Department of
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Physical response to the spring 2011 environmental flow release to the Snowy River estuary

SNOWY FLOW RESPONSE MONITORING AND MODELLING PROGRAM

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Cover image: The mouth of the Snowy River estuary under open conditions.

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Summary

Over the period 5 to 24 October 2011 a spring snow-melt environmental water release to the Snowy River via Jindabyne Dam occurred as part of the Snowy River Increased Flows program. The environmental water was released as a large pulse disturbance. A total of 84 Gigalitres were released over a 19 day period, with a maximum discharge rate of 12,000 MLd^{-1} over three days recorded. The objectives of the release were primarily focussed on the upper freshwater reaches of the Snowy River between Jindabyne to the junction with the Delegate River and were intended to scour the riverbed sediments and start to reshape the channel morphology by creating a better defined channel within the former river bed. However, environmental water requirements of estuaries are poorly understood and the 2011 spring water release provided an excellent opportunity to gain a better understanding of the physical changes to the Snowy River estuary. Additionally, the release provided a secondary benefit to calibrate the existing Snowy River estuary models.

The aims of the estuary study were to assess the salinity change and recovery within the Snowy and Brodribb estuarine channels, and to define any geomorphic changes to the entrance channel of the Snowy River. The data collection was conducted on four field trips, each of a few days duration, at approximately two week intervals in October and November 2011. Tide and salinity loggers were deployed over the period of measurement. Salinity profiles were taken at a high tide on each trip. Detailed bathymetric soundings were made of the Snowy River entrance channel using survey grade echo-sounders to measure physical changes of entrance conditions.

This report presents preliminary results and interpretations of the physical response to the release in the Snowy River estuary. The principal results were the recording of the “washout” of salt water from the upper Snowy estuary, followed by its slow return. At the peak flow of 12,000 MLd^{-1}, the lower estuary was brackish to a depth of 1.5-2m, but returned to predominantly sea water two weeks after the peak inflow. In both upper and lower Snowy, the vertical salinity gradients were increased by the flow, strengthening the salt wedge. At peak inflow, a weak salt wedge developed in the Brodribb River, just upstream of the confluence with the Snowy, but the flow remained well mixed over the depth in most of the Brodribb River throughout the release.

The “washout” has the potential to deflocculate bank silt deposits, raising water turbidity and weakening the banks, but has the benefit that overbank flows would be fresh and would not contribute to soil salination. The area of the estuary with oceanic or brackish salinity was reduced during the release, as it is during natural fresh events.

The geomorphic results were less clear owing to the occurrence in March and August 2011 of fresh inflows of greater magnitude than the environmental release in October 2011. The peak flow of the spring environmental water release caused minor erosion to the channel. Following the peak, additional sediment deposition occurred on the western edge of the channel because of a coastal storm on 25 October. This added another external forcing process to the entrance condition in the period encompassing the gradual flow reduction after the environmental flow release peak. In addition, a small catchment event some two weeks after the peak release flow further impacted on the entrance condition and salinity distribution within the estuarine reaches.

The data set is well suited to validating computer models of the estuary, and this study will be used in the near future to improve the validation of the two simple models which have already been used to demonstrate the feasibility of modelling the response of the estuary to transient flows. Once fully validated such models could form the core of a decision support tool to aid in management of the estuary.

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Introduction

Over the period 5 to 24 October 2011 a spring “snowmelt” environmental water release to the Snowy River via Jindabyne Dam occurred as part of the Snowy River Increased Flows program. A total of 84 Gigalitres were released over a 19 day period, with a maximum discharge rate of 12,000 MLd^{-1} over three days recorded, creating a large pulse disturbance. The objectives of the release were primarily focussed on the upper freshwater reaches of the Snowy River between Jindabyne to the junction with the Delegate River and were intended to scour the riverbed sediments and start to reshape the channel morphology by creating a better defined channel within the former river bed. The bed of the Snowy River is highly disturbed and contains large deposits of fine sediment from tributary inputs (Rose and Erskine 2012). Since regulation, the water releases from Jindabyne Dam have not been of sufficient magnitude, frequency or duration to adequately maintain the condition of the riverbed, a major constraint to the recovery of the freshwater reaches of the Snowy River (Erskine *et al*. 1999; Williams *et al.* 2011; Brooks *et al.* 2011).

Although the main aim of the Spring 2011 environmental release was to introduce a geomorphic flow by mobilising sediment up to the size of 256mm within the upper fluvial channel, the magnitude and duration of the release provided an opportunity to assess the influence of the release on the Snowy River estuary. The environmental water requirements of Australian estuaries are poorly understood (Peirson *et al* 2002. A data collection program was devised to record the salinity dynamics (i.e. change and recovery) and to assess any geomorphic changes to the estuary entrance channel. It is anticipated that understanding the physical response of the estuary to the larger environmental water releases will assist in providing a greater understanding of the requirements of aquatic biota within the estuary, such as Australian Bass.

This report follows the previous study by Mclean and Hinwood (2011) who assessed the smaller 2010 spring environmental water release but expands on the research by repeating the methodology of water level and salinity recording with automated loggers, long-profile salinity and temperature profiling over the course of the flow release and “recovery” period and hydrographic survey of the entrance dimensions on four occasions over the measurement period. This data will add to the studies of transient freshes in the Snowy Estuary (Water Technology, 2010; Hinwood and McLean, 2010) and provide a comparison with the smaller magnitude environmental flow release in Spring 2010.

The aim of this document is to present the preliminary analysis of the data from the Spring 2011 environmental flow release.

Study Area

The Snowy River hydrologic regime and the Snowy Mountains Scheme (SMS)

To contextualise the Spring 2011 environmental flow, it is necessary to briefly consider the "natural", pre-SMS river flow regime and the two regimes pertaining post-SMS. 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 snowmelt recession lasted for several months, and could have been regarded as a press disturbance to the estuary. The annual flow volume at Jindabyne was approximately 1,152 GLy^{-1} with approximately 50% of this volume passing during spring, particularly during October. Snow melt from the upper parts of the catchment formed the bulk of this increased discharge, raising the baseflow discharge to above 1000MLd^{-1} for 6 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 (Pendlebury *et al.* 1996; Morton *et al*. 2010). The lowest mean daily flow on record was in May 1912 at 106 MLd^{-1}. Particularly dry years occurred in 1938, 1940 and 1944 with total annual flow less than 600GLy^{-1}. High flow events occurred frequently, with annual floods of 20,000 MLd^{-1}. The highest mean daily flow on record, before the SMS, exceeded 76,000 MLd^{-1} in October 1917. The wettest years included 1913, 1915, 1917, and 1952 where annual flow volume exceeded 1,800 GLy^{-1}.

Additional variability in flow regime is attributed to rainfall events, where the river rose quickly and typically had a longer recession. These long flow recessions are typical of many of the montane rivers across the Snowy Mountains.

The Snowy Mountains Scheme (SMS) was constructed between 1955 and 1967. For the Snowy River, the overall long term diversion rate for the Snowy Scheme is 1130 GL year, with the entire flow regime adversely affected (Pendlebury *et al*. 1996, Morton *et al*. 2010). Large reductions in the median daily flow occurred along the length of the Snowy River with the greatest impact being in the upland reach at Dalgety where median flow declined from 2,469 MLd^{-1}to 40 MLd^{-1} (Morton *et al.* 2010). The SMS resulted in the spring snow melt signal being lost in the upper reaches below Jindabyne. Additionally, the hydrological contribution of tributaries had increased proportionally post the development of the SMS, increasing from 53% to 95% contribution of discharge at Jarrahmond in Victoria (Morton *et al*. 2010).

Most of the catchment below Jindabyne to the Delegate River is in a rain shadow and it's not until the junction with the Jacobs and the Pinch rivers that a small snow melt hydrological signal is delivered to the Snowy River. This highlights the importance of delivering the correct hydrological cues to the Snowy River from Jindabyne. Downstream of Jindabyne, the first major non rain shadow affected tributary entering the river is the Delegate River (90 km downstream from Lake Jindabyne) which is typically influenced by east coast weather patterns rather than snow melt (typically a warmer water relative to snow melt water).

Snowy River Increased Flows

In the late 1990s the NSW and Victorian state governments and the Commonwealth sought ways to return water to the Snowy River. The Snowy Water Inquiry (1998) prepared 23 costed options for the recovery of rivers affected by the SMS and recommended 15% MANF (140 GLyr^{-1}) for the Snowy River below Jindabyne, with flows mimicking a natural seasonal pattern SWI (1998). After a period of negotiations between shareholder governments (the NSW and Victorian state governments and the Commonwealth), returning up to 21% of MANF was adopted as a key goal of water reform (SWIOID 2002; Vanderzee and Turner 2002).

The Snowy River Increased Flows (SRIF) were calculated as 38 GL yr^{-1} (~4% MANF, the approximate combined MANF from the Mowamba River and Cobbin Creek) for the first 12 months, 142 GL yr^{-1} (15% MANF) after the first 12 months, and 212 GL yr^{-1} (20% MANF) after the first 7 years of increased flows, with options to increase flows up to 294 GL yr^{-1} (28% MANF) should there be agreement from shareholder governments to make further funding available.

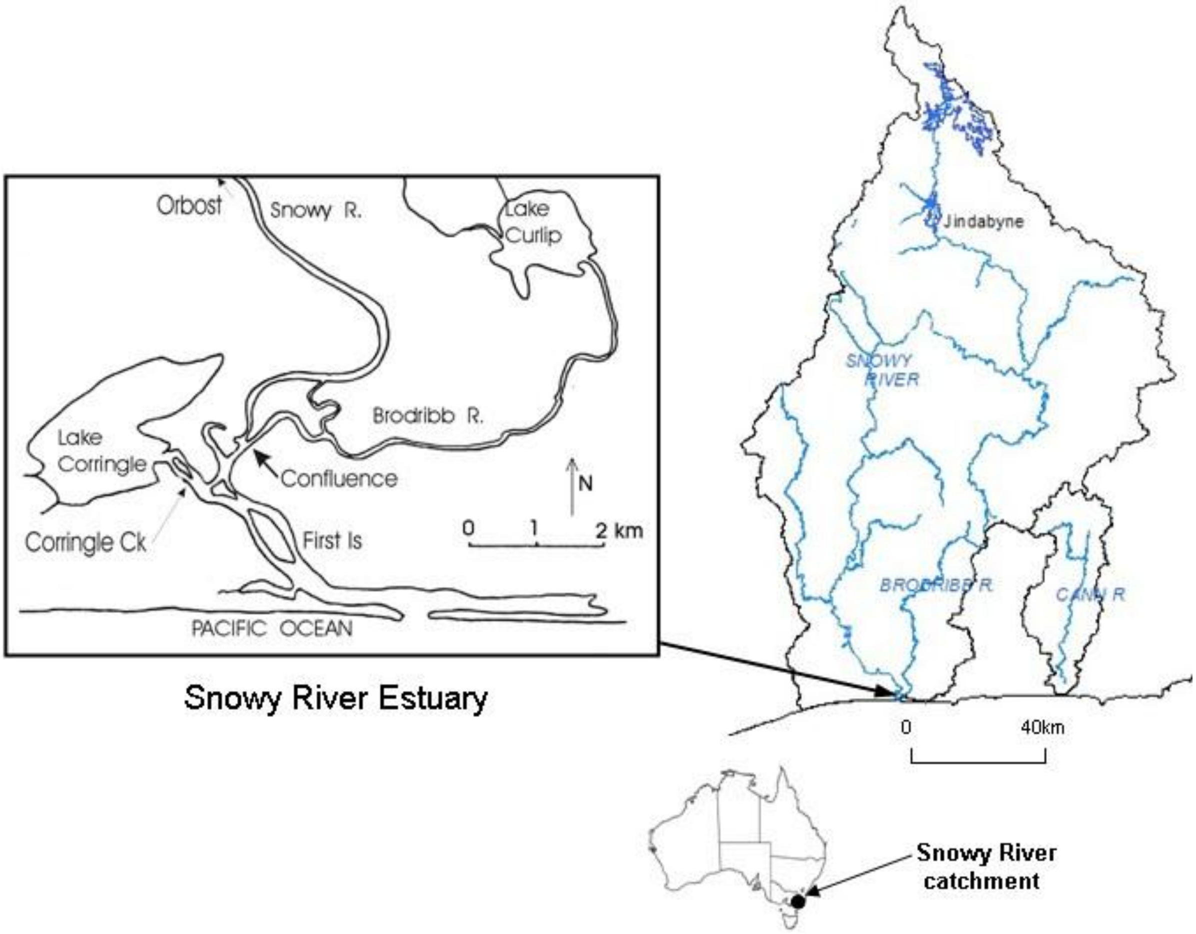


Figure 1. Location of the Snowy River and estuary, south eastern Australia.

The re-introduction of a spring snowmelts signal has been identified as a key component of the SRIFs to the Snowy River. Two spring environmental water releases have been delivered to the Snowy River, in 2010 a peak discharge of 3,080 Mld^{-1} and the Spring 2011 release of 12,000 MLd^{-1} (Figure 2). Given the configuration of the 2010 and 2011 spring releases they could be regarded as a single pulse disturbance.

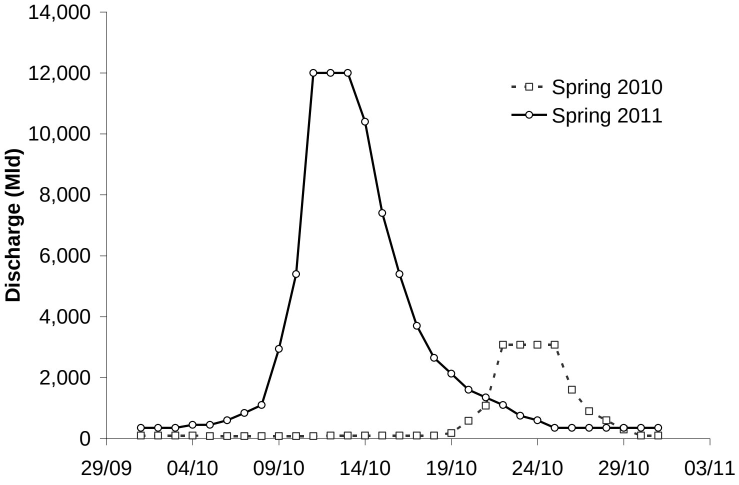


Figure 2. **Proposed Spring environmental water releases from Jindabyne Dam to the Snowy River for 2010 and 2011.**

Methods

The data collection was conducted on four field trips, each of 3 or 4 days duration, at approximately two week intervals in October and November 2011. The trips were timed to 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 channels (Figure 3) and tide loggers were installed at Orbost, Lake Corringle and Cape Conran. Salinity profiles were taken at a high tide on each field trip, in both the Snowy and Brodribb Rivers (for locations see Figure 8). Detailed soundings were made of the entrance channel and its plan form was surveyed.

Data on the environmental water releases were obtained from NSW Office of Water. The discharges in the Snowy River at Jarrahmond and the Brodribb River at Sardine Creek were obtained through the Department of Sustainability and Environment, Victoria. 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.

Field activities to measure the physical effects on the estuary, measured on the four data collection trips are listed in Table 1.

Table 1. Field activities to assess physical changes in the Snowy River estuary, 2011.

Activity	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
Survey entrance channel	Complete	Complete	Complete	Complete
Conduct salinity traverse of the Snowy and Brodribb River channels at high water	Complete	Complete	Complete	Complete
Tide and salinity loggers	Install all	Download and re-install	Download and re-install	Remove and download all

As shown in Table 1 and 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 and Upper Snowy on the Snowy at the confluence with the Little Snowy and tide and temperature loggers were also 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 tide so additional tide and salinity loggers were installed in the Brodribb River at the boat ramp jetty, upstream of the Marlo Road Bridge, at the Lake Curlip jetty and a tide logger was installed at Cape Conran. The principal tide station was Marlo Jetty. The water levels were tied to AHD by RTK survey.

To improve data security, most loggers were downloaded then re-installed on trips 2 and 3. Most of the tide loggers used were new, specially purchased AquaStar unvented pressure-type instruments, which provided improved recording stability and security over the older Odyssey pressure type used in 2010. In addition, a Reefnet Sensus logger was installed at each recording location as a back-up. All of the tide loggers also recorded temperature and they all required calibration for atmospheric effects via an atmospheric pressure logger which was installed at the project base in Marlo. Where water was sufficiently deep, loggers were installed on boards attached to existing jetties. At four locations the EGCMA installed 38mm water pipes to which the loggers could be mounted. At Lake Corringle and Cape Conran the water depth at the gauge site proved too shallow and tide readings from these locations have not been used in the study.

The entrance surveys each comprised a low-tide waterline mapping and a hydrographic survey of the areas below low tide level. The entrance hydrographic survey was performed using a CeeducerPro survey-quality echo sounder with integral DGPS location. The low-tide mapping of the channel boundaries was made using an RTK survey system, linked to the VicCOR survey network. The boundary surveys were undertaken close to low tide to allow first-order comparison of entrance planform changes. Temporary tide boards were installed on the estuary and seaward ends of the entrance channel during these surveys and were set to AHD by RTK survey.

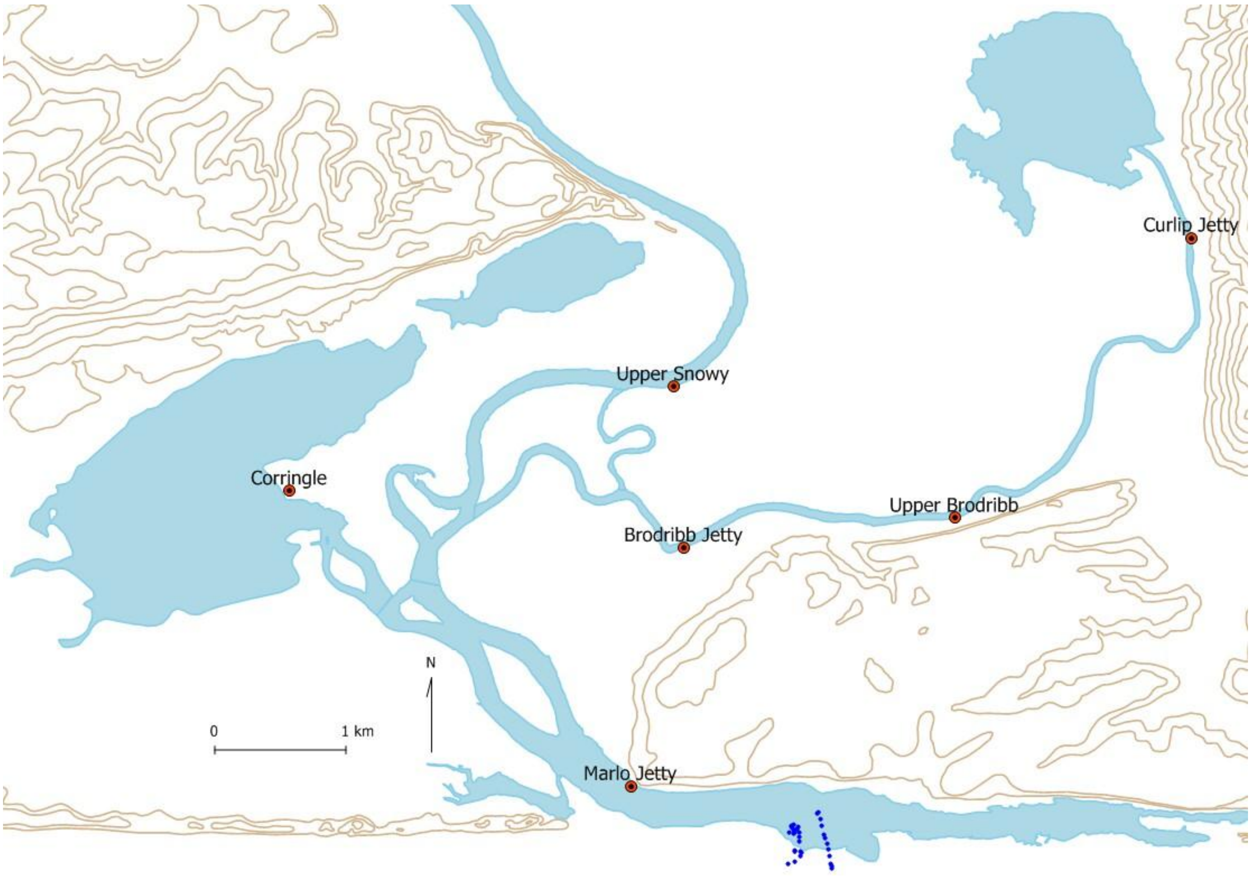


Figure 3. Data collection stations in the Snowy River estuary October-November 2011. The location of the entrance is indicated by the blue dots.

Results

Hydrology

The discharges of the Snowy and Brodribb rivers in 2011 are shown in Figure 4. The two sites display similar hydrological patterns through time, but the Brodribb River discharge is typically 5% to 10% of that in the Snowy River. These data show several flood peaks of very short duration, with a rapid rise, followed by weeks of gradual recession. A flood of 53,000 MLd^{-1} occurred in the Snowy River on 21 July and the Brodribb peaked at about 15,000 MLd^{-1} due to unusually heavy rainfall coming from an East Coast Low, situated to the south-east of the study area. A fresh of 12,900 MLd^{-1} occurred in the Snowy River on 11 August. Another minor fresh occurred after the release on the 11 November (just before Trip 4).

The key difference in the characteristics between the pulse environmental flow release and the natural catchment derived runoff events is that the release lasted about 3 days in contrast to the typical storm runoff peaks of one day.

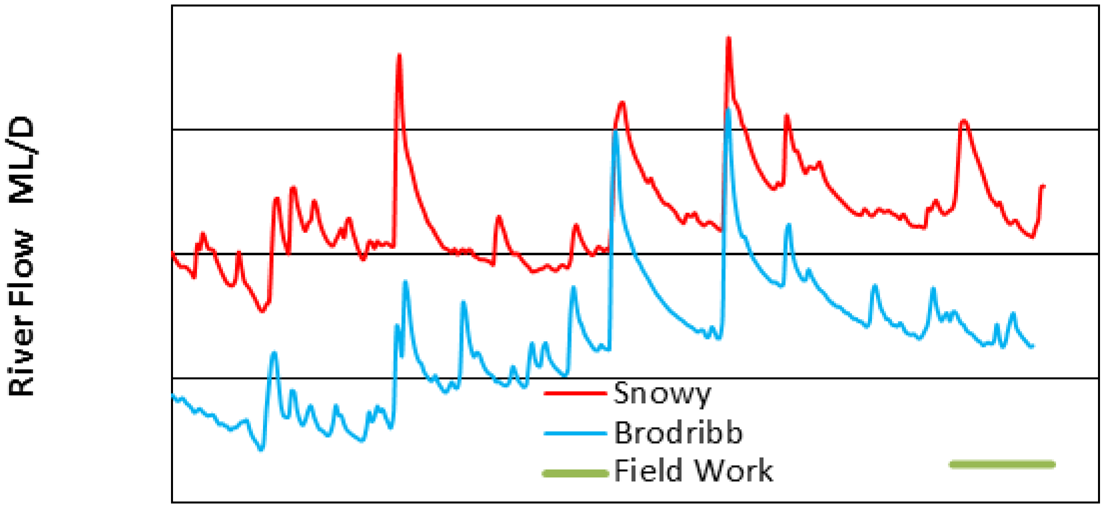


Figure 4. River discharge (MLd^{-1}) in the Snowy River at Jarrahmond (Red) and the Brodribb River (Blue) at Sardine Creek, 2011.

Water level data

General characteristics of the data

Complete tide records covering the period from October to November 2011 (i.e. Trip 1 to Trip 4) were obtained at each of the five principal sites: Marlo, Upper Snowy and Orbost on the Snowy River and Brodribb Jetty, Upper Brodribb and Curlip Jetty on the Brodribb River. Incomplete records were obtained at Lake Corringle and Cape Conran with both sites being too shallow to enable the full tide cycle to be captured on all days. In addition, a record was available for Marlo from 3 August to 9 September from work by the consultants outside this project. Commonly used abbreviations in tidal analysis and survey are listed in Appendix A.

The tide record at Orbost and the Snowy flow at Jarrahmond during this project are shown in Figure 5. These records show the direct response of the water level at Orbost to the flow at Jarrahmond. The Orbost water level lags Jarrahmond by about one day. The abrupt rise and fall at the end of these records was caused by a minor fresh flow which occurred two days before Trip 4. Prior to this fresh the Snowy flow and the Orbost water level were both levelling off smoothly.

The water level records obtained in October-November 2011 are shown in Figure 6. The results for Lake Corringle were very similar to Marlo, were incomplete and have been omitted. The trace for Upper Brodribb was very similar to that from Brodribb Jetty and has been omitted for clarity. The general trends observed are typical of most estuaries: the upstream stations had elevated mean water levels, in particular elevated low water levels, reduced tidal amplitude and increasing phase lag with distance upstream.

The water levels in the estuary responded directly to the 12,000 MLd^{-1} environmental flow release, whereas no significant changes in water level occurred with the 3,080 MLd^{-1} environmental water release in the 2010 (see comparison below). The water level in the Upper Snowy estuary responded first, while the rise in the other water levels lagged by one to two days. This lag is presumably due to the Upper Snowy estuary being sited on the Snowy River which had to pass all of the inflow in a relatively narrow channel while further downstream the flow divided, flowing down the lower Snowy River and running upstream in the Brodribb River and also into Lake Corringle. The inflow then had to fill the latter channels and associated wetlands as the water level rose, significantly reducing the rate of rise.

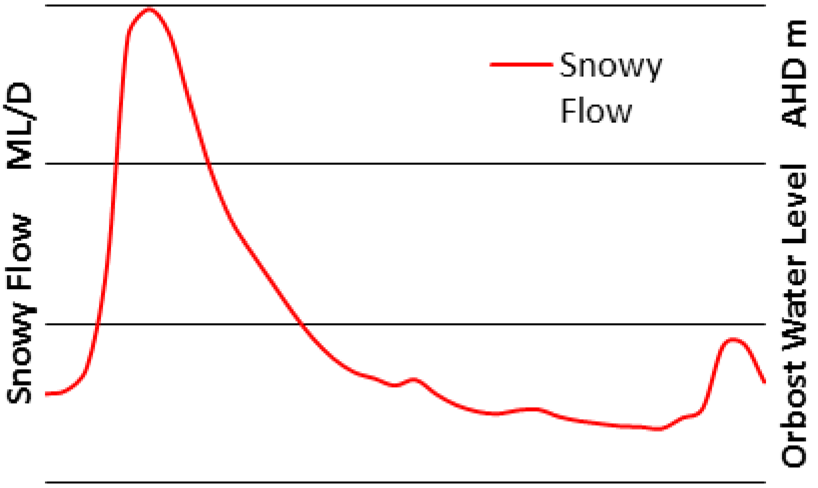


Figure 5. River discharge in the Snowy River at Jarrahmond and Water Level at Orbost for October-November 2011.

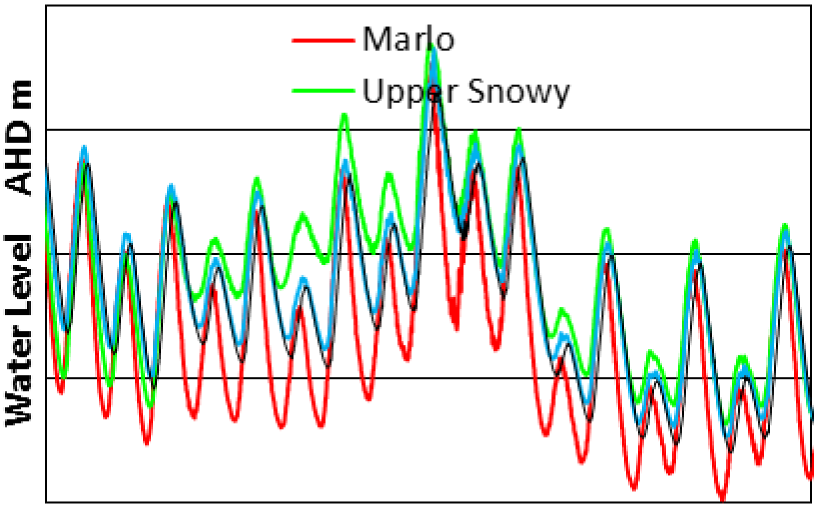


Figure 6. Water levels in the Snowy and Brodribb estuarine channels - October-November 2011

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 at about the end of the peak flow, probably through scouring of sediment bed forms in the entrance channel. This phenomenon has been previously reported in Lauchlan Arrowsmith and Hinwood (2011). To gain a more objective assessment, a tidal analysis was performed for the period August-November 2011, as described in the next section.

Analysis of the tides August – November 2011

The availability of an additional three months tidal record at Marlo has enabled the response and recovery of the entrance to be indirectly assessed by studying the changes in the M2 constituent of the tide (refer to Appendix A for abbreviations and terminology). When the entrance is constricted, the tidal amplitude in the estuary is decreased, the phase (lag) is increased and the mean water level in the estuary is higher. In estuaries with a small river flow, the relationship between the estuary tide and the entrance has been used to obtain a continuous surrogate measure of the entrance dimensions (Hinwood and McLean, 2001; McLean, Hinwood and McPherson, 2003). The effect of river inflow complicates this picture as a high river flow causes similar changes to a constricted entrance. The two effects may be separated through the use of a simple dynamic model (McLean and Hinwood, 2010). The first step in the analysis is to determine the amplitude and phase of the leading tidal constituents, day by day, over the period of record, then to interpret the results. This additional task was included as it adds considerably to the understanding of the conditions experienced and the longer term trends. The method of tidal analysis is outlined in Appendix B and the results are shown in Figure 7; dynamic modelling of the system has not been done.

In the tidal analysis, the five largest tidal constituents were calculated within a moving window of length 14 days. The clearest and most reliable information is given by the dominant M2 constituent and this is plotted in Figure 7B, with the phase plotted beneath the M2 line. There is a gradual and smooth reduction in the amplitude over the whole period, presumably recovering from the major flood in which the Snowy River inflow peaked at 53,000 MLd^{-1} on 21 July, 2011. The flood would have scoured and enlarged the entrance, allowing the efficient penetration of the tides and increasing the tidal range within the estuary. The reduction in the M2 value in Figure 7B was most likely caused by the entrance gradually constricting through the deposition of sand from coastal sources. The river inflow varied up and down over this period but had relatively little effect on the amplitude of the M2. The phase of the M2 was nearly constant over the period. Dynamic studies have shown that the phase changes rapidly when an entrance is severely constricted but otherwise is relatively insensitive, showing that the entrance was relatively wide open during this period. The phase did show a small oscillation of 14 day period, associated with the spring-neap cycle, but there was no evidence of spring-tidal pumping.

Large changes are evident in the measured tidal record, but the fact that 14 day plots are smooth strongly suggests that these changes are tidal. Two freshwater inflows occurred during the period 3 August-10 November, one with the Snowy River inflow peaking at 12,900 MLd^{-1}on 11 August followed by the Environmental water release peaking at 11,900 MLd^{-1}on14 October. The smooth 14 day trace shows that the adjustment to the occurrence of these fresh flows and the recovery following them occurred very rapidly. Features that warrant further investigation are the smooth but quite large fall in the mean water level and some fluctuations in the magnitudes of the M2 which appear to correlate with small phase changes in the M2 and the smaller constituents. Such investigation would include comparisons with meteorological and ocean tide records.

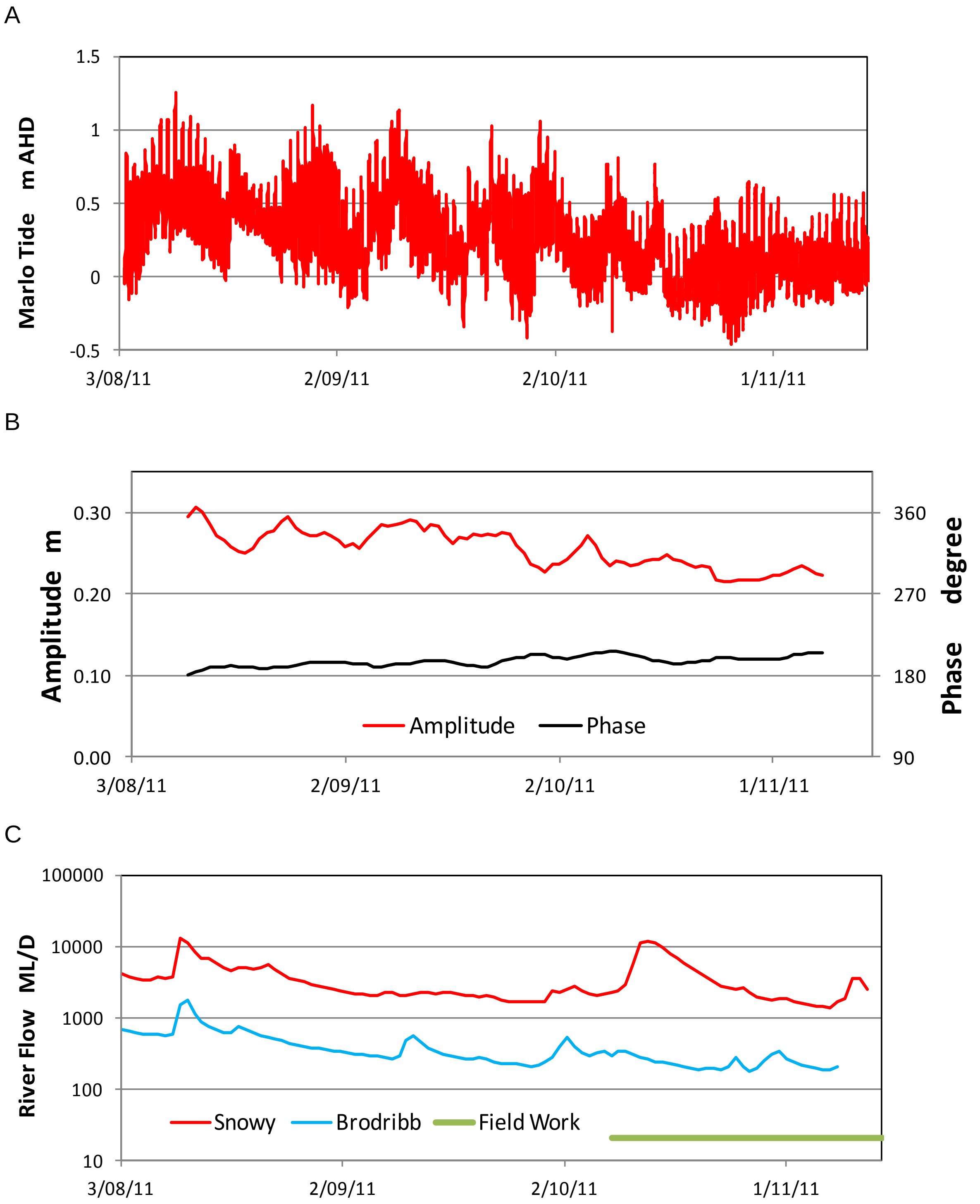


Figure 7. Time series of the Marlo A) tide record; B) Amplitude (upper line) and phase of the M2 tidal constituent; C) River inflows to the estuary, August-November 2011

Salinity data

Salinity Profiling

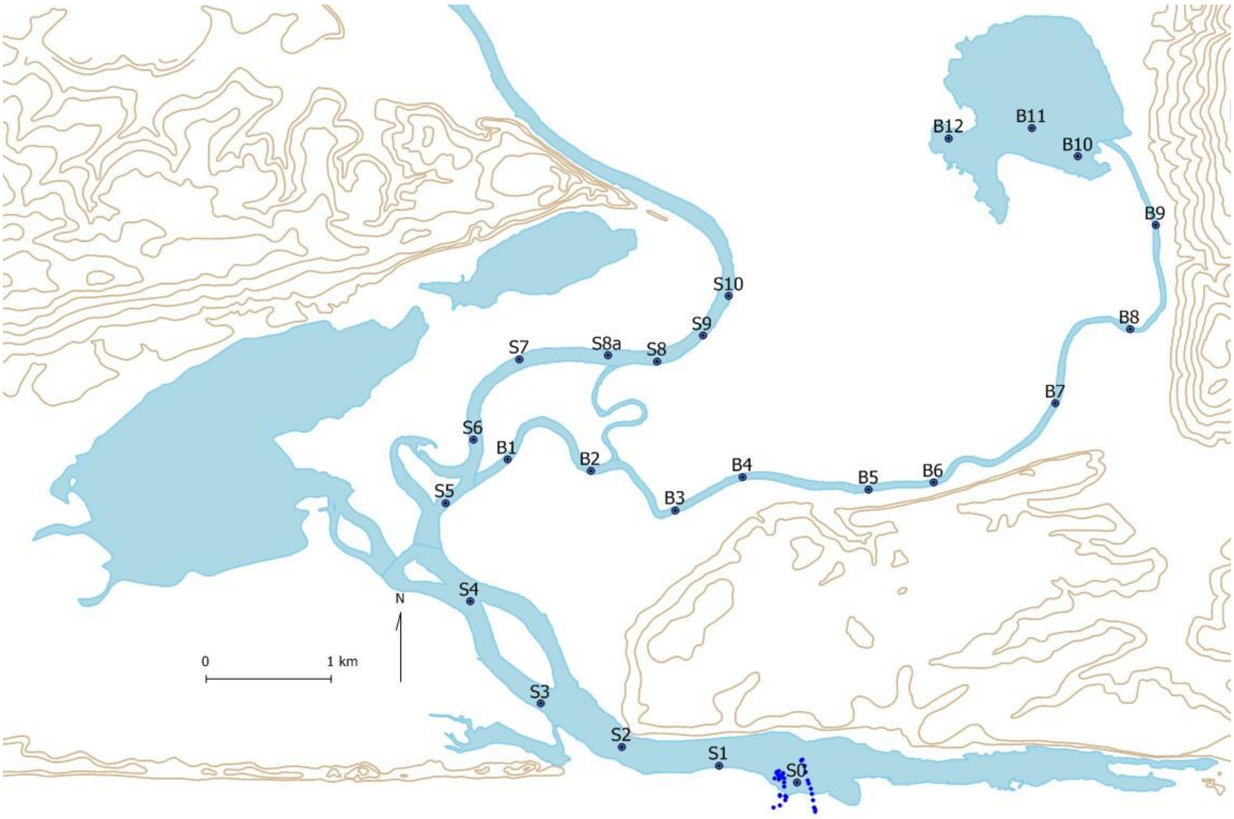


Figure 8. Salinity profiling stations in the Snowy River estuary October-November 2011.

The vertical profiles of salinity, obtained on a high tide on each trip, provide the most detailed picture of the salinity pattern. The profiles on each trip have been consolidated into a single longitudinal section with computer-drawn salinity contours. The profiles from each of Trips 1 through 4 for the Snowy River Estuary are shown in Figure 8. The computer drawn contours illustrate the general vertical and longitudinal patterns.

The profile from Trip 1 shows that saline water has only penetrated upstream to about 7km from the ocean, much less than previously observed under dry-weather flows (personal observations). There was a strong interface near the surface extending to about 6km upstream with the vertical structure changing from about the confluence with the Brodribb (4.4km from the entrance) and salinities becoming more uniform vertically while decreasing with distance upstream. Above 7km, the water in the channel was fresh. This measurement preceded the peak flow by about 3 days but was on the rising limb of the flow, well above dry-weather flow conditions and thus the pattern reflects the additional fresh water in the system.

The Trip 2 measurement was right at the end of the peak flow period and illustrates the displacement downstream of the salt wedge by the fresh water as well as the compression of the salt/fresh interface in the mid-estuary. By the Trip 3 measurement, the salinity structure had recovered to a pattern more typical of average, low flow conditions in the estuary. 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. Trip 4 exhibits a slight displacement of salt water downstream under the influence of a small catchment event in early November which added more freshwater to both the Snowy and Brodribb systems.

The profiles from the Brodribb (Figure 10) comprise the conditions for the Snowy below their confluence and the measurements taken at stations along the Brodribb River channel and extending into Lake Curlip. Trip 1 (Figure 10A) shows the presence of fresh water along the whole of the Brodribb in response to a catchment event just preceding the flow release as well as the beginnings of the flow release water from the Snowy system. Because of the Lake Curlip and wetland water storage, the effects of the natural catchment event are extended much longer than for a single in-line channel. A parcel of very slightly more saline water can be observed at the Lake Curlip end and by Trip 2 (Figure 10B) this has been displaced downstream while the mixed water in the lower Snowy has not impacted greatly on the lower Brodribb. By Trip 3 (Figure 10C), the normal vertically well mixed pattern has been re-established for the Brodribb system although the waters in Lake Curlip and the upper Brodribb remain much fresher than in normal or dry weather conditions. It should be noted that this pattern is significantly different from that usually observed in the Snowy system and is typical of the salinity regime for the Brodribb. By Trip 4 (Figure 10D) rainfall in the local Brodribb catchment has slightly displaced the saline water downstream although the pattern remains similar to that of Trip 3. For Trip 4, in the lower Brodribb, the upper layer 4 is largely fresh, due to both the recent catchment event and the residual fresh water from the Snowy flow release.

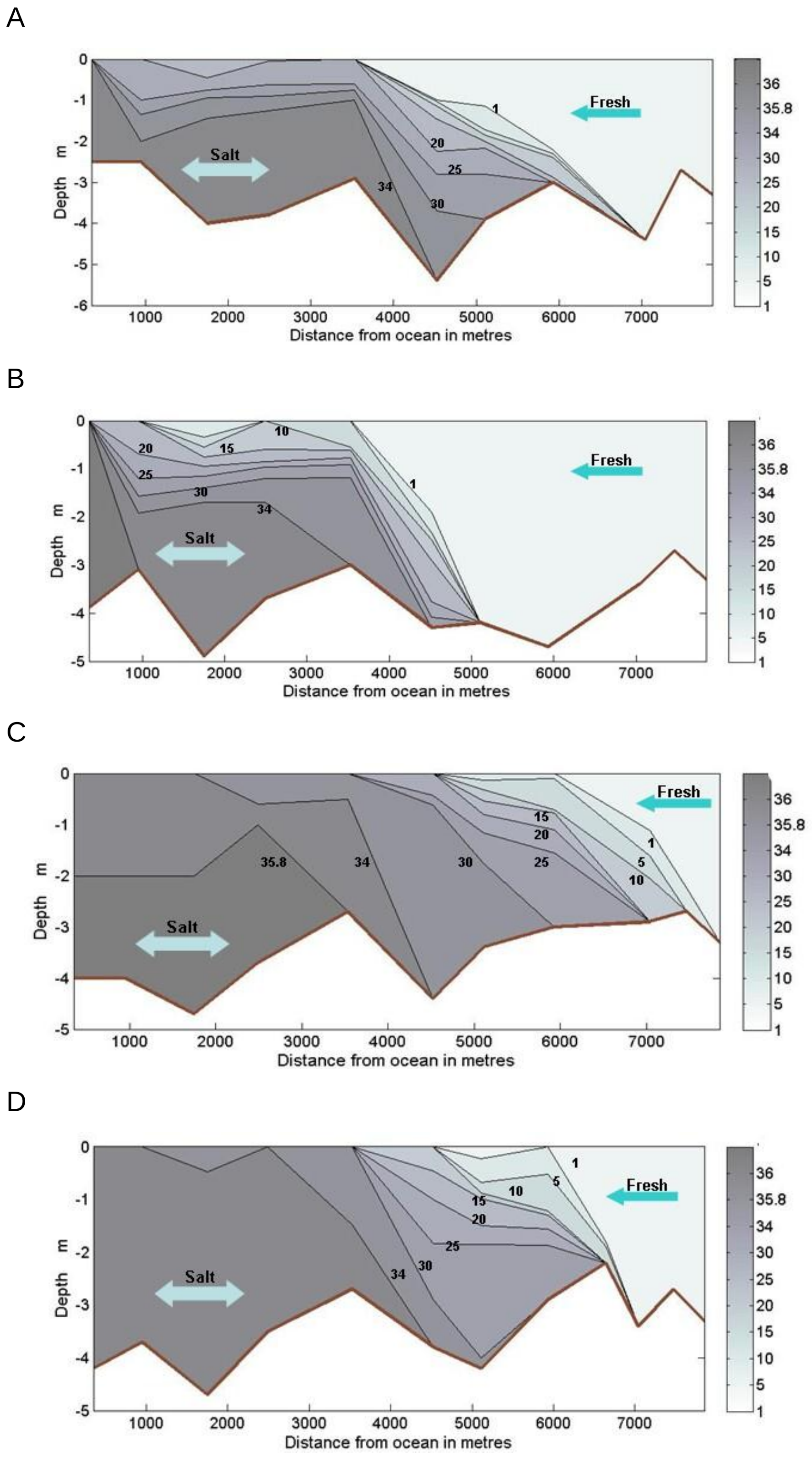


Figure 9. **Longitudinal profiles of salinity in the Snowy River on each trip. A Trip 1, 12 October (rising limb); B Trip 2, 16 October (just after flow peak); C Trip 3, 30 October 2010 (recovery period); D Trip 4, 14 November 2011 (recovery period, small fresh).**

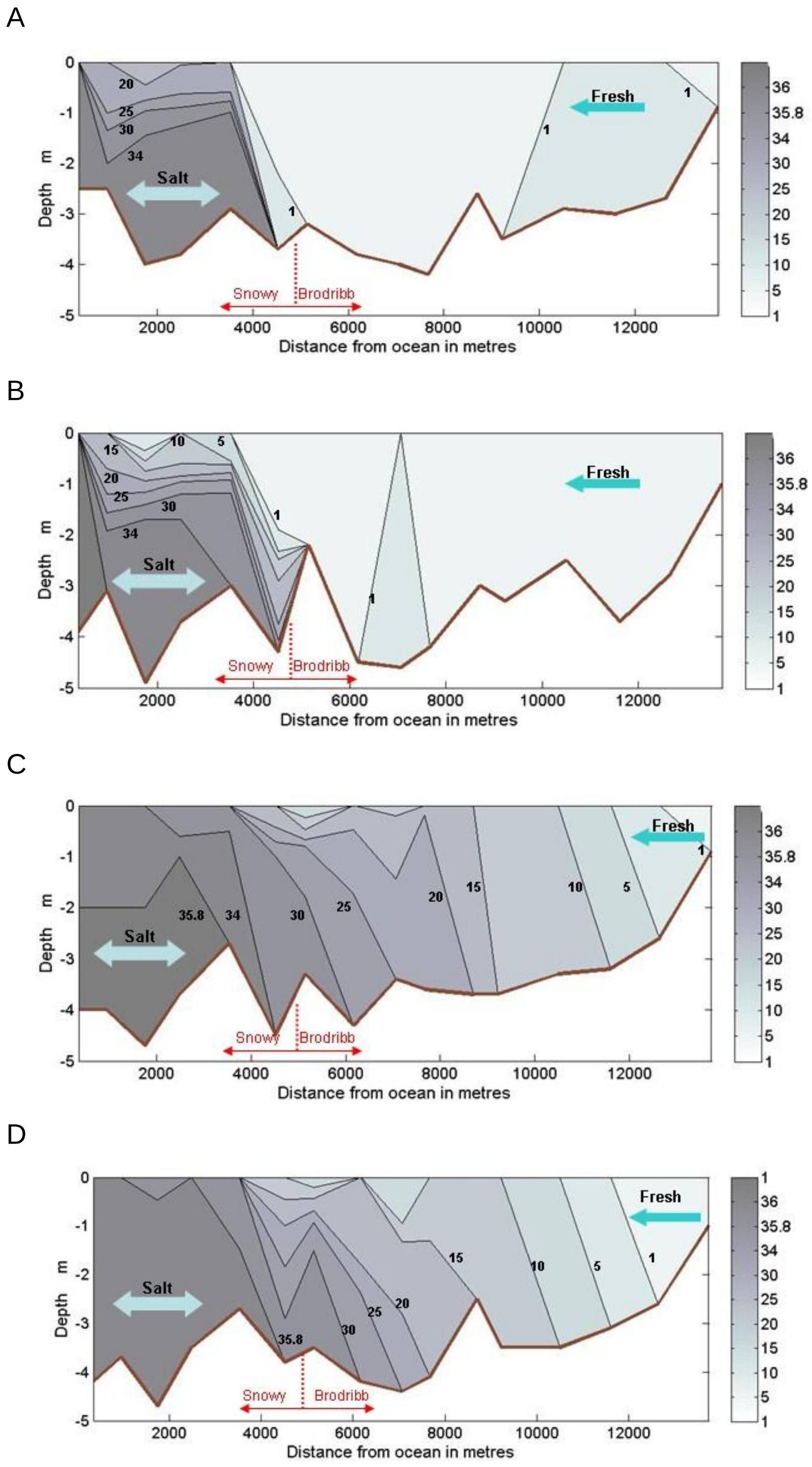


Figure 10. Longitudinal profiles of salinity in the lower Snowy-Brodribb River on each trip. A Trip 1, 13 October (rising limb); B Trip 2, 17 October (just after flow peak); C Trip 3, 31 October (recovery period) ; D Trip 4, 14 November 2011 (recovery period, small fresh).

Time records of salinity from recorders

While the profile data provides 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 clearly shows 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 summarize the mean, maximum and minimum salinities experienced at key locations in the two estuaries from a point just before the flow release peak and during the salinity “recovery”. A further “fresh” from the catchment has interrupted the salinity recovery towards the end of the measurement period.

Figure 11 shows the record from the loggers placed at the Upper Snowy station, Brodribb Jetty and Marlo Jetty from Trip 1 through Trip 4. 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).

Summary data plots from four of the loggers are shown in Figure 11, indicating 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 of the tide on the salinity and temperature at any point is the movement upstream and downstream. This movement transports more saline, and usually cooler (at this time of year) water upstream on the flood tide and fresher, usually warmer water on the ebb tide. A second action of the tide is to change the depth of immersion of the loggers. Variation in the immersion of the loggers 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.

In addition to the effects of the tide, the records also show changes due to the river inflow, the ocean tide and the mean sea level. As all these factors act together and are continually changing; a full analysis of their relative effects requires modelling which is not part of the present project, however the principal effects have been identified and are explained below.

Figure 11 shows that the salt wedge was washed downstream from 12 to about 20 October, while the river inflow was high, and for several days thereafter. The salinity interface observed on Trip 2 (Figure 9B) was sharper and stronger than on the other trips, so that as it was carried back and forth by the tides the salinity at any point near this salt wedge would have experienced greater changes than under the lower flow conditions of Trips 1 and 3. 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 in figure 11 illustrate the effects of a natural fresh flow from the catchment towards the end of the measurement period. At all stations, the salinity was reduced during the passage of the flow but recovered quickly. While the salinity was low the salinity range was also reduced, except for the lower logger at Marlo where the salinity range was increased from its usual limited high salinity range. During recovery the salinity rose as did the salinity range, again the lower logger at Marlo differed as the salinity range reduced. These patterns of change are qualitatively similar to those produced by the environmental flow release.

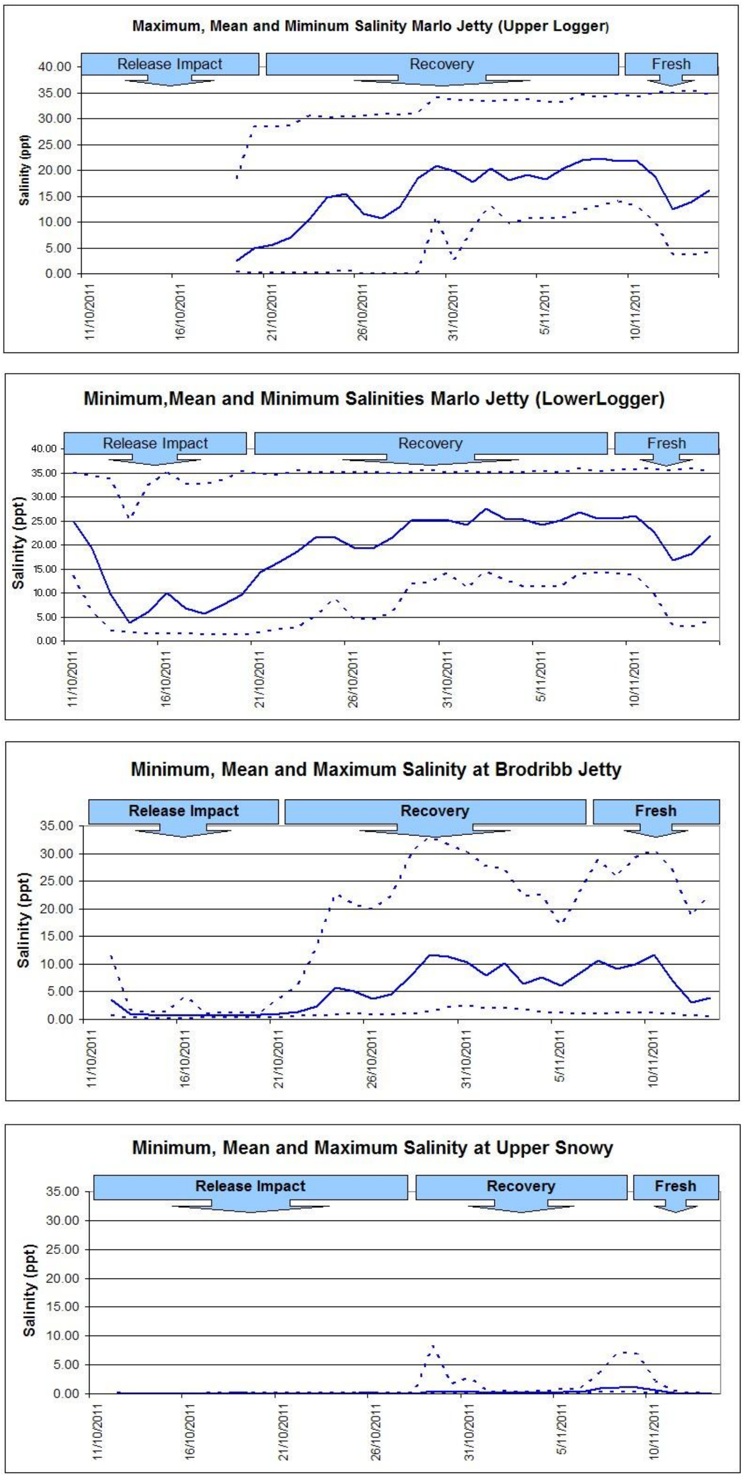


Figure 11. Minimum (dotted), Mean (solid line) and Maximum (dotted) salinity at three stations in the Snowy and Brodribb estuaries, November-December 2011.

Entrance morphology

Four entrance surveys were conducted over the measurement period, corresponding with Trips 1 to 4. Trip 4 was impacted by a freshwater catchment inflow and the entrance survey has not been included in this analysis.

The mapped low-tide waterlines (or wetted edge) of the entrance channel are shown in Figure 12. The ocean is to the south. The eastern boundary showed little change over the period while the western boundary was initially modified at the estuary end by the increased flow from the release and later, at the ocean end, by washover deposits associated with a coastal storm on 25 October 2011. These coastal storm deposits represent the largest change in the shoreline over the period of measurement. This was an external forcing, independent of the environmental flow release. The mid-entrance change to the western boundary between 12 and 18 October 2011 was more a function of slightly different water levels at the time of survey than a substantial change in near-shoreline topography.

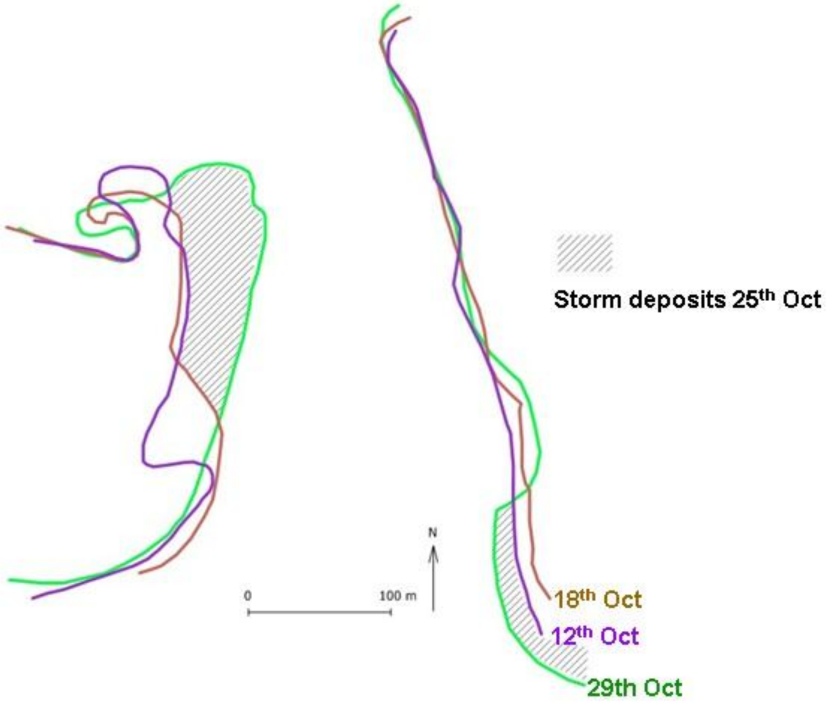
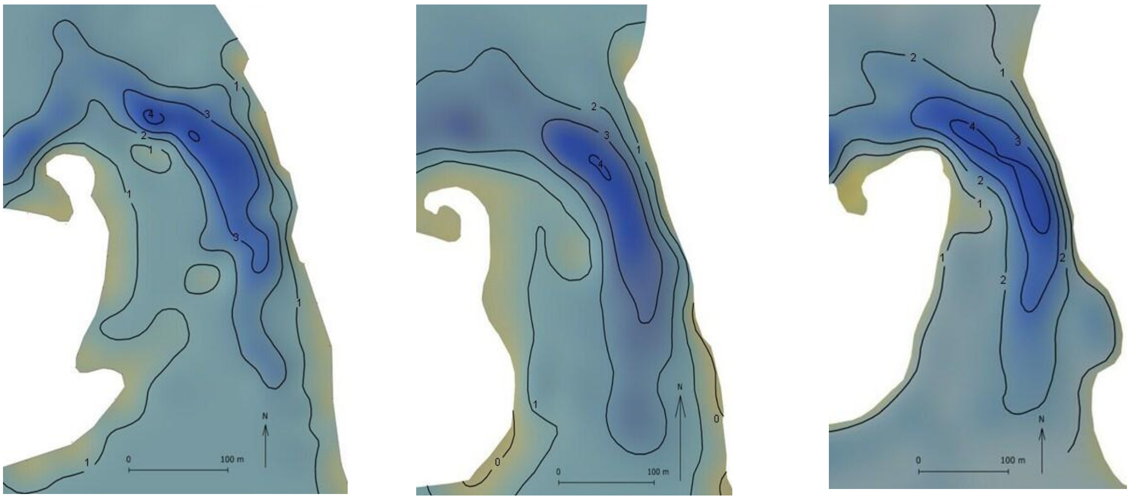


Figure 12. Entrance channel boundaries in the Snowy River estuary, October 2011.

Figure 13. shows the hydrographic survey results for Trip 1 (before the flow peak on 12 October), Trip 2 (just after the peak on 18 October) and Trip 3 (on the lower declining limb of the flow on 29 October). At the beginning of the Spring 2011 environmental flow release the entrance channel dimensions were still quite large, following a major catchment inflow from August when the entrance was scoured. The contours for the three surveys are quite similar in basic pattern, indicating that the initial entrance capacity was large enough to accommodate the environmental flow release without substantial change.



Trip 1 – 12 October

Trip 2 – 18 October

Trip 3- 29 October

Figure 13. Hydrographic surveys of the Snowy River entrance, depth contours m below AHD Zero.

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 level through the entrance. The cross sectional areas below -1m AHD changed only slightly, but the shore line at about 0m AHD at the estuary end and mid-way along the channel widened significantly. Thus the cross sectional areas available for flow did increase, particularly for conditions near HW when the tide in the entrance is flooding. It is worth noting that observations on these trips and in previous studies (personal observations) have shown that the estuary end of the entrance channel provides the principal resistance to both ebb and flood flows.

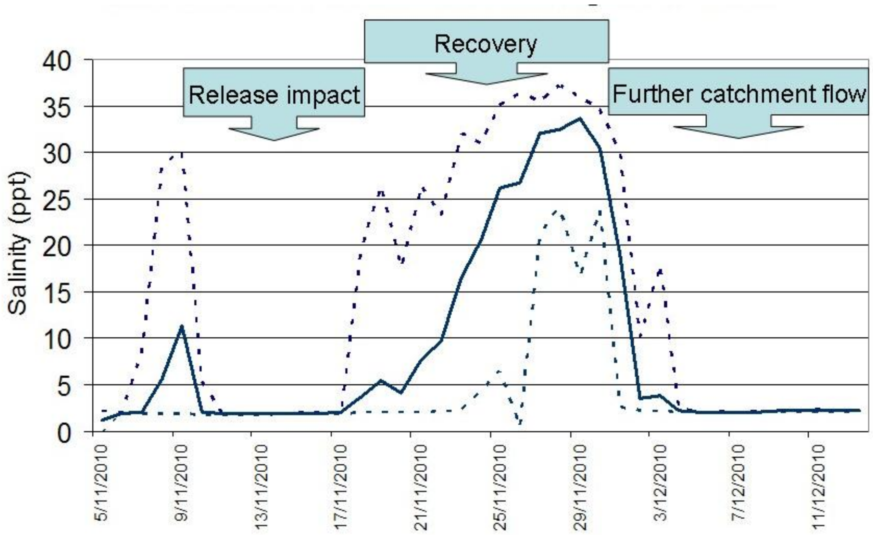
By Trip 3 on 29 October, the entrance had been modified on the western side by a significant washover deposit from a coastal storm on 25 October. This caused a narrowing of the entrance and resultant vertical scouring as the flows from the declining limb of the flow release were constrained.

Comparison of two spring environmental water releases

Two spring environmental water releases have been delivered to the Snowy River, in 2010 a peak discharge of 3,080 MLd^{-1} and 12,000 MLd^{-1} in 2011. The impacts of the two spring environmental water releases on the Snowy River estuary were similar in basic effects but varied in magnitude, and typically related to the different flow volumes, where the 2011 release was of an order of magnitude larger than that in 2010.

The variation in impact 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 14). There was a larger displacement of the saline water for 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.

A



B

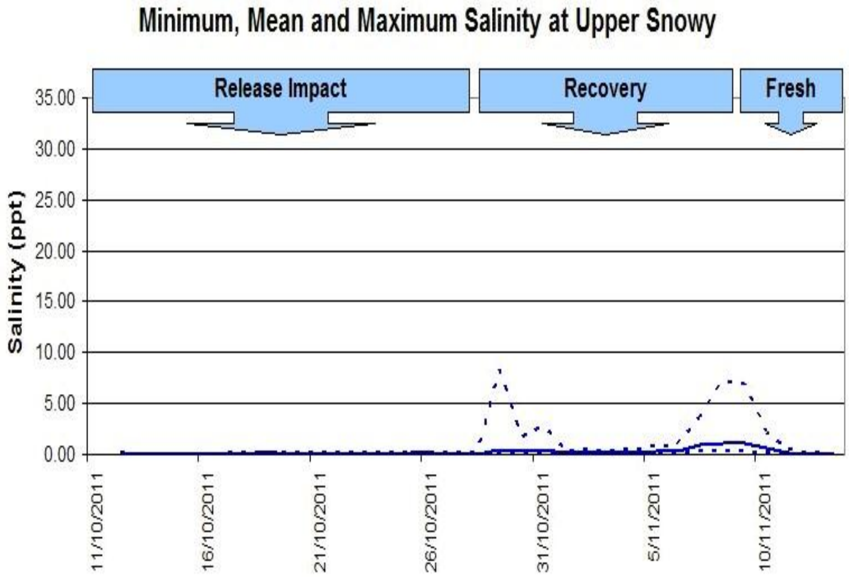


Figure 14. **Minimum (dotted), Mean (solid line) and Maximum (dotted) salinity at the Upper Snowy river estuary station in the upper layer of water, (A) November-December 2010 (B) October-November 2011.**

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 timeframe 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. Unfortunately no salinity data could be gathered from the Brodribb in 2010 for comparison.

The long profiles of salinity for Trip 2 (just after the peak release flow) for both releases are shown for comparison in Figure 15. 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 2m, compared with 0.7m in 2010.

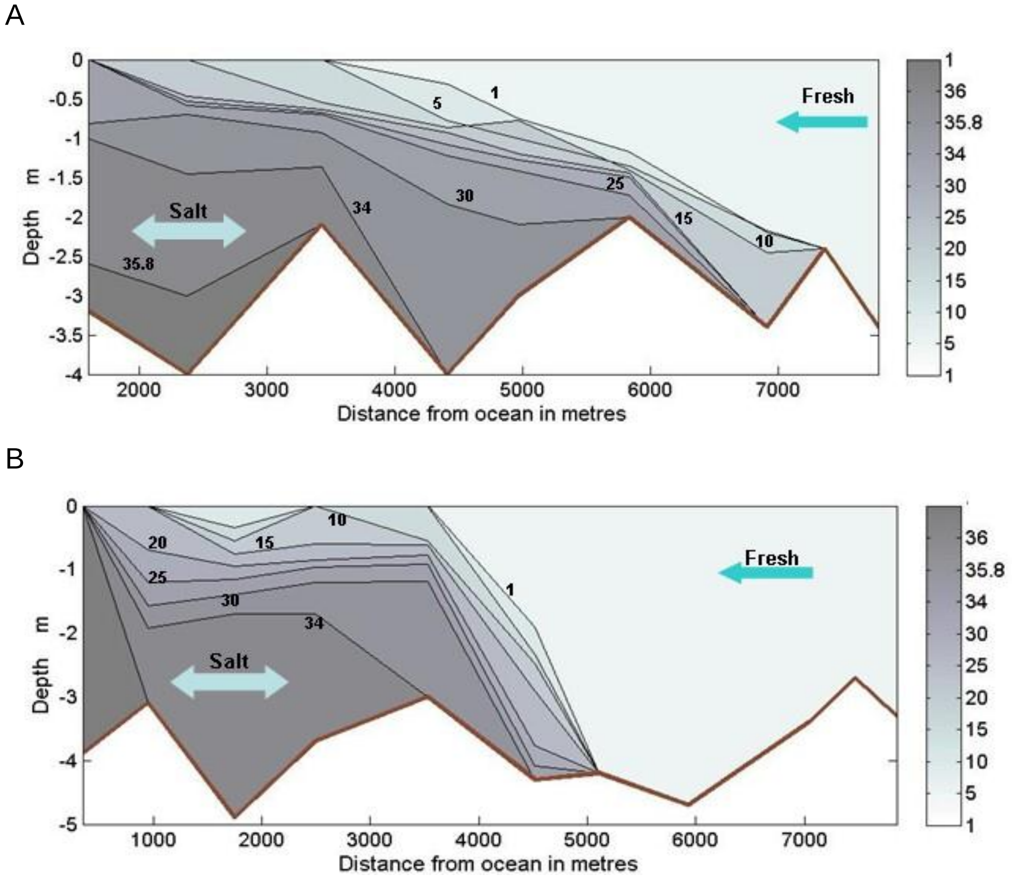


Figure 15. **Longitudinal profile of salinity in the Snowy River just after flow peak (Trip 2) (A) 16 November 2010, (B) 16 October 2011**

In both the 2010 and 2011 releases the actual entrance location is remarkably similar. In both cases the pre-existing entrance condition was approximately large enough to accommodate the release flows without major alignment or channel pattern change. The entrance state for the 2011 release was initially larger than in 2010, as a result of a major scouring catchment flow in August 2011, but, under the action of the release, enlarged in area above -1m AHD at the estuary end, which is the location of the principal flow resistance.

Conclusions

The impact of the Spring 2011 environmental flow release on salinity in the Snowy River estuary was to push the saline water seawards while the river flow was high. This resulted in reduced salinity and reduced salinity range in the upper estuary, and reduced salinity but increased salinity range in the lower estuary. The environmental water release was not sufficient to flush the entire estuary but the salt wedge structure was pushed down close to the mouth and the upper freshwater layer was clearly observable at the Marlo Jetty. Recovery to pre-environmental flow salinities was well on the way two weeks after the peak flow, largely as a result of the larger spring tides pushing seawater in through the large entrance. The salt wedge persisted longer in the Snowy following the larger 2011 flow as a result of the higher flows on the recession from the peak, compared with 2010, despite stronger tidal stirring.

The enhanced tidal stirring is considered to have accelerated the recovery of the usual vertically well-mixed salinity in the Brodribb. The changes in the salinity structure, including formation, persistence and longitudinal displacement of the salt wedge have implications for vertical mixing, including oxygen and heat transport to the deeper water layer. The salt wedge which is usually present in the Snowy River upstream of 3.5 km inhibits vertical mixing; the high flow increased the vertical salinity gradient, further reducing mixing, but pushed the salt wedge downstream, shortening it. Also during the higher flow, a salt wedge was formed in the lower Brodribb River. During the recovery phase, vertical salinity gradients in the lower estuary remained strong as the salt wedge extended upstream into the Snowy but the Brodribb River rapidly returned to a partially-mixed to well-mixed regime.

The Spring 2011 environmental flow, in conjunction with a moderate coastal storm, caused small increases in depth and configuration of the entrance channel. The environmental flow had been preceded by a much larger natural catchment flow and sustained flows above the dry-weather flow for about a month, consequently the entrance channel dimensions are likely to have been close to equilibrium for the environmental flow before it reached the estuary. Despite this, the entrance cross sections did increase through increase in the inter-tidal 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.

The study has confirmed the findings in 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. Further analysis of the data could calibrate the relationships between the Marlo tide, entrance conditions and river flow predicted by the previous work by Hinwood and McLean 2010.

The present data set provides a useful characterization of a reasonable size catchment flow as well as a prediction of the likely effects of a flow release of this magnitude with the entrance in a wide-open condition. This extends the data available for calibration of the 3D hydrodynamic model as well as adding to the dataset available for the characterization of the relationship between entrance condition and tidal exchange in the estuary.

Recommendations

Data requirements

The present pulse event based data collection has provided useful data but understanding influence of environmental releases on the estuary dynamics needs a more integrated and long term monitoring and modeling program. For example, the current records are too brief to capture extreme events or to develop the robust statistics that are essential for cost-benefit analysis. The records are also poorly suited to gaining the understanding of the system which could underpin the next generation of models or decision support tools. Developing a comprehensive and cost-effective long-term monitoring and modeling strategy would provide improved value for money, compared with the single event oriented data collection. Development of such a monitoring and modeling program will benefit greatly from the data gathered in this project, but goes well beyond the scope of this opportunistic event based project. Despite this long term monitoring and modeling requirement, the current project has identified several obvious information needs and these are outlined below.

Future monitoring methodology

The experience of monitoring the changes associated with the 2010 and 2011 environmental water releases (i.e. single pulse disturbances) provides some guidance for future data collection. The following recommendations should be considered:

i) The antecedent condition of the estuary is critical to understanding the changes caused by a brief transient flow event. Installation of a permanent water-level recorder in the estuary at Marlo Jetty is an urgent priority. An additional gauge to measure ocean tide and the salinity dynamics in the Brodribb River would provide greater explanatory capability.

ii) A program of planned monitoring, triggered by the occurrence of selected flow and other events would extend the range of data sets beyond those achievable with environmental water releases from Jindabyne. Such monitoring could include permanent recording of stream flow lower down the Brodribb, entrance observations from land-based cameras or satellite records, and long-term temperature and salinity observations.

iii) The entrance condition has been shown to be the major control on estuary tides and on salinity recovery. Entrance surveys for a wider range of flows are needed as simple extrapolation of the few available data sets is not warranted due to the complexity of the hydraulic and sedimentation regimes.

iv) Any future monitoring would greatly benefit from good permanent instrumentation supports. These supports must be in water of sufficient depth, must be robust enough for a boat to be moored alongside, and in well selected reaches of the estuary. This means jetties where they are suitable, otherwise driven piles. Our 2010 “zero cost” supports lead to some loss of instruments and data, while the 2011 pipe supports proved to be insufficiently robust and not all were in deep enough water. Other benefits of improved supports include reduced installation time and elimination of the need for resurveying on each monitoring, significantly reducing the time and cost of subsequent monitoring.

v) High quality instrumentation for water-level, salinity and water temperature is required.

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Appendix A – Glossary of Abbreviations

AHD	Australian Height Datum; the reference level for all surveys and very roughly equal to mean sea level.
DGPS	Differential GPS (see below), uses a radio link to precisely located base station(s) to improve the accuracy of GPS, compensating for variations in atmospheric conditions.
EGCMA	East Gippsland Catchment Management Authority
GPS	Global Positioning System; the satellite based system for determining position.
HW	High Water, high tide level.
LW	Low Water, low tide level.
RTK	Real Time Kinematic, a technique for improving the accuracy of GPS position fixing by using the carrier wave transmitted by a satellite rather than its much shorter signal.

Appendix B – Determination of the M2 tidal amplitude and phase

The following explanation of the method of tidal analysis is taken from Hinwood and McLean (2001). The waterlevels measured in a tidal estuary undergo changes in response to the tides, river flow, and the resistance to flow provided by the entrance and entrance channel. To quantify the changes, simple measures of the response are required over a period sufficiently long to reveal the responses or to achieve a regime state if one exists. Examination of the water level series for this and other estuaries (McLean and Hinwood, 1999) showed that a large part of the water surface oscillation is tidal. Hence it may be expected that a tidal harmonic analysis using a moving window will provide a measure of the changes which occur due to storms or floods. In this analysis, a time window is chosen and the waterlevel data within the window are analysed to determine the amplitude and phase of the leading tidal constituents. The window is then advanced by one day and the analysis repeated, and so on until a complete time series of the leading constituents has been computed.

Selection of the length of the time window is a compromise. The extremes of the estuary responses persist for only a few days. A window of this length would enable such rapid changes to be followed in time, but is too short to enable sufficiently reliable determination of the harmonic constants. On the south-eastern coast of Australia previous work by the authors has shown that at least 4 constituents are required: M2, S2, O1, K1, and a couple of others should be tested, in particular the N2. The dominant constituent is the lunar semi-diurnal, denoted by M2, and having a tidal period of about 12hr 25 min, the smaller S2 and N2 also have periods of about 12 hr while the S1 and K1 have periods of about 14 hr. Following Rayleigh’s criterion, two constituents within a tidal record can be distinguished if the time window is longer than the reciprocal of the difference between their frequencies. This is quite a robust criterion, permitting visual separation of the constituents on a spectral plot in the absence of significant noise. For the 4 constituents above it requires a window 14 days in length, while to obtain a reliable estimate of the N2 increases this to 28 days. These figures have been considered in selecting the window length. Note that the harmonic constants from this analysis are not intended for tidal prediction and should not be used for that purpose.

The analysis was performed using a 14-day window which was confirmed by trial as the minimum that gave stable values of the coefficients. The use of the 14-day window means that a storm event causing a water level anomaly starts to influence the computations 7 days before its occurrence and there are still effects of the pre-storm conditions up to 7 days after its occurrence. Thus stable values of the pre-storm conditions must be taken at least 7 days before the occurrence of the storm.