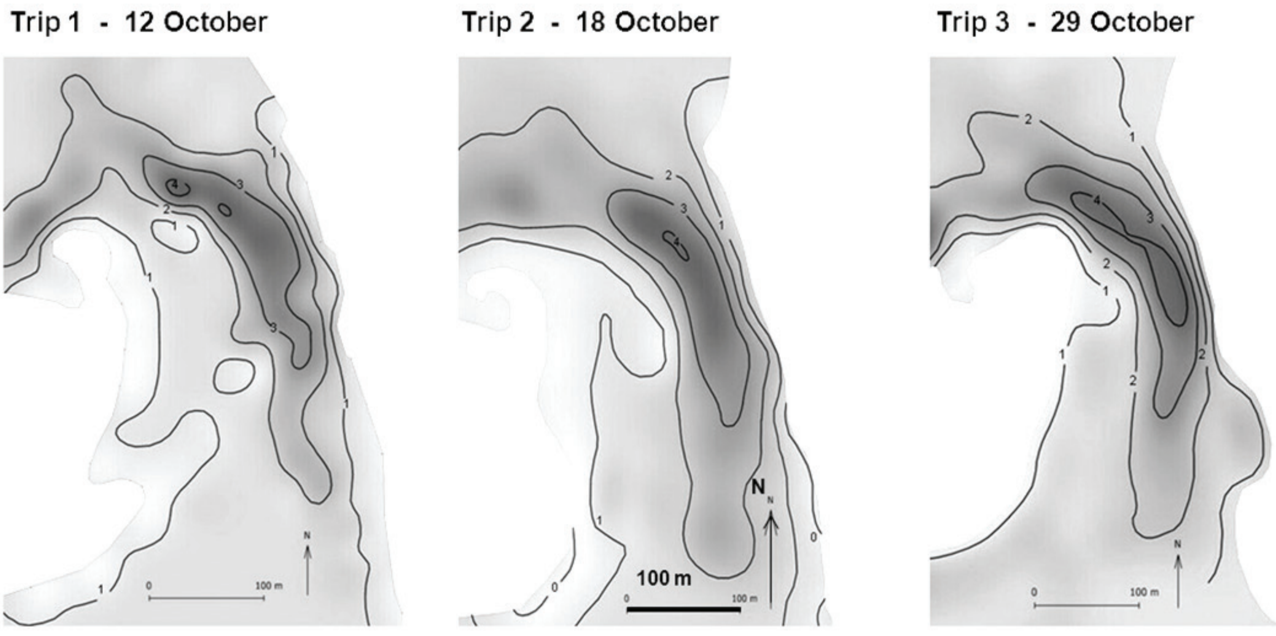

Figure 13: Hydrographic surveys of the Snowy River entrance in October 2011. Depth contours are in metres below 0.0 AHD.

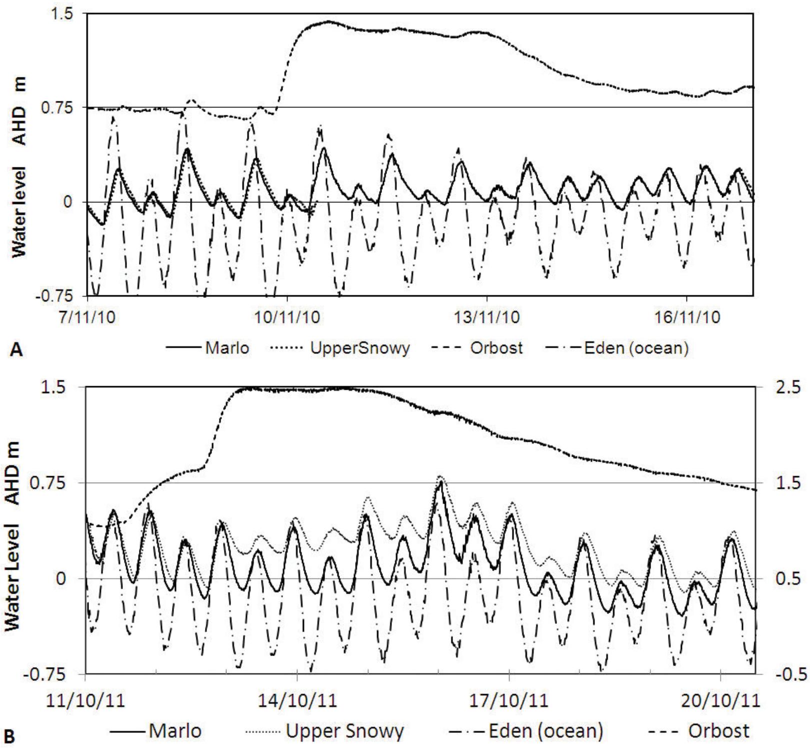

Figure 14: Modification of the ocean tide (Eden) within the Snowy River reaches of the estuary for each EFR. A: 2010 EFR (gap in Upper Snowy data caused by instrument malfunction); B: 2011 EFR (note different scale on right of figure for Orbost).

In summary, the entrance channel had been enlarged by prior high river flows and the subtidal depths were increased only slightly by the EFRs. The entrance cross-sections did increase in the intertidal zone, increasing channel areas at high water levels such as during a high river flow or flood tide. It is probable that a release of this magnitude and duration would erode an initially constricted channel to a size approaching that measured. Infilling of the channel depends primarily on coastal processes and is not linked directly to the river flows; however, in time an oversized channel will fill by storm actions or gradual capture of longshore drift.

Hydrodynamic response

Hydrodynamic processes in the estuary are driven by tidal flow and river inflows, modified by the effects of density differences that are primarily due to salinity differences. As described under 'Hydrologic response', the mean water level was raised by both EFRs although the change in the 2010 EFR was very small. The bulk movement of water through the estuary from the river to the ocean resulted in much stronger ebb currents and weaker flood currents, biasing sediment transport to scouring, as described above and in Hinwood and McLean (2014). This bulk water movement dominated the salt transport, driving the saltwater downstream, as described in the next section.

The tidal response to the two EFRs in the Snowy River reaches of the estuary is shown in Figure 14. The amplitude of the ocean tide at the Snowy River entrance is approximately the same as that at Eden 140 km along the coast to the north, but lags Eden by about 30 minutes. The tide at Eden has a range of about 0.8 m for neaps to 1.7 m for springs and has a strong diurnal inequality. Prior to each EFR, the tide at Marlo was attenuated with a range of about 0.5 m and lagged the ocean tide at Eden by 1–3 hr. The phase lag increased upstream and the amplitude decreased, but this attenuation was gradual until the tidal limit was approached well upstream of the Upper Snowy station.

In each EFR the peak river flows attenuated the tide and this is shown in Figure 14, where the small 2010 EFR reduced the tidal range at Marlo to about 0.4 m. The larger 2011 EFR reduced amplitudes by a similar amount at Marlo but greatly reduced the tide in the upper estuary. Following the peak inflow, the water levels remained high for only a day before falling rapidly to a quasi-stable level. This level was lower than the pre-release level and the tidal amplitudes were larger. These changes indicate clearly that the flow resistance in the entrance channel reduced over a couple of days centred on 17 October, four days after the peak inflow, probably through scouring of sediment bed forms in the entrance channel, as changes in the cross-section were minor. This phenomenon has been reported previously by Arrowsmith and Hinwood (2011).

Thus, at Marlo and the Upper Snowy station, the mean water level was dominated by the ocean tide and was less affected by the river flows, whereas the tidal attenuation was dominated by the entrance state.

A similar plot for the Brodribb River in the 2011 EFR is shown in Figure 15. Again, the dominant effect of the ocean tide on the mean water levels is clear and the attenuation of the tide throughout the Brodribb segment is similar to that at Marlo, as is to be expected.

The attenuation of the tide at Marlo may be more clearly seen in Figure 16 which shows the amplitude and phase of the M2 constituent. This constituent has been extracted from the tidal record at Marlo using a 14d moving window, as described in Hinwood and McLean (2001). In Figure 16 it may be seen that as the river flow rises the M2 amplitude

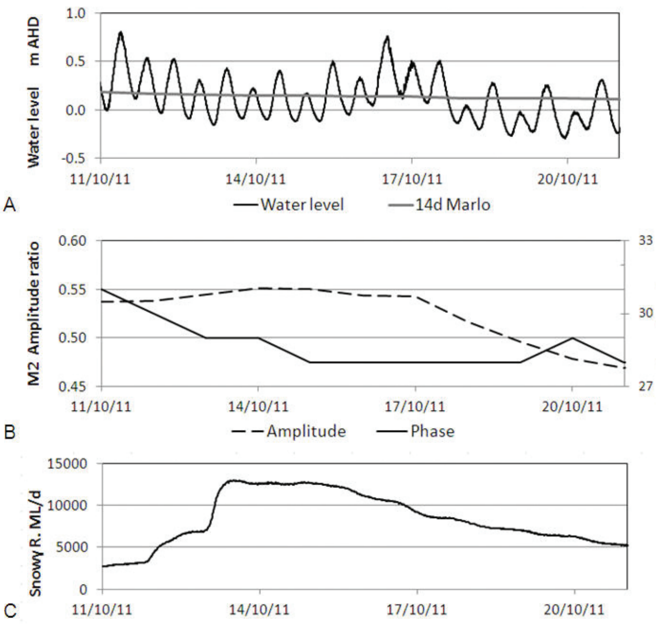

Figure 15: Changes in the M2 tidal constituent at Marlo during the 2011 EFR showing attenuation and lag at the peak flows, then increased amplitude and reduced phase following the peak flow. A: Measured water level; B: M2 amplitude and phase; C: Snowy River discharge at Jarrahmond.

falls and the phase increases, and then as the entrance scours and the river flow falls, the changes are reversed.

The high flows in the Upper Snowy River reaches of the estuary resulted in a tidally-averaged hydraulic gradient between the Upper Snowy and Brodribb Jetty stations. The water level difference between these stations is shown in Figure 17. For about five days during the high flows, the reversed hydraulic gradient extended the length of the Brodribb River and showed that fresh Snowy River water was being pushed up into the Brodribb system. This period was followed by several days of zero mean gradient, then these hydraulic gradients reversed as Lake Curlip and associated wetlands drained.

On a tidal time scale, the hydraulic gradient swung from positive to negative, injecting pulses of fresh water into the lower Brodribb near low tide, as noted by Hinwood and McLean (1999). Mixed water from the lower Brodribb was then pushed out around the time of high water. This tidal fluctuation was not suppressed during the period of high flow but was not strong enough to reverse the positive hydraulic gradient at that time.

Salinity response

The salinity response for the two environmental flows exhibited a similar gross pattern in the upper and lower Snowy channels, but with a different magnitude in the displacement of the salt wedge downstream, related to the difference in flow release volume and timing. During the release in 2010 only the Snowy channel was instrumented, while in 2011 both the Snowy and the Brodribb estuarine channels were monitored. The latter data is presented in detail in order to illustrate the different system salinity patterns and responses to the flow release in the Snowy catchment. Comparisons between the two flow releases are then presented as a summary diagram with comments.

The vertical profiles of salinity, obtained on a high tide on each trip in 2011, provide a detailed picture of the salinity pattern. The profiles have been incorporated into longitudinal sections with interpolated salinity contours. The profiles from each of Trips 1 through 4 for the Snowy River estuary are shown in Figure 18. Figure 19 shows the longitudinal profiles for the Brodribb River estuary, repeating the lower Snowy profiles while adding the Brodribb data above the confluence with the Snowy.

The profiles in Figure 18A, from Trip 1, show that saline water has only penetrated upstream to about 7 km from the ocean in the Snowy, much less than previously observed under dry-weather flows (personal observations by the authors). There was a strong interface near the surface extending to about 6 km upstream with the vertical structure changing from about the confluence with the Brodribb (4.4 km from the entrance) and salinities becoming more uniform vertically while decreasing with distance

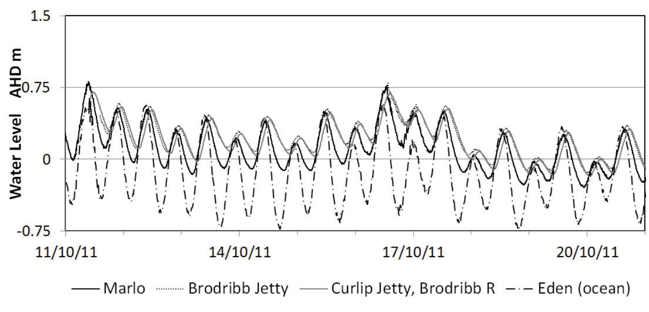

Figure 16: Modification of the ocean tide (at Eden) within the lower Snowy – Brodribb River reaches of the estuary for the 2011 EFR.

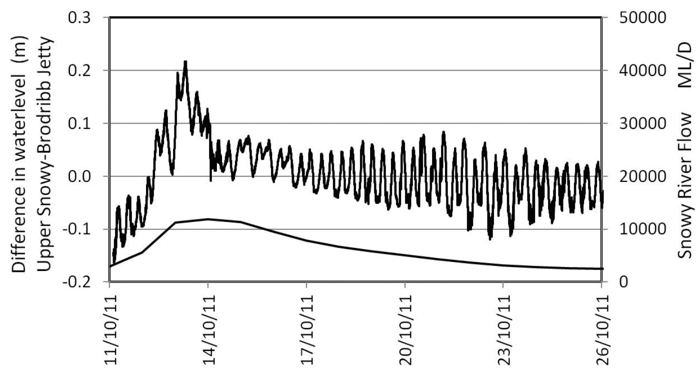

Figure 17: Difference in water level between Upper Snowy and Brodribb Jetty, showing positive hydraulic gradient from the Snowy into the Brodribb during high flows. Lower curve is Snowy River flow at Jarrahmond.

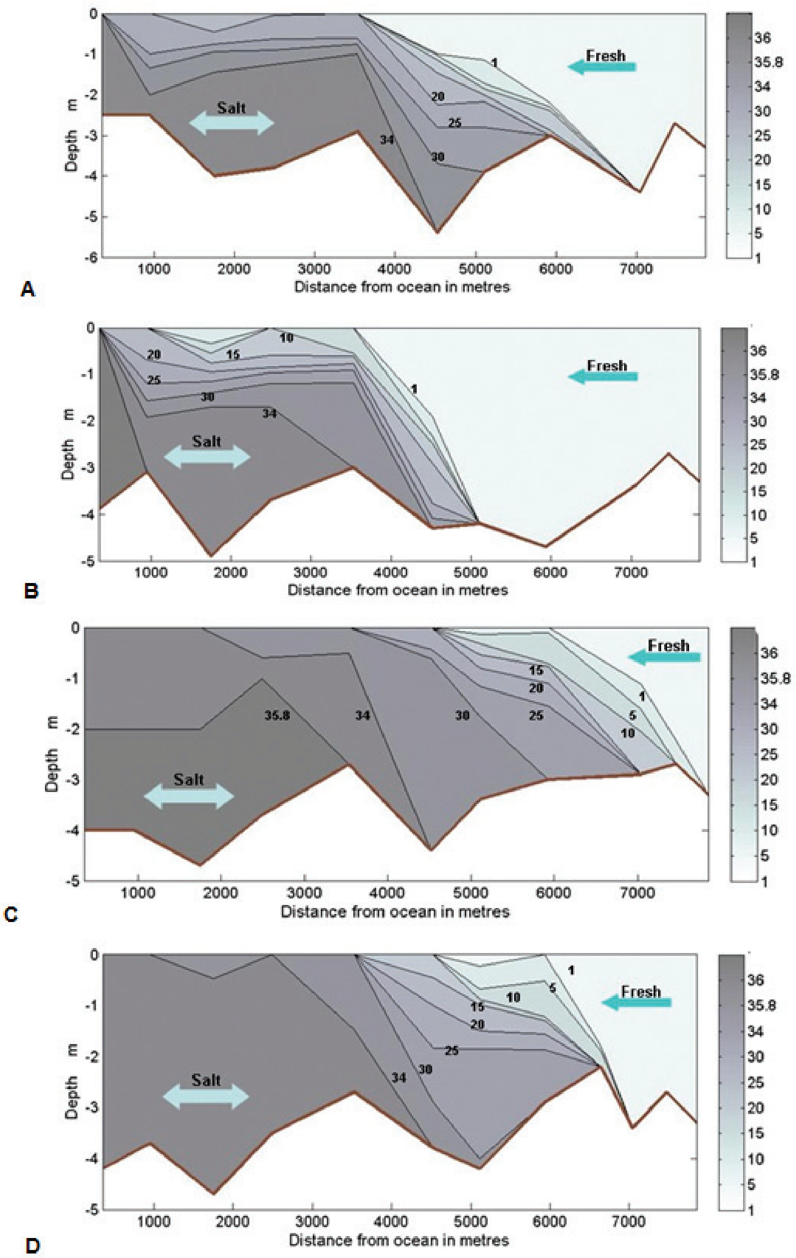

Figure 18: Longitudinal profiles of salinity in the Snowy River on each trip. A: Trip 1, 12 October 2011(rising limb); B: Trip 2, 16 October (just after flow peak); C: Trip 3, 30 October (recovery period); D: Trip 4, 14 November (recovery period, small fresh).

upstream. Above 7 km, the water in the channel was fresh. This measurement preceded the peak flow by about three days and the pattern reflects the additional fresh water in the system as the EFR flow built up. The Brodribb system (Figure 19A) was flushed of salt, reflecting previous fresh flow impacts from that catchment.

The Trip 2 measurement (Figure 18B), at the end of the peak flow period, illustrates the displacement downstream of the salt wedge in the Snowy as well as the compression of the salt/fresh interface in the mid-estuary. The Brodribb (Figure 19B) maintained its fresh condition; the spike at 7 km may be due to more saline water entering the Brodribb from the Little Snowy River. By Trip 3 (Figure 18C), the salinity structure had recovered to a pattern more typical of average, low-flow conditions in both estuarine channels. The rapid intrusion of the saltwater front, as a salt wedge, has been observed in previous studies in coastal plain estuaries with an elongated estuarine river segment (e.g. Nichols 1977, 1994; Eyre & Twigg 1997) but has not been well documented in barrier estuaries. Strong tidal flushing from the spring tides and falling mean water levels from 18 October would have accelerated the recovery of salinity observed on Trip 3. The Trip 4 profile in Figure 18D exhibits a slight displacement of saltwater downstream under the influence of a small catchment event in early November, which added more freshwater to both the Snowy and Brodribb systems.

The Snowy system (Figure 18D) exhibited the typical salt-wedge long profile found during low to medium catchment flows while, for the Brodribb (Figure 19D), the normal vertically well-mixed pattern was re-established, although the waters in Lake Curlip and the upper Brodribb remained much fresher than in normal or dry weather conditions. By Trip 4, rainfall in the local Brodribb catchment had slightly displaced the saline water downstream.

While the 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. The locations of the salinity loggers are shown in Figure 3. Selected records have been processed to summarise the mean, maximum and minimum salinities at key locations in the two estuaries from a point just before the flow release peak and during the salinity 'recovery'. A further minor flow event from the catchment has interrupted the salinity recovery towards the end of the measurement period.

Figure 20 shows the record from the loggers placed at the Upper Snowy station, Brodribb Jetty and Marlo Jetty from Trip 1 through Trip 4 in 2011. These loggers were fixed about 700 mm below the mean water level. Marlo Jetty records also show a logger mounted lower in the water column about 1600 mm below the mean water level (Lower Logger on plot). The plots show the salinity envelopes as well as the mean salinities calculated from the instrument records. All records show oscillations caused by the tide, the main effect being the movement upstream and

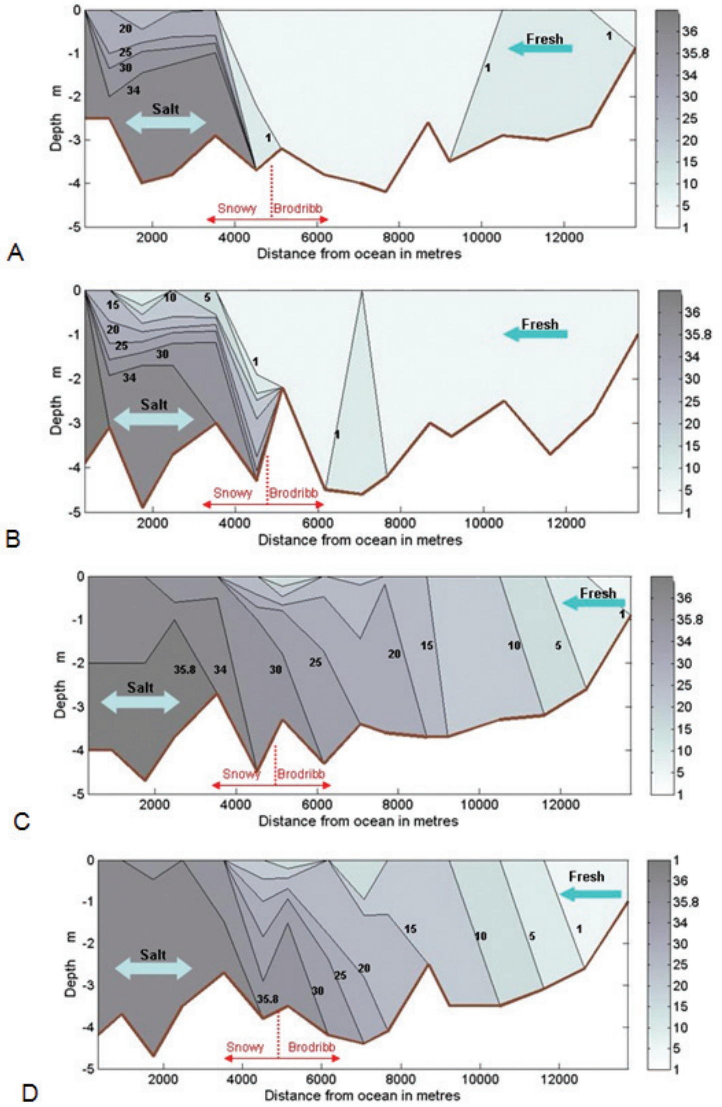

Figure 19: Longitudinal profiles of salinity in the lower Snowy – Brodribb River on each trip. A: Trip 1, 13 October 2011 (rising limb); B: Trip 2, 17 October (just after flow peak); C: Trip 3, 31 October (recovery period) ; D: Trip 4, 14 November (recovery period, small fresh).

downstream at tidal frequencies. A second action of the tide is to change the depth of immersion of the loggers and this results in more saline water at the logger on the high tide and less saline on the low tide. Thus the two changes have the same type of effect. The records also show changes due to the river inflow, the ocean tide and the mean sea level. With the passage of the environmental flow down the system, the salt wedge was washed downstream from 12 to 20 October 2011, while the river inflow was high, and for several days thereafter. The salinity interface observed on Trip 2 in the Snowy was sharper and stronger than on the other trips. In the upper estuary, salinity variation increased when saline water returned but, in the upper layer of the water column this increase was limited to a very short period over the time of measurement.

The latter sections of the plots illustrate the effects of a natural fresh flow from the catchment towards the end of the measurement period.

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 21). 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 long profiles of salinity for Trip 2 (just after the peak release flow) for both releases are also shown for comparison in Figure 21. The larger magnitude flow in 2011 displaced the salt-wedge structure further downstream than for the 2010 release and deepened the brackish water layer in the lower estuary to about 2 m, compared with 0.7 m in 2010. The threshold flow for purging the Upper Snowy of saltwater has been shown to be very close to the peak flow in 2011; that is, 12,000 ML/d. With saltwater purged from the Upper Snowy, penetration of saltwater into the Brodribb would have been reduced and penetration of freshwater enhanced, and the Brodribb too was purged of saline water in 2011, despite low flows from the Brodribb catchment.

Both environmental releases tended to push the saline water seawards with the maximum displacement of saline water in the Snowy River estuary occurring 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. In 2011 the estuary remained sharply stratified for longer, with higher freshwater inflows persisting on the recession of the release, leading to the surface waters remaining fresh longer than in 2010. Direct comparison is made difficult by the stronger tidal signal in the estuary in 2011 due to the larger initial entrance. Despite the stronger tide in 2011 facilitating mixing of the waters, the strong stratification persisted in the Snowy, but in the Brodribb the waters mixed rapidly.

Long-term estuary response — extended observations 2011–2012

Although the formal monitoring program for the 2011 EFR ceased after Trip 4 in November 2011, a tide recorder was left in place on Marlo Jetty and a record was obtained through to 1 May 2012.

The available tidal record, starting in August 2011 and ending in May 2012, is shown in Figure 22. This period starts a few weeks after the large flood in July 2011 and ends a few weeks after a near-closure, which was

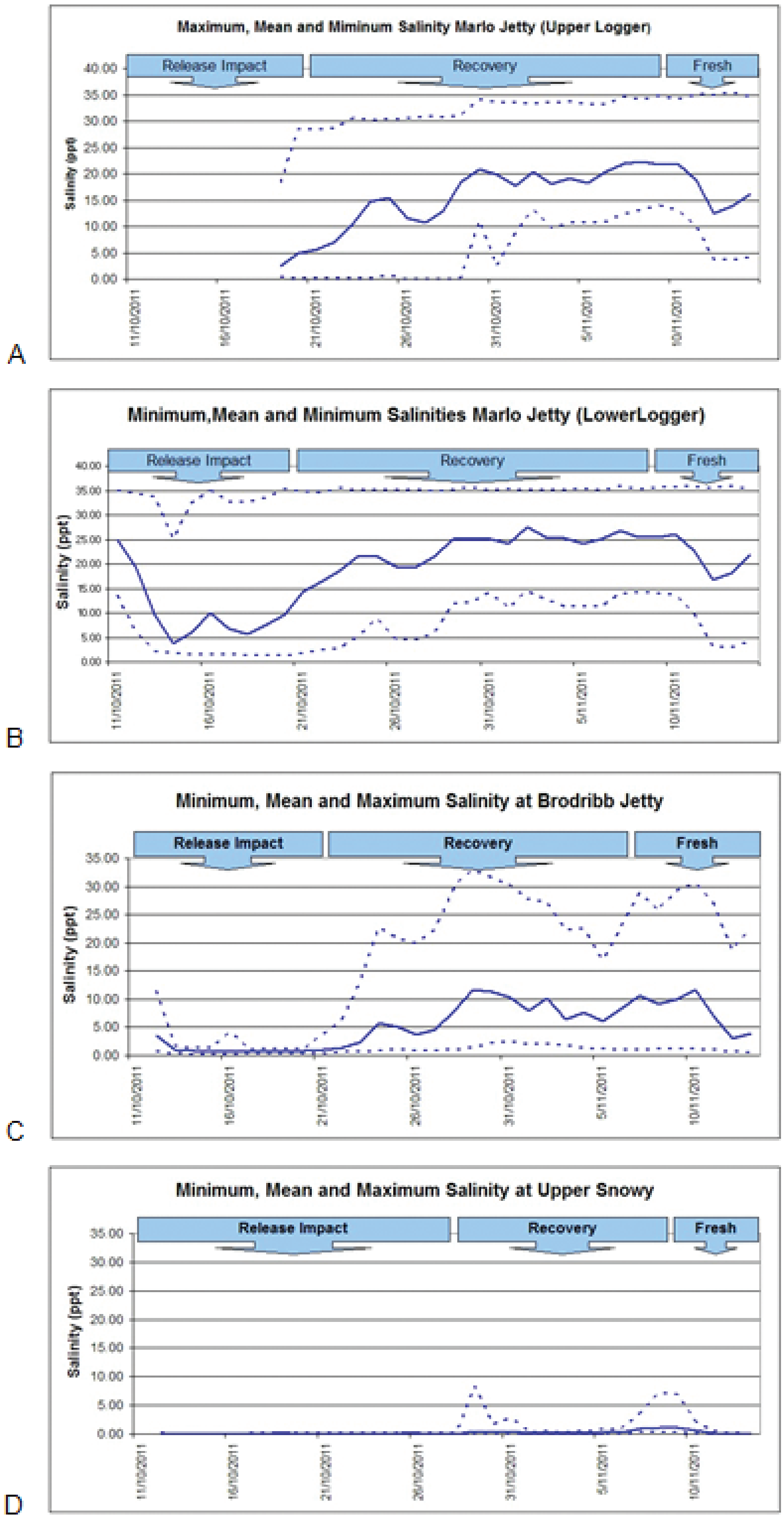

Figure 20: Salinity at three stations in the Snowy and Brodribb estuaries, November–December 2011. Minimum (dotted); mean (solid line); and maximum (dotted).

immediately followed by a flood that rapidly scoured the entrance channel. From August 2011 to March 2012 the overall trend was towards closure. In the absence of any catchment flood flows, the entrance continued to reduce in cross-sectional area, eventually becoming effectively closed on 1 March 2012. This coincided with a neap tide and a slightly lowered MSL, both of which would contribute to closure. The flood on 2–3 March 2012 scoured the entrance channel, allowing the mean water level to drop and the tidal amplitude to increase.

A clearer and more objective measure may be obtained by tidal harmonic analysis, using a moving window to show the changes in tidal amplitudes and phases day by day, as in Figure 15.

Figure 22B shows a gradual reduction in tidal amplitude and an increase in phase of the M2 over the whole period, following the major flood on 21 July, in which the Snowy River inflow peaked at 53,000 ML/d. This attenuation of the tide is most likely to have been caused by the entrance shoaling through the deposition of sand from coastal sources. Two fresh flows occurred during the period 3 August – 10 November, one peaking at 12,900 ML/D on 11 August followed by the EFR peaking at 11,900 ML/D on14 October. These natural variations and the 2011 EFR affected the M2 amplitude and phase while their higher flows lasted but they had no lasting effect on the M2.

This long sequence of tides shows that the long-term regime of the Snowy River entrance tends to near-closure for river discharges less than the 2010 EFR, which combined with the catchment runoff, peaked at about 6000 ML/d. Discharges of the magnitude of the 2011 EFR, which peaked at 13,000 ML/d, were sufficient to enlarge the entrance but the effect lasted only a few weeks. Much larger floods, even though of very short duration, scoured the entrance quite significantly but their effect too was confined to only a couple of months.

CONCLUSIONS

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. The morphological effects at the estuary entrance were independent of salinity

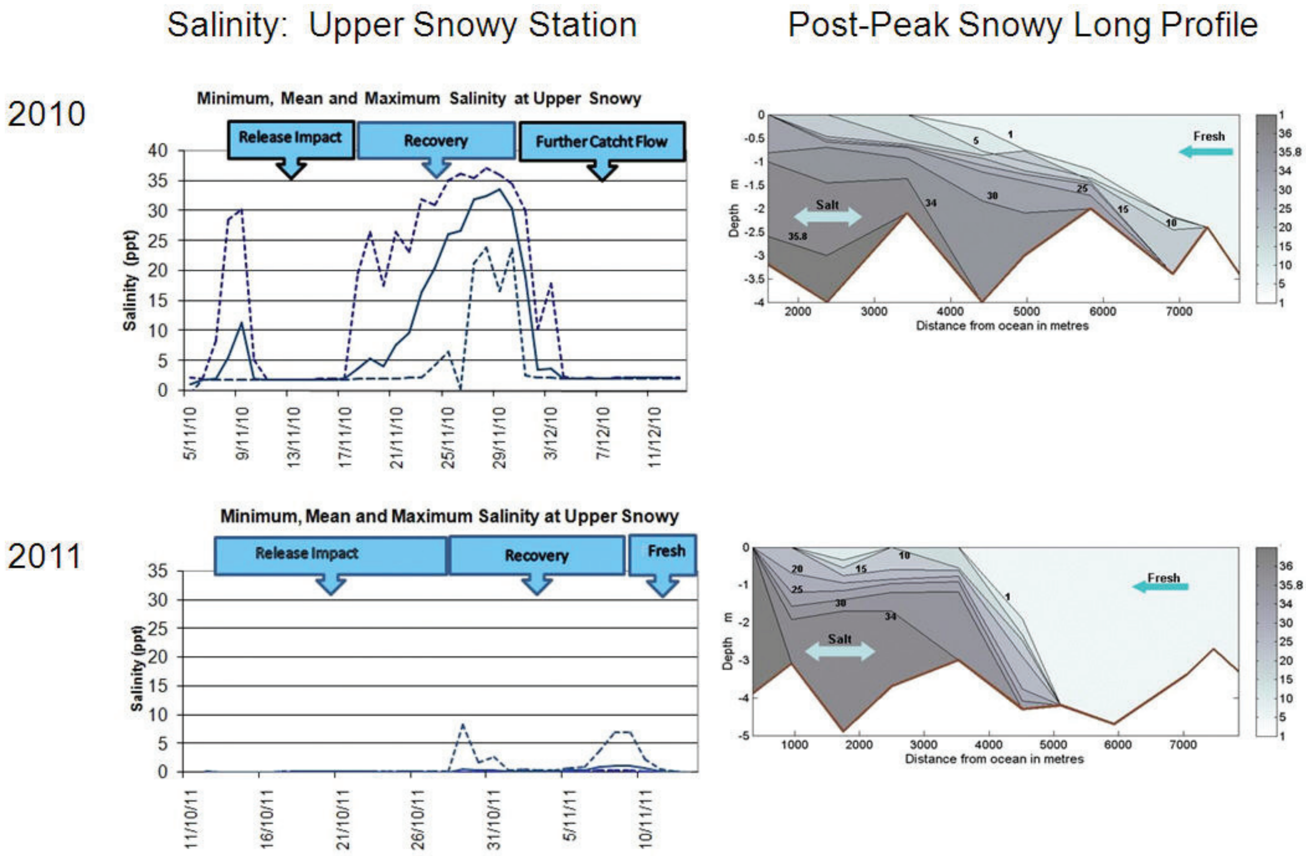

Figure 21: Comparison of salinities in 2010 and 2011. Left side plots: Upper Snowy station, upper salinity logger. Right side plots: Longitudinal salinity profiles in the Snowy immediately post-peak (Trip 2).

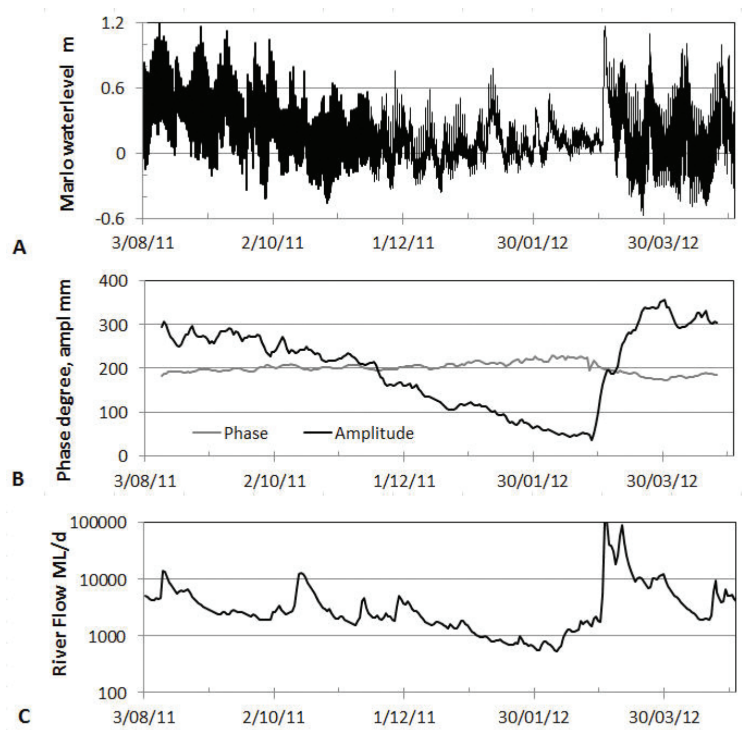

Figure 22: Estuary tide at Marlo and river inflows, August 2011 – May 2012. A: Measured tide; B: M2 tidal amplitude and phase from moving window analysis; C: Combined Snowy and Brodribb discharge (log scale).

structure and related directly to the instantaneous volume of flow and its scouring capacity on the channel at the time of the releases. In both the 2010 and 2011 cases, the pre-existing entrance morphology had been conditioned by previous natural flows soon enough before the EFRs for the scour effects from the natural flows to be preserved. Scour effects at the entrance, although observable during the EFRs, were not as extensive as they would have been if the entrance had been in a more constricted form after a long period without appreciable catchment flow events. This has been illustrated in Figures 16 and 17, which show a pattern of gradual constriction during low inflows and rapid entrance channel expansion related to large catchment events widely-spaced in time. As the flows were at an interval less than that of the recovery period, the entrance regime adjusted to one of minor change in response to the intervening flows.

In summary, each EFR caused minor but discernible increases in depth and very minor longshore movement of the entrance channel, with the smaller 2010 EFR having very little effect. Each environmental flow had been preceded by a larger fresh flow and consequently the entrance channel dimensions are likely to have been close to equilibrium for the environmental flows before they reached the estuary. Enlargements of the entrance channel were predominantly by scouring in the intertidal zone, due to a combination of wave action and the lesser consolidation of the intertidal sands (Hinwood & McLean 2014).

The study has confirmed the findings by Hinwood and McLean (2010) that tidal and salinity patterns within the estuary are strongly affected by both river flow and the state of the entrance, with the entrance condition being a significant driver of water exchange in the Snowy River Estuary. The entrance dimensions and hydraulic resistance are in turn dependent on river flow, tides and coastal processes.

While the design of an EFR regime is of immediate concern in the management of the Snowy River, these conclusions would apply to the response of any barrier estuary to a transient flow, whether natural or man-made. In all barrier estuaries, the entrance area regulates the tidal prism but is itself largely determined by catchment inflows. Small increases in inflow are unlikely to increase the entrance area but larger inflows will do so and are likely to increase the intertidal area first. Even small increases in fresh water inflows will push salinity contours seawards, particularly in the upper part of the water column, and will steepen vertical salinity gradients. Larger inflows may purge the estuary of saltwater. Salinity recovery is rapid in the principal estuarine channels but may take weeks where poorly-connected wetlands can store fresh flood waters.

Acknowledgements
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Appendix: Details of fieldwork

The dates of the four field trips for the 2010 EFR were:

Trip 1, 4–6 November 2010

Trip 2, 15–16 November 2010

Trip 3, 26–28 November 2010

Trip 4, 14–15 December 2010

The data collection using direct reading instruments was conducted on these field trips. Data recording commenced on the first trip and concluded on the fourth trip, except for water level recording at Marlo, which continued until March 2011. Instruments used were:

Direct-reading T/S meters: 2 x TPS model WP84 Salinity/Temperature Meter, 1 x YSI model 30 hand- held Temperature/Salinity Meter.

Tide: 9 x Dataflow Systems Odyssey Pressure/Temperature Loggers (vented) and 8 x Reefnet Sensus Ultra Pressure/Temperature Loggers (unvented) with the latter mainly for back-up. In addition, 6 x temporary tide boards were installed.

Survey: Ceeducer Pro survey echo-sounder with integral DGPS, custom boat mounting; Trimble R8 GNSS Real Time Kinematic (RTK) Rover Surveyor RTK system, linked to the VicCORs survey network; Survey level; 2 handheld GPS units.

The dates of the four field trips for the 2011 EFR were:

Trip 1, 10–13 October 2011

Trip 2, 15–19 October 2011

Trip 3, 28 October – 1 November 2011

Trip 4, 13–15 November 2011

Direct-reading T/S meters: As for 2010 EFR.

The recording instrument array for the 2011 monitoring was expanded to permit a detailed assessment of both the Snowy and Brodribb River channels. The final 2011 instrument list is as follows:

Tide: 6 x INW Aquistar model 30 Pressure/Temperature recorders (unvented) were located at the Snowy and Brodribb River stations and provided a dedicated atmospheric pressure station at Marlo; 8 x Reefnet Sensus Ultra and 9 x Dataflow Systems Odyssey Pressure/Temperature Data Loggers were used as primary tide loggers at Orbost and Cape Conran, and as back-up at the other stations. In addition, 10 x temporary tide boards were installed.

Salinity: 9 x Dataflow Systems Odyssey Conductivity, Temperature recorders.
Survey: As for 2010 EFR.