Journal & Proceedings of the Royal Society of New South Wales, vol. 150, part 2, 2017, pp. 152–171. ISSN 0035-9173/17/020152-20

Bedform maintenance and pool destratification by the new environmental flows on the Snowy River downstream of the Jindabyne Dam, New South Wales

Wayne Erskine[1], Lisa Turner[2], Teresa Rose[3], Mike Saynor[4] and Ashley Webb[5]*

[1] The late Wayne Erskine was Conjoint Professor, School of Environmental and Life Sciences, The University of Newcastle, Australia; Adjunct Professor, Research Institute for the Environment and Livelihoods, Charles Darwin University, Darwin, Australia; and Formerly Appointed Member, The Snowy Scientific Committee, Canberra, Australia. He died on 27 July 2017, after the revised paper had been accepted for publication.

[2] Forestry Corporation of NSW, PO Box 100, Beecroft NSW 2119, Australia

[3] RIVEROSE, 69 Bettington Circuit, Charnwood ACT 2615, Australia

[4] Environmental Research Institute of the Supervising Scientist, Darwin NT 0801, Australia

[5] NSW Department of Primary Industries, Tamworth Agricultural Institute, 4 Marsden Park Road, Calala NSW 2340, Australia

*Corresponding author. Email: ashley.webb@dpi.nsw.gov.au

Abstract

The hydrology, geomorphology and aquatic ecology of the Snowy River below the Snowy Mountains Hydroelectric Scheme were greatly altered by large-scale interbasin water transfers for power generation and the supply of water for irrigation until recent increases in environmental flow releases from Jindabyne Dam. Between 1967 and 2000 maximum releases from Jindabyne Dam were smaller than the lowest ever recorded mean daily discharge before flow regulation. The New South Wales and Victorian Governments agreed to return up to 28% of the natural mean annual flow to the river in keeping with recommendations from a community-sponsored Expert Panel. Detailed analyses of bedforms for 303 continuous km below the Scheme indicate that the new environmental flow regime will increase the pool-riffle spacing by between 3 and 294 m by increasing scour of pools and runs, and by reversing long-term channel contraction and pool infilling. Furthermore, strong thermal gradients and persistent oxygen stratification that produce bottom anoxia in upland pools will not develop under most environmental flows because of strong mixing. Even marked salt stratification in the upper estuary which can produce density differences of up to 14.9 kg/m^3 between surface and bottom waters is unlikely to develop in future.

Introduction

A key issue for many regulated rivers throughout the world is the determination of environmental flows to sustain aquatic ecosystems, to restore rivers degraded by flow regulation and to protect biodiversity for future generations (Petts 1996; Arthington et al. 2006; Poff et al. 2010; Williams, 2017). The basis of the problem is the conflict between the needs of aquatic ecosystems and the consumptive and economic requirements of water users (Petts 1996; Arthington et al. 2006; Poff et al. 2010). Dam releases driven by power generation, irrigation and water supply needs have greatly altered the timing, magnitude and duration of flows and sediment fluxes, thus severely degrading the morphology and habitat of many Australian rivers and their water-dependent flora and fauna (for example, Sherrard and Erskine 1991; Benn and Erskine 1994; Sammut and Erskine 1995; Erskine 1996a; Erskine et al. 1999a; 1999b; Arthington et al. 2006).

Large interbasin water transfers for hydroelectric power generation substantially changed the hydrology of the Snowy River downstream of Jindayne Dam between 1967 and 2000 (Figure 1). The maximum releases from the dam before recent structural changes to the outlet and spillway were usually only 63% of the lowest mean daily discharge ever recorded at the same site over the 54 years before the Scheme (Brizga & Finlayson 1994; Erskine et al. 1999a). Such hydrologic changes have also significantly impacted on the geomorphology and aquatic ecology of the river (Davies et al. 1992; Brizga & Finlayson 1994; Erskine et al. 1999a; 1999b; 2001; Turner & Erskine 2005). According to Brookes and Shields (1996), river rehabilitation refers to a partial return of a river to a pre-regulation structure or function which can require enormous amounts of expenditure (Williams 2017).

The implementation of a ‘restoration protocol’ (Stanford et al. 1996; Lake et al. 2007) or an ‘ecologically acceptable flow regime’ (Petts 1996; Poff et al. 1997) which will partially reverse the recent geo-ecological changes of the Snowy River was first proposed by a community-sponsored expert panel (Anon 1996).

The Snowy Water Inquiry was set up as part of the corporatization of the Scheme’s management authority. The Inquiry provided, among other things, the New South Wales and Victorian Governments with fully costed options for the restoration of the Snowy River (Anon. 1998). However, the Inquiry never considered the restoration option, i.e. the complete structural and functional return of the Snowy River to a pre-regulation state (Brookes & Shields 1996). The Inquiry’s recommended flow option (option D) involved the release of 10% of the pre-Scheme mean annual flow from Jindabyne Dam with another 5% being delivered by the decommissioning of the Mowamba River Aqueduct. This option was supposedly sufficient to provide minimum habitat utilisation flows, flushing flows and channel maintenance flows. However, these flows were not quantified. The Inquiry’s composite option F crudely approximated the Expert Panel’s (Anon. 1996) recommended flow regime (25% of the pre-Scheme mean annual flow) but was not recommended (Anon. 1998). River and catchment works were also recommended to further improve stream condition (Anon 1998). A similar situation has also occurred more recently throughout the Murray-Darling basin (Williams 2017).

The New South Wales and Victorian Governments did not implement the Inquiry’s recommendations. Instead a new water allocation was finalized on 6 October 2000 following the efforts of Victorian Independent MP Mr Craig Ingram. It was agreed that A$300 x 10^6 would be spent over the next 10 years to return 21% of the natural mean annual flow to the Snowy River. A subsequent increase to 28% was envisaged after 10 years. Rose (2017) has shown that the new environmental flow regime has certainly improved, to some degree, river condition and health.

The purpose of this paper is to determine whether the Expert Panel’s recommended environmental flows were adequate to reverse channel contraction and pool infilling by increasing bedforms and aquatic habitats, and to destratify upland pools near Jindabyne Dam as well as shallow pools in the upper estuary. Turner & Erskine (2005) established that upland pools and pools in the upper estuary were occasionally oxygen stratified during low flows and/or unusually hot weather. These issues were not considered by the Expert Panel (Anon. 1996) or by the Snowy Water Inquiry (Anon. 1998) or by previous research on the Snowy estuary (Hinwood & McLean 1999a; 1999b). The Snowy Mountains Hydroelectric Scheme (SMHS) is briefly outlined below because it is necessary to appreciate the magnitude of its impacts on the Snowy River below Jindabyne Dam.

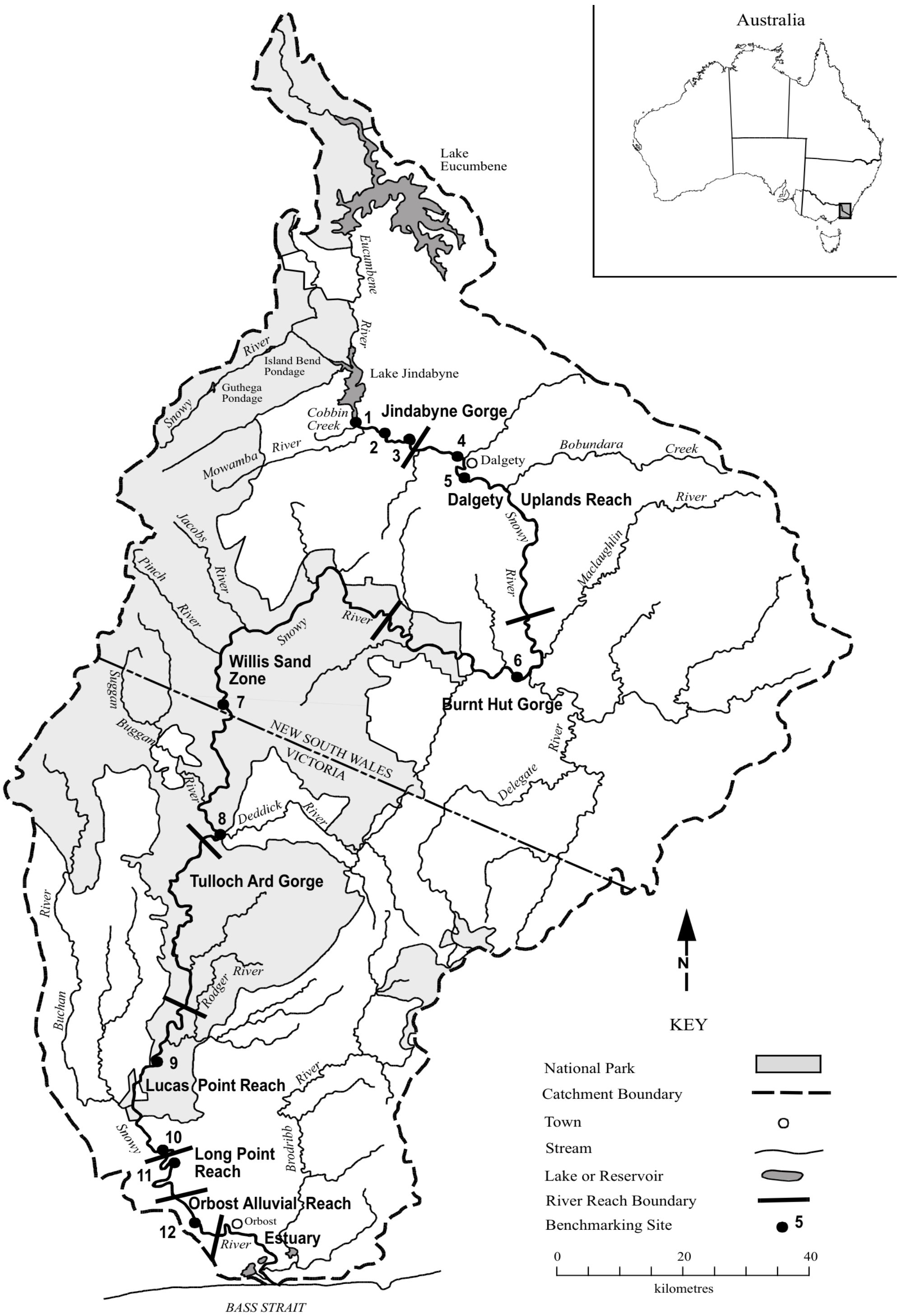
Snowy Mountains Hydroelectric Scheme

The SMHS diverts water from the upper Snowy, Murrumbidgee and Tooma rivers in the Snowy Mountains into either the Tumut or Swampy Plains River, generating hydroelectric power in the process. The Scheme was built between 1949 and 1974 at an historical cost of A$800 x 10^6 (Frost 1983). Engineering features of the Scheme include 16 large dams, many more smaller structures, 145 km of tunnels, seven power stations, one pumping station and 80 km of aqueducts (Anon 1993; Dann 1969; 1970). The total generating capacity of the Scheme is 3.74 x 10^6 kW and, on average, 2.36 x 10^9 m^3/yr of additional water is made available for irrigation purposes on the Murray and Murrumbidgee rivers (Anon 1993).

Just within the Snowy River catchment, there are two large dams (Eucumbene and Jindabyne), two small dams (Guthega and Island Bend), one pumping station, one power station, five tunnels and nine aqueducts (Anon. 1993). Eucumbene and Jindabyne Dams are the most important in terms of their effect on flow regulation of the Snowy River and Eucumbene Dam is the largest reservoir in the SMHS (Anon. 1993).

Jindabyne Dam stores runoff from the Snowy River catchment below Island Bend and Eucumbene Dams as well as spills and releases from both dams (Figure 1). Eucumbene Dam has never spilled. The original siphon outlet on Jindabyne Dam could release up to 0.57 m^3/s (Howard & Holliday 1968) and was rebuilt to release the new environmental flows (see below). The Mowamba River Aqueduct diverts up to 4.8 m^3/s from Cobbin Creek and Mowamba River, two right bank tributaries of the Snowy below Jindabyne, upstream into Jindabyne Dam (Howard & Holliday 1968). In 1961, the licensing authority determined the releases from Jindabyne Dam only on the basis of the existing and predicted downstream consumptive water uses to be 'visible flow' in the Snowy River above its junction with the Mowamba River, a discharge of not less than 0.081 m^3/s immediately downstream of the Mowamba River, a discharge of not less than 0.284 m^3/s immediately downstream of the Dalgety gauging station, a discharge of not less than 0.197 m^3/s immediately downstream of the Snowy-Delegate rivers junction and a maximum release from Jindabyne Dam of 0.57 m^3/s or the estimated natural inflow to the reservoir when less than 0.57 m^3/s (Clarke & Bate 1992; Bate & Whalley 1993).

Figure 1 (opposite): The Snowy River catchment showing the river reaches defined in Table 1 and Snowy River benchmarking sites, some of which were used for stratification studies.


Australia
Lake Eucumbene
Eucumbene
River
Lake Jindabyne
Island Bend Pondage
Guthega Pondage
Snowy
River
Cobbin Creek
Jindabyne Gorge
Mowamba
River
Dalgety
Bobundara
Creek
Dalgety
Uplands Reach
River
Snowy
River
Maclaughlin
Jacobs
River
Pinch
River
Snowy
River
Willis Sand Zone
Burnt Hut Gorge
Suggan
Buggan
River
NEW SOUTH WALES
VICTORIA
Delegate
River
Deddick
River
Tulloch Ard Gorge
River
Buchan
Rodger
River
Lucas Point Reach
River
Brodribb
Snowy
Long Point Reach
Orbost Alluvial Reach
Orbost
River
Estuary
BASS STRAIT
N
KEY
National Park
Catchment Boundary
Town
Stream
Lake or Reservoir
River Reach Boundary
Benchmarking Site
0
20
40
kilometres
1
2
3
4
5
6
7
8
9
10
11
12

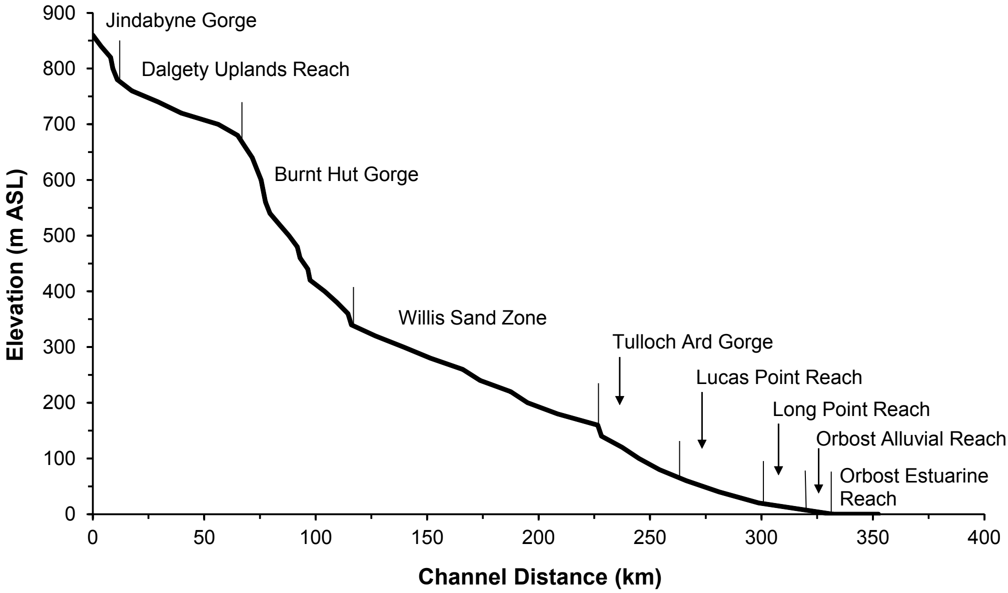


Figure 2: Longitudinal profile of the 352.5 km of the Snowy River downstream of Jindabyne Dam compiled from 1:25,000 and 1:50,000 topographic maps. The channel reaches outlined in Table 1 and mapped in Figure 1 are also shown.

Table 1: Channel reaches in italics and post-regulation changes in flows, sediment inputs, channel morphology, bed sediment and riparian vegetation on the Snowy River below Jindabyne Dam. Bedform terminology follows Grant et al. (1990). Channel reaches are shown in Figures 1 and 2. River types follow Erskine et al. 2017.

Channel Reach	**Reach Characteristics**	**Post-Regulation Channel Changes up to 2000**
Jindabyne Gorge (11.5 km long) Granodiorite Gorge river type	Channel deeply incised into plateau of Late Silurian granodiorite of the Kosciuszko Batholith, producing a gorge. River debouches from the gorge at the Barneys Range fault scarp. Bedrock and boulders laterally and vertically confine the channel, producing a steep slope (7.1 m/km) punctuated by gravel riffles, rapids and cascades with boulder and bedrock steps separating occasional long remnant pools, especially on valley bends. There is often a narrow inner bedrock channel flanked by bedrock shelves veneered with thin sediment deposits and peat. Limited bar and bench development at valley expansions and bends, and downstream of tributary junctions.	Mean annual flow reduced by 98% and all floods suppressed. Episodic thermal and oxygen stratification develops in deep remnant pools. Channel contraction; vegetation invasion on channel margins; pool infilling with clastic and biogenic sediment; formation of *Phragmites australis* chokes on former riffles, tributary mouth bars and thick fine-grained sediment laminae in bed; peat formation on bedrock ledges beside inner bedrock channel. Fine sediment intrusion into bed sediment; lichen colonization of exposed bedrock surfaces.
Dalgety Uplands Reach (57.5 km long) Laterally bedrock confined and vertically bedrock constrained river type	Channel flows across Monaro Tableland and frequently impinges against or flows across a range of rocks of Ordovician Adaminaby Group and Late Silurian granodiorite and adamellite of the Berridale Batholith. Short sections of gorge occur repetitively. Flatter bed slope (2.1 m/km). Well-developed, vegetated bars of sand and gravel. Relatively shallow pools floored by fine-grained sediment laminae and submerged macrophytes. Limited floodplain development.	Mean annual flow reduced by 94% and flood flows greatly suppressed. Channel contraction; vegetation invasion of channel margins; bed aggradation and sediment storage; formation of *Phragmites australis* chokes, tributary mouth bars and thick fine-grained sediment laminae in bed; fine sediment intrusion into bed. Lichen colonization of exposed bedrock surfaces.
Burnt Hut Gorge (57 km long) Adamellite Gorge river type	Steep gorge (5.9 m/km) cut into Monaro Tableland, exposing mostly Late Silurian adamellite of the Berridale Batholith and Silurian Yalmy Group. Bedrock fall (Snowy Falls) at downstream end. River closely vertically constrained and laterally confined by bedrock. Channel characterised by steep bedrock and gravel rapids and long pools.	Substantial flow reduction. Suspended sediment plumes generated by unregulated Delegate River. Sand inputs from gully erosion of granitoid areas on Monaro Tableland. Vegetation invasion, particularly by exotic tree species; fine sediment intrusion into bed.

Channel Reach	**Reach Characteristics**	**Post-Regulation Channel Changes up to 2000**
Willis Sand Zone (93.5 km long) Laterally bedrock confined and vertically bedrock constrained river type	Channel alternates between relatively flat, sand-bed sections flanked by extensive side bars and steeper bedrock sections with rapids, falls and bedrock inner channels. Slope much less than upstream (1.6 m/km). Valley floor trough wider than upstream. Granodiorite and adamellite of the Kosciuszko Batholith outcrop in bed.	Substantial flow reduction. Substantial historical local sand input from soil erosion. Vegetation invasion, particularly by exotic plant species; loss of native riparian trees due to lower water tables; extensive sandy side bar and bench development in flatter sections.
Tulloch Ard Gorge (41.5 km long) Volcanic Gorge river type	Deep, narrow channel cut through resistant granodiorite and Snowy River Volcanics Group. Steep bedrock gorge (2.4 m/km) with long pools and steep rapids, cascades and falls.	Substantial flow reduction. Little sediment storage in channel, except in large pools; and weed invasion of riparian zone.
Lucas Point Reach (22.5 km long) Laterally bedrock confined and vertically bedrock constrained river type	Channel laterally confined and vertically constrained by bedrock. Slope less than upstream (1.2 m/km) deep pools present and some sand storage in pools, point bars and benches. Bedrock and gravel rapids, gravel armoured bars and small inner bedrock channel present.	Mean annual flow reduced by 29%. Vegetation invasion, particularly by exotic plant species in the riparian zone; sand storage in pools, bars and benches.
Long Point Reach (18 km long) Laterally bedrock confined river type	Deeply incised, irregular, sinuous bedrock valley which laterally confines channel. Abrupt change to sandy bed-material because of slope reduction (0.7 m/km). Common sand bars and benches with spatially disjunct riparian vegetation.	Mean annual flow reduced by 12%. Exotic vegetation invasion; pools rapidly infilled with sand after flood scour; substantial sand storage in the bed but gravel armoured sections still occur.
Orbost Alluvial Reach (11 km long) Straight sand-bed channel river type	Extensive floodplain borders sand-bed channel which occasionally impinges against bedrock valley sides. Relatively straight sand-bed channel in upstream section with transverse, longitudinal and side bars, often flanked by benches. Slightly sinuous channel with point bars further downstream. Smaller channel capacity in slightly sinuous section because of extensive flood channels on the floodplain.	Substantial flow reduction. Replacement of bank-attached, alternating sandy side bars with sandy transverse and longitudinal bars in straight section; loss of small pools opposite side bars in straight section; sand storage in channel. Loss of native riparian vegetation and weed invasion of riparian zone.

Channel Reach	Reach Characteristics	Post-Regulation Channel Changes up to 2000
Orbost Estuarine Reach (20.5 km long) Sand-bed estuarine channel river type	Barrier type estuary (Roy 1984) at an advanced stage of infilling with fluviatile and marine sediment. Estuarine lakes still present in side embayments. Fluvial sand slug extends to mouth of the Little Snowy River. Sand transported to coast. Extensive sections of *Phragmites australis*-lined and pasture-covered banks. Mouth episodically closes due to sedimentation. Occasional cutoffs present.	Thermal, oxygen and salt stratification develops during prolonged low summer flows in upper estuary. Bank-attached, alternating side bars largely replaced with transverse and longitudinal bars in upper estuary; sand storage in channel as a sand slug in upper estuary. Substantial erosion of estuarine islands in lower estuary.

Recommended environmental flows

The Government agreed environmental flow regime for the Snowy River downstream of Jindabyne Dam was to progressively return 28% of the natural mean annual flow over more than 10 years so that the Expert Panel's (Anon. 1996) targets were achieved. The Expert Panel's environmental flow regime is outlined because it is used below to assess bedform maintenance and pool destratification. An annual flood of up to 139 m^3/s for 3-5 days at Jindabyne and at least 231.5 m^3/s at Dalgety was recommended to create and enlarge the channel so as to reverse channel contraction, pool infilling, riparian vegetation invasion and fine sediment intrusion into the bed (Rose 2017). The range of flood peak discharges with annual exceedance probabilities of 99 to 1% before flow regulation at Jindabyne was relatively small (125.8 to 1093 m^3/s) (Erskine et al. 1999a). As a result, flood variability as measured by the Flash Flood Magnitude Index of Baker (1977) was only 0.202, which is low by Australian standards (McMahon et al. 1992; Erskine 1986; 1996b; Erskine & Saynor 1996; Erskine & Livingstone 1999). Therefore, natural channel-forming discharges before flow regulation were moderate floods of frequent occurrence equivalent to or less than the mean annual flood (411 m^3/s) (Leopold et al. 1964; Dury 1976; Baker 1977). The large bank-full capacities reported elsewhere in New South Wales by Pickup & Warner (1976), Nanson (1986) and Erskine (1994; 1996b), among others, do not apply here because of low flood variability. The smallest recorded unregulated annual flood occurred in 1938 and was only 123 m^3/s, so the Expert Panel recommended an annual flood of 139 m^3/s to initiate fluvial disturbance to reverse long-term channel shrinkage but not to re-establish the pre-Scheme channel, i.e. rehabilitation, not restoration.

Natural monthly streamflows at Jindabyne before regulation increased progressively from February to October before declining progressively to February (Erskine et al. 1999a). Similar seasonal flow distributions for unregulated conditions were recorded at the Dalgety, Basin Creek and Jarrahmond gauges (Erskine et al. 1999a). The need for variable flows on at least a monthly scale but preferably more frequently was emphasised by Anon. (1996). The Expert Panel adopted the 95% flow duration discharge for the unregulated period at Jindabyne for each month downstream of the Mowamba River junction to include natural runoff from the Mowamba River following decommissioning of the Aqueduct and recommended that a minimum discharge of 2.3 m^3/s be adopted between Jindabyne Dam and the Mowamba junction (Anon. 1996). The 95% flows ranged from 2.2 to 27.8 m^3/s depending on the month and greatly exceed the maximum release specified in the original licence of 0.57 m^3/s. The purpose of decommissioning the Mowamba Aqueduct was to return some natural daily flow variability to the Snowy River (Anon. 1996).

River reaches

River reaches are homogeneous lengths of channel within which hydrological, geological and adjacent catchment conditions are sufficiently constant to produce either a uniform morphology or a consistent pattern of alternating morphologies (Kellerhals et al. 1976; Erskine 2005). The classification scheme of Erskine et al. (2001) has been adopted for the Snowy River. Nine river reaches are mapped in Figure 1 and described in Table 1, which also summarises post-regulation channel changes documented by published work. River types are also included in Table 1. Figure 2 shows that the reaches exhibit consistent slopes and that reach boundaries usually coincide with abrupt breaks in slope. Bedform terminology in Table 1 follows Grant et al. (1990).

River reaches are appropriate spatial units for flow management, monitoring of river condition and determining channel changes as part of an adaptive management framework (Stanford et al. 1996; Erskine et al. 2001). The same reaches were also adopted for determining river response to the new environmental flow regime (Rose 2017).

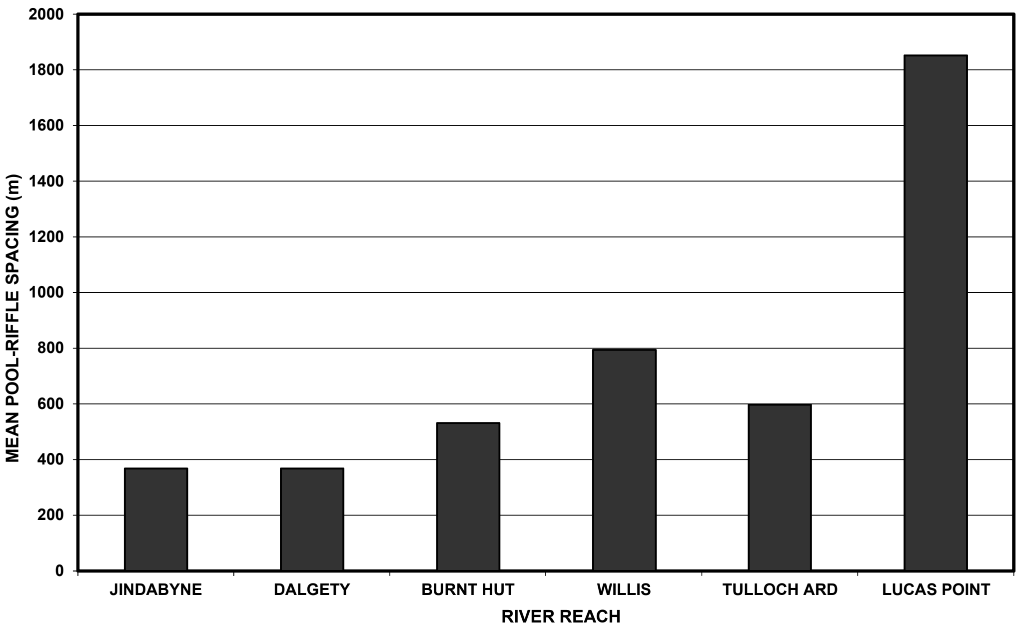


Figure 3: Mean pool-riffle spacing for the six upstream river reaches on the Snowy River contained in Table 1 and Figures 1 and 2

Bedforms

Bedforms were mapped for the 352.5 km of the Snowy River downstream of Jindabyne Dam from pre-2000 vertical air photographs (Webb & Erskine 2000). Dates of the photographs ranged from February 1994 to February 1998 and ranged in scale from 1:20,000 to 1:25,000. The length of every distinct bedform was measured to construct a complete longitudinal sequence (Webb & Erskine 2000). This paper is restricted to the 303 km covering the six upstream reaches (Figure 1 and Table 1).

According to the velocity reversal hypothesis (Leopold et al. 1964), pools are sites of flood scour and riffles are sites of flood deposition. Flood suppression should therefore result in the infilling of the upstream end of pools provided there is a source of sediment. Erskine et al. (1999a; 1999b; 2001) reported channel contraction, particularly at riffles and pool infilling on the Snowy River downstream of Jindabyne Dam. Figure 3 shows the mean pool-riffle spacing for the six upstream reaches. As expected, there is a trend of increasing pool-riffle spacing with catchment area, with the exception of the Tulloch Ard Gorge. This gorge is eroded into very resistant rocks (Orth et al. 1993; 1995) and hence is constrained from readily adjusting to discharge.

Pool-riffle spacing in the late 1990s ranged between 6.7 and 16.2 bank-full channel widths and hence was greater than the 5-7 channel widths commonly reported in the literature (Leopold et al. 1964; Richards 1982). This is not surprising because the channel did not reach a new equilibrium condition adjusted to the post-Scheme discharges. Further channel contraction and pool infilling would have occurred if the releases from Jindabyne had not been increased so that more frequent greater flood scour was re-introduced. Pool-riffle spacing is directly related to channel width (Leopold et al. 1964) but channel width is directly related to bank-full discharge (Leopold et al. 1964; Richards 1982). Therefore, bank-full discharge indirectly controls bedforms. Figure 4 shows that the mean annual flood

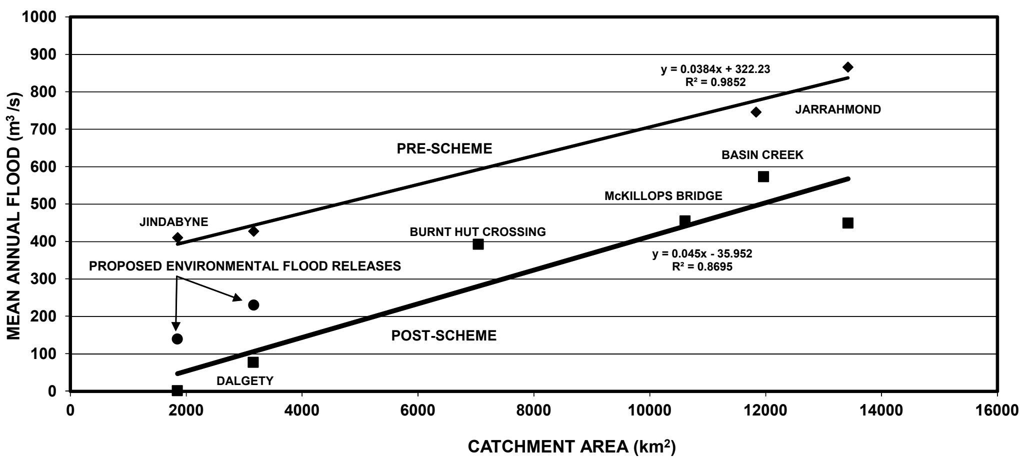


Figure 4: Least-squares linear regression equations for the mean annual flood-catchment area relationships before and after flow regulation of the Snowy River by the Snowy Mountains Hydroelectric Scheme. Mean annual flood is the mean of the $\log_{10}$-transformed annual maximum flood series.

(antilog of mean of the $\log_{10}$ of the annual flood series) on the Snowy River downstream of Jindabyne Dam has been greatly reduced by flow regulation at every gauging station. The regressions were performed on the data of Erskine et al. (1999a) with the addition of the post-Scheme data for the Burnt Hut Crossing and McKillops Bridge gauges and with the adoption of the maximum release from Jindabyne specified in the operational licence. The increase in slope of the regression for the post-Scheme period indicates that the rate of increase in mean annual flood with catchment area is now greater, as expected. Similarly, the large reduction in the y-intercept value indicates that the upper catchment has been effectively removed as a generator of flood discharge. Indeed between 1967 and 2000 Jindabyne Dam only spilled twice in October and November 1974 and 1975 when the flood gates on the spillway were tested. The rate of channel adjustment to such large-scale flood suppression will vary with the degree of bedrock confinement of the channel boundary and the amount of sediment supplied to, and stored in, the channel and available for subsequent fluvial redistribution (Erskine 1996b).

The least squares linear regression of 1990s pool-riffle spacing (*PRS*) on mean annual flood (*MAF*) is:

$$PRS = 0.5703\ MAF + 371.27 \qquad (1)$$

It is significant at $p = 0.03$. Applying the recommended mean annual floods from the Expert Panel (Anon. 1996) to this equation and allowing for downstream flood routing and tributary inflows, yields increases in pool-riffle spacing of between 3 and 294 m between Jindabyne and McKillops Bridge but a predicted decrease in the Lucas Point Reach. This decrease is highly unlikely because the pools and riffles are largely structurally controlled (Table 1). Therefore, the fully implemented Expert Panel's (Anon. 1996) recommendations should produce increased pool scour and a reversal of long-term contraction. Recent monitoring shows that this has been the case in response to the new environmental flow regime (Rose 2017).

Stratification

Although Lake Jindabyne thermally stratifies each year between about October and April, and hypolimnetic dissolved oxygen saturation progressively declines until the autumn overturn (Turner & Erskine 2005; Bowling 1993; Bowling et al. 1993; Kinross & Acaba 1996; Maini et al. 1996), our monitoring has shown that the former siphon outlet ensured that releases closely matched epilimnetic water quality in the lake. As a result, there were no cold anoxic releases.

Turner & Erskine (2005) reported strong thermal gradients with well-developed oxygen stratification and anoxic conditions below the oxycline which varied in depth from 2.75 to 4.25 m in deep upland pools for 50 km below Jindabyne Dam during warm weather (Figure 5). Continuous data-logging of water quality near the surface and near the bottom for continuous 24 h periods demonstrated that the strong thermal gradients and oxygen stratification persisted throughout the day and night (Turner & Erskine 2005).

Oxygen stratification with hypolimnetic anoxia was only recorded where the remnant pools were deeper than 4 m during summer baseflows. Depth is an important control on the development and persistence of stratification in weir pools on the Nepean River (Turner & Erskine 1997a; 1997b).

The upper reaches of many barrier estuaries in East Gippsland were strongly salt, oxygen and reverse thermally stratified during very low freshwater inflows in May 1998 at the time of the Snowy Water Inquiry (Anon. 1998). Estuary fishermen often referred to catching 'warm Southern Bream' (*Acanthopagrus butcheri* Munro) at that time. This was not surprising because the water temperatures at that time below the halocline, where the bream were caught, were up to 6.6 °C warmer than surface waters. Autumn mixing was inhibited by the very high salinities below the halocline at the head of the estuary and the very low freshwater inflows. A thin, usually 0.25 m deep, freshwater lens was present above the halocline throughout the upper 5 km of the estuary which were not investigated in earlier studies (Hinwood & McLean 1999a; 1999b; McLean & Hinwood 2015). The thin freshwater inflow had a salinity of 0 ppt but the upper estuary at the limit of tidal influence (1 km upstream of the Princes Highway Bridge at Orbost on the Snowy estuary) had measured salinities below the halocline of up to 21.6 ppt. A minor fish kill occurred in the upper Snowy estuary where bottom anoxia developed at that time, but not in other nearby estuaries (Cann River/Tamboon Inlet and Genoa River/Mallacoota Inlet) (Erskine et al. 1999b). Figure 6 shows the highly stratified conditions that existed in the upper Snowy estuary at Orbost on 3 May 1998. The oxycline and halocline were generally coincident at between 0.25 and 0.5 m below the surface in the upper 5 km of the Snowy estuary but bottom anoxia was only well developed in the upper estuary. Further downstream, the estuary was not oxygen stratified and the halocline deepened to a consistent depth of 0.5 m. Following a major flood in June 1998 (Erskine et al. 2017), the estuary was well mixed to the mouth.

Destratification

The Richardson Number (*Ri*) is used to predict the stability of stratification and is the ratio of the stabilising forces of density stratification to the destabilising effect of velocity shear (Christodoulou 1986; Horne & Goldman 1994; Western et al. 1996; Dyer 1997). Due to practical problems of measuring density and velocity gradients, the layer Richardson Number was used by Dyer (1982) to determine whether mixing will occur in estuaries when only the surface layer is moving in relation to the bottom layer. The layer Richardson Number (Ri_L) is:

$$Ri_L = \left(\frac{\delta\rho}{\rho}\right).g.D/U^2 \qquad (2)$$

where $\delta\rho$ is the density difference between the surface and bottom layer, ρ is water density, g is the gravitational acceleration constant and D is the depth of the surface layer flowing with a velocity U, relative to the deeper layer (Dyer 1982; 1997).

Dyer (1982) found that fully developed mixing (i.e. complete breakdown of density stratification) occurred at $Ri_L < 2$, that mixing was increasingly active for $20 > Ri_L > 2$ and that turbulence was ineffective in breaking down density stratification at $Ri_L > 20$. Christdoulou (1986) re-examined the literature on interfacial mixing in stratified flows and proposed four different power equations for different ranges of the Richardson Number.

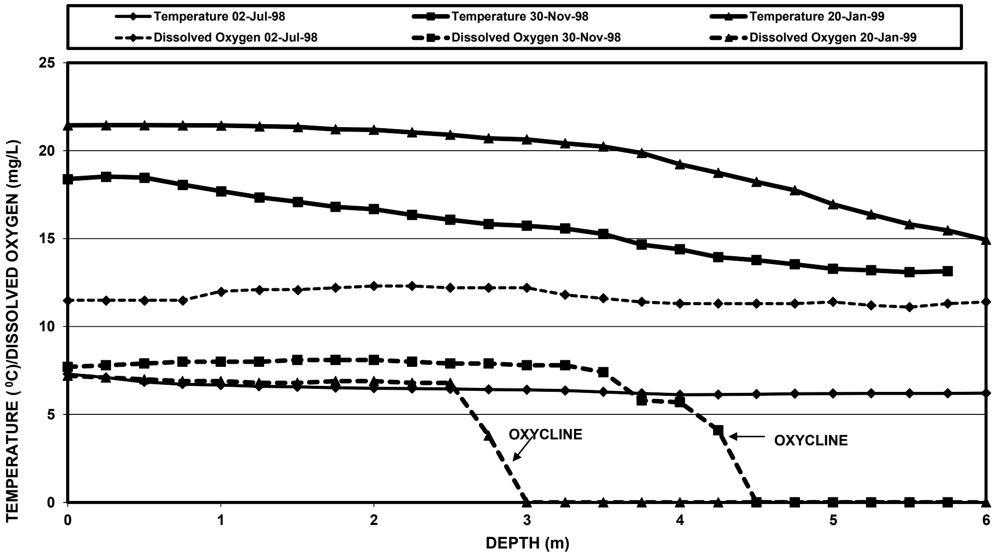


Figure 5: Examples of thermal and oxygen profiles in a remnant pool at Benchmarking site 2 (Figure 1). Isothermal conditions existed on 2 July 1998 but there were strong thermal gradients on 30 November 1998 and 20 January 1999. Anoxic conditions were present below the oxycline for the two summer profiles.

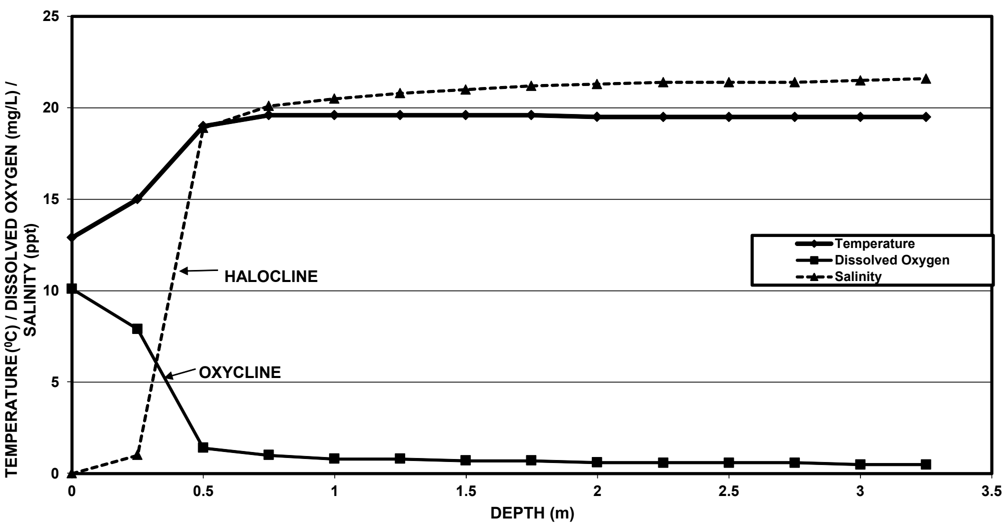


Figure 6: An example of salt, oxygen and reverse thermal stratification that was measured in the Snowy River estuary at the Princes Highway Bridge (Orbost) on 3 May 1998.

Density profiles were calculated from the thermal and salinity depth profiles because they are required as inputs to the layer Richardson Number calculations. Figure 7 shows three profiles for benchmarking site 2 and demonstrates that when strong thermal gradients were present in the Jindabyne Gorge density increased by up to 0.86 kg/m^3 from the surface to the bottom. On the other hand, density differences above and below the halocline in the upper estuary on 3 May 1998 were very large (Figure 8). Clearly the salinity differences greatly compensated for the reverse thermal stratification, producing a density difference of 14.87 kg/m^3. This indicates that much higher flows are required to effect destratification in the estuary than in the Jindabyne Gorge (Turner & Erskine 2005).

The approach adopted to calculate layer Richardson Numbers was to investigate well gauged reaches where discharge was measured at gauging stations. Detailed depth profiles of various water quality parameters undertaken at multiple sites were used to identify temporary and/or seasonal pycnoclines. This permitted the accurate specification of epilimnetic flow depth. Detailed observations of zones of slackwater, wind lanes and reverse currents under a range of streamflows and wind conditions were made at each site. This enabled the calculation of mean cross-sectional area of active flow (A):

$$A = W.D \qquad (3)$$

where W is average active flow width and D is mean epilimnetic depth. The continuity flow equation was then manipulated to calculate mean flow velocity (U) at each site for each day of measurements:

$$U = Q/A \qquad (4)$$

where Q is discharge. This was necessary because attempts to measure flow velocity with a current meter were unsuccessful because of the very low values and because a strain gauge could not be obtained for field work. Dyer (1982) concluded that mixing characteristics are better parameterized in terms of bulk flow properties than local gradient values at the pycnocline which may indicate an apparently more stable stratification. Christodoulou (1986) demonstrated the appropriateness of using mean flow velocity as the velocity measure irrespective of flow type and noted that it is the simplest to estimate. The estimated mean flow velocities during field measurements ranged between 0.002 and 0.019 m/s. The calculated epilimnetic mean flow velocity and densities were then used to determine the layer Richardson Number at each site.

The layer Richardson Number predicts that rapid destratification ($Ri_L < 2$) requires relatively small flows in the Jindabyne Gorge (<10 m^3/s) and that slower destratification ($Ri_L < 20$) requires relatively minor flows (<4 m^3/s). The Expert Panel's (Anon. 1996) recommended mean daily flows for at least 8 months of the year will ensure that pools generally do not stratify. While larger flows are required to cause destratification in the upper estuary when it is salt stratified, these flows are still relatively small for such a large river (20-30 m^3/s). The Expert Panel's (Anon. 1996) recommended annual flood of 139 m^3/s at Jindabyne and at least 2315 m^3/s at Dalgety would cause mixing and destratification of the estuary, if unregulated tributary inflows compensated for downstream routing effects. Furthermore, if larger releases are maintained from Jindabyne Dam, it is likely that salt wedge penetration into the upper estuary (Erskine et al. 1999b; 2001; Turner & Erskine 2005) will not occur in future.

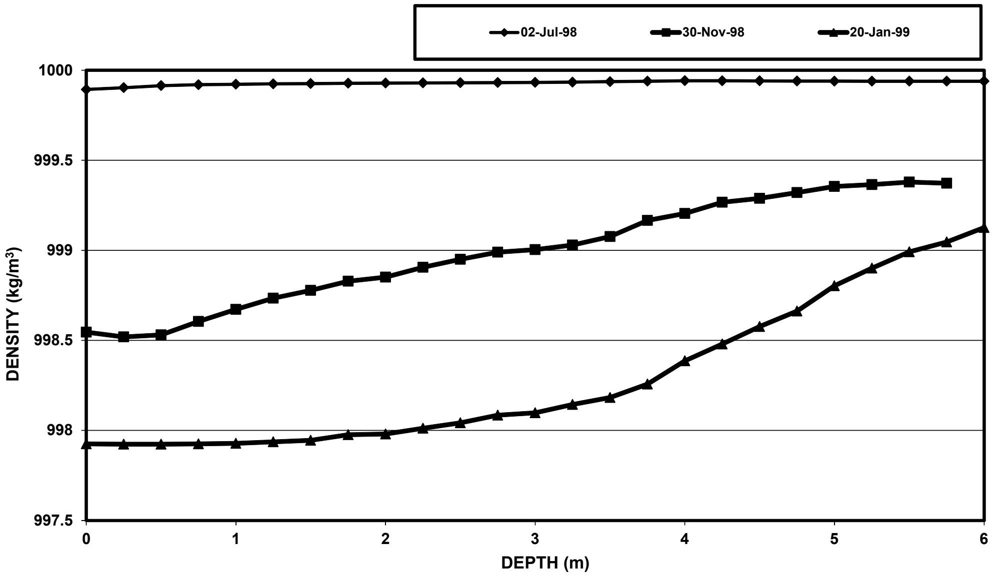


Figure 7: Density profiles in a remnant pool at Benchmarking site 2 during winter isothermal conditions (2 July 1998) and during strong summer thermal gradients (30 November 1998 and 20 January 1999). For location of site, see Figure 1.

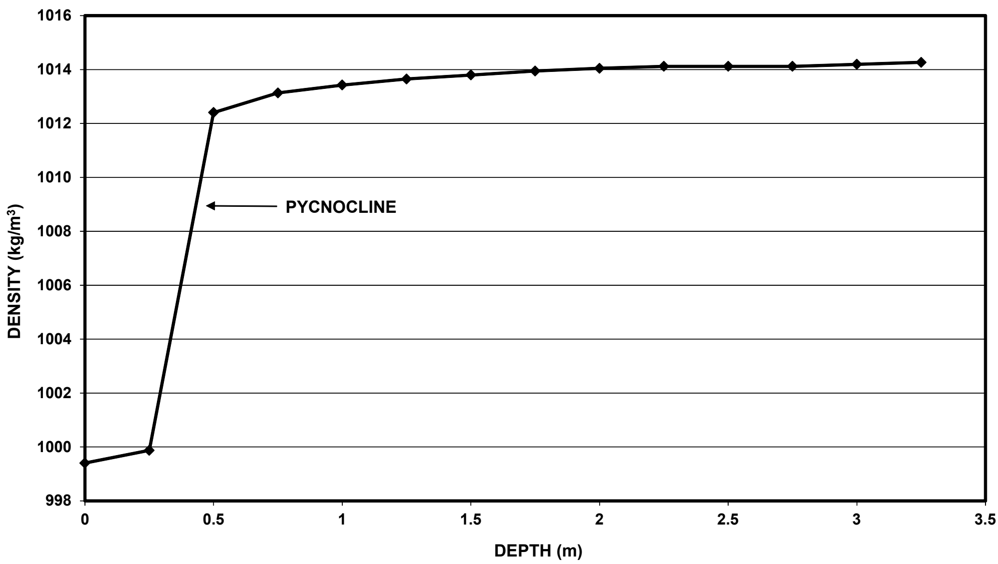


Figure 8: Density profile for the Snowy River estuary at the Princes Highway Bridge (Orbost) on 3 May 1998. See Figure 6 for thermal and salinity profiles.

Discussion and Conclusions

Hall (1989) and Harris & Silveira (1997) carried out fish habitat assessments at six sites in the lower six reaches of the Snowy River. Recommended flows for optimum habitat provision for a range of native fish species ranged from 6.9 to 11.6 m^3/s in the reaches above the estuary (Hall 1989). The proposed minimum flows by the Expert Panel (Anon. 1996) alone will meet these targets for 6 months of the year. Allowance for tributary inflows between Jindabyne Dam and Hall's (1989) sites should result in the optimum flows for habitat maximisation being reached in most months. Clearly, environmental flows for pool destratification will also meet minimum habitat requirements for fish. Furthermore, the Expert Panel's (Anon. 1996) recommended annual flood will scour pools, rework riffle and run bottom sediments and hence improve fish habitat.

The essential components of an environmental flow regime should include at least channel maintenance flows that maintain the size, shape and bedforms of the channel and re-establish ecological connectivity, habitat maintenance flows that remove accumulating silt and organic detritus and destratify pools, minimum flows to sustain aquatic and semi-aquatic ecosystems within the riverine corridor, optimum flows to maximise habitat for target species and the natural seasonal flow distribution (Petts 1996; Stanford et al. 1996, Erskine et al. 1999a; Arthington et al. 2006; Poff et al. 2010). While the Expert Panel process was a rapid assessment method the recommended flows are now known to be appropriate to re-introduce scour of pools and runs, and to destratify temporarily stratified upland pools and the episodically but strongly salt stratified upper estuary (Turner & Erskine 2005). While these factors were certainly considered by the Expert Panel at the time, the degree of analysis undertaken was minimal and based on expert opinion. Synergies between panel members and agency staff can also be effective in resolving issues and determining solutions to problems.

The Snowy River case study further illustrates the major problems that arise when efforts are made to introduce an updated environmental flow regime when the issue is not covered in a legally binding licence. The message is clear that it is important to cover the major issues in the first place so that appropriate water allocations are made initially. What has happened on the Snowy River is similar to other rivers in Australia (Williams 2017) but government response has not always been forthcoming (Sherrard & Erskine 1991; Benn & Erskine 1994; Turner & Erskine 1997a; 1997b).

Acknowledgements

This work was funded by an Australian Research Council grant, an Australian Postgraduate Award, the NSW Department of Natural Resources, Victorian Department of Natural Resources and Environment, Australian Department of Environment and Heritage, East Gippsland Catchment Management Authority and NSW Environment Protection Authority. We thank them for funding. The editor and referee constructively criticised the manuscript.

References

Anon (1993) *Engineering Features of the Snowy Mountains Scheme*. Snowy Mountains Hydro-Electric Authority, Cooma, NSW, Aust.

Anon (1996) *Expert Panel Environmental Flow Assessment of the Snowy River below Jindabyne Dam*. Snowy Genoa Catchment Management Committee, Cooma, NSW, Aust.

Anon (1998) *Snowy Water Inquiry Final Report*. Snowy Water Inquiry, Sydney, NSW, Aust.

Arthington, A. H., Bunn, S. E., Poff, N. L. & Naiman, R. J. (2006) The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications*, 16, 1311-1318.

Baker, V. R. (1977) Stream-channel response to floods, with examples from central Texas, *Geological Society of America Bulletin*, 88, 1057-1071.

Bate, R. & Whalley, P. (1993) "Water quality in the Snowy River catchment within NSW", in Technical Working Group of the Snowy River Interstate Catchment Co-ordination Committee (ed.) *Resource Management Issues in the Snowy River Catchment*, Snowy River Interstate Catchment Co-ordination Committee, Cooma, NSW, Aust., 29-36.

Benn, P. C. & Erskine, W. D. (1994) Complex channel response to flow regulation: Cudgegong River below Windamere Dam, Australia. *Applied Geography*, 14, 153-168.

Bowling, L. C. (1993) *Water Quality Studies of Lake Jindabyne – Final Report to the Snowy Mountains Hydro-Electric Authority*. NSW Department of Water Resources Technical Services Report No. TS 93.098, Parramatta, NSW, Aust.

Bowling, L. C., Acaba, Z. & Whalley, P. (1993) *Water Quality in the Snowy River Catchment Area, 1992/93*. NSW Department of Water Resources Technical Services Report No. TS 93.079, Parramatta, NSW, Aust.

Brizga, S. O. & Finlayson, B. L. (1994) Interactions between upland catchment and lowland rivers: an applied Australian case study. *Geomorphology*, 9, 189-201.

Brooks, A. & Shields, F. D. (1996) "Perspectives on River Channel Restoration", in: Brooks, A. & Shields, F. D. (eds.) *River Channel Restoration*, Wiley, Chichester, UK, 1-19.

Christodoulou, G. C. (1986) Interfacial mixing in stratified flows. *Journal of Hydraulic Research*, 24, 77-92.

Clarke, J. & Bate, R. (1992) "Water quality issues and management," in Wasson, R. J. (ed.) *Erosion, Sedimentation and Water Quality in the Snowy River Catchment*, Technical Working Group of Snowy River Interstate Catchment Co-ordinating Group, Cooma, NSW, Aust., 30-40.

Dann, H. E. (1969) Two decades of engineering – The Snowy Mountains Scheme. *Journal of the Institution of Engineers Australia*, 41, 23-30.

Dann, H. E. (1970) The Snowy Mountains Scheme – Sixteen Large Dams. *World Dams Today '70*, 1970, 471-476.

Davies, B. R., Thoms, M. C. & Meador, M. (1992) An assessment of the ecological impacts of inter-basin water transfers, and their threats to river basin integrity and conservation. *Aquatic Conservation: Marine & Freshwater Ecosystems*, 2, 325-349.

Dury, G. H. (1976) Discharge prediction, present and former, from channel dimensions. *Journal of Hydrology*, 30, 219-245.

Dyer, K. R. (1982) Mixing caused by lateral internal seiching within a partially mixed estuary. *Estuarine Coastal & Shelf Science*, 15, 443-457.

Dyer, K. R. (1997) *Estuaries: A Physical Introduction*. Wiley, Chichester, UK.

Erskine, W. D. (1986) River metamorphosis and environmental change in the Macdonald Valley, New South Wales, since 1949. *Australian Geographical Studies*, 24, 88-107.

Erskine, W. D. (1994) "Sand slugs generated by catastrophic floods on the Goulburn River, New South Wales". in Olive, L. J., Loughran, R. J. & Kesby, J. A. (eds.) *Variability in Stream Erosion and Sediment Transport*. International Association of Hydrological Sciences, Wallingford, UK, 143-151.

Erskine, W. D. (1996a) Downstream hydrogeomorphic impacts of Eildon Reservoir on the mid-Goulburn River, Victoria. *Proceedings of the Royal Society of Victoria*, 108, 1-15.

Erskine, W. D. (1996b) Response and recovery of a sand-bed stream to a catastrophic flood. *Zeitschrift für Geomorphologie*, 40, 359-383.

Erskine, W. D. (2005) "Stream classification," in Lehr, J. R., Keeley, J., Lehr, J. & Kingery III, T. B. (eds.) *Water Encyclopedia: Surface and Agricultural Water*, Wiley-Interscience, Hoboken, NJ, USA, 65-71.

Erskine, W. D. & Livingstone, E. (1999) "In-channel benches: the role of floods in their formation and destruction on bedrock-confined rivers," in Miller, A. & Gupta, A. (eds.) *Varieties of Fluvial Forms*. Wiley, Chichester, UK, 445-475.

Erskine, W. D. & Saynor, M. J. (1996) "Effects of catastrophic floods on sediment yields in southeastern Australia," in: Walling, D. E. & Webb, B. W. (eds.) *Erosion and Sediment Yield: Global and Regional Perspectives*, International Association of Hydrological Sciences, Wallingford, UK, 523-530.

Erskine, W. D., Saynor, M. J. & Lowry, J. (2017) Application of a new river classification scheme to Australia's tropical rivers. *Singapore Journal of Tropical Geography*, 38(2), 167-184.

Erskine, W. D., Terrazzolo, N. & Warner, R.F. (1999a) River rehabilitation from the hydrogeomorphic impacts of a large hydro-electric power project: Snowy River, Australia, *Regulated Rivers: Research & Management*, 15, 3-24.

Erskine, W. D., Turner, L. M. & Rose, T. A. (2017) Sedimentological and geomorphological effects of the 1997 and 1998 flood sequence on the lower Snowy River, Victoria. *Proceedings of the Royal Society of Victoria*, 128, 25-43.

Erskine, W. D., Turner, L. M., Terrazzolo, N. & Warner, R. F. (1999b) Recovery of the Snowy River: Politics and river rehabilitation. *Australian Geographical Studies*, 37, 330-336.

Erskine, W. D., Webb, A. A., Turner, L. M. Miners, B., Rose, T. & Bevitt, R. (2001) "Benchmarking of present river condition after 34 years of large-scale interbasin water transfers: Snowy River, Australia," in Rutherfurd, I., Sheldon, F., Brierley, G. & Kenyon, C. (eds.) *Proceedings of the Third Australian Stream Management Conference, The Value of Healthy Rivers, Volume 1, Brisbane, Queensland, 27-29 August 2001*, Cooperative Research Centre for Catchment Hydrology, Clayton, Vic., Aust., 205-210.

Frost, A. C. H. (1983) *Hydro-Electricity in Australia.* Australian Government Publishing Service, Canberra, ACT, Aust.

Grant, G. E., Swanson, F. J. & Wolman, M. G. (1990) Pattern and origin of stepped-bed morphology in high gradient streams, Western Cascades, Oregon. *Geological Society of America Bulletin*, 102, 340-352.

Hall, D. N. (1989) Preliminary assessment of daily flows required to maintain habitat for fish assemblages in the Latrobe, Thomson, Mitchell and Snowy rivers Gippsland. *Arthur Rylah Institute for Environmental Research Technical Report No. 85*, Heidelberg, Vic.

Harris, J. H. & Silveira, R. (1997) "Assessing the condition of rivers in New South Wales, Australia: a test of the index of biotic integrity," in Harris, J. H. & Gehrke, P. C. (eds.) *Fish and Rivers in Stress: The NSW Rivers Survey*. NSW Fisheries Office of Conservation and Cooperative Research Centre for Freshwater Ecology, Cronulla, NSW, Aust. 133-168.

Hinwood, J. B. & McLean, E. J. (1999a) A parametric hydrodynamic model of a complex estuary. *Journal of the Australian Institute of Mining and Metallurgy*, 1999(3), 249-256.

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

Horne, A. J. & Goldman, C. R. (1994) *Limnology*. McGraw-Hill Inc., New York, USA.

Howard, S. R. & Holliday, N. G. (1968) Design and construction of Jindabyne Dam. *Civil Engineering Transactions, Institution of Engineers Australia*, CE10, 143-159.

Kellerhals, R., Church, M. & Bray, D. I. (1976) Classification and analysis of river processes. *Journal of Hydraulics Division, Proceedings of the American Society of Civil Engineers*, 102, 813-829.

Kinross, C. & Acaba, Z. (1996) *Water quality of the Snowy River catchment area, 1994/95*. Technical Services Report No. TS 96.059, NSW Department of Land and Water Conservation, Parramatta, NSW, Aust.

Lake, P.S., Bond, N. & Reich, P. (2007) Linking ecological theory with stream restoration. *Freshwater Biology*, 52, 597-615.

Leopold, L. B., Wolman, M. G. & Miller, J. P. (1964) Fluvial Processes in Geomorphology. W. H. Freeman, San Francisco, CA, USA.

Maini, N., Acaba, Z. & Bowling, L. (1996) *Water quality of the Snowy River catchment area, 1995/96 Progress Report*. Centre for Natural Resources Report No. 97.042, NSW Department of Land and Water Conservation, Parramatta, NSW, Aust.

McLean, E. J. & Hinwood, J. B. (2015) Response of the Snowy River estuary to two environmental flows. *Proceedings of the Royal Society of Victoria*, 127, 28-43.

McMahon, T. A., Finlayson, B. L., Haines, A. T. & Srikanthan, R. (1992) *Global Runoff*. Catena Paperback, Cremlingen, Germany.

Nanson, G. C. (1986) Episodes of vertical accretion and catastrophic stripping: a model of disequilibrium flood-plain development. *Geological Society of America Bulletin*, 97, 1467-1475.

Orth, K., Vanden Berg, A. H. M., King, R. L., Nott, R. J. & Tickell, S. J. (1993) *Murrindal 1:100,000 Geological Map*, Geological Survey of Victoria, East Melbourne, Vic, Aust.

Orth, K., Vanden Berg, A. H. M., Nott, R. J. & Simons, B. A. (1995) *Murrindal 1:100,000 Map Geological Report*, Geological Survey of Victoria Report 100.

Petts, G. E. (1996) Water allocation to protect river ecosystems. *Regulated Rivers: Research & Management*, 12, 353-365.

Pickup, G. & Warner, R. F. (1976) Effects of hydrologic regime on the magnitude and frequency of dominant discharge. *Journal of Hydrology*, 20, 51-75.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E. & Stromberg, J.C. (1997) The natural flow regime: a paradigm for river conservation and restoration. *BioScience*, 47, 769-784.

Poff, N.L., Richter, B.D., Arthington, A.H., Bunn, S.E., Naiman, R.J., Kendy, A., Acreman, M., Apse, C., Bledsoe, B.P., Freeman, M.C., Henriksen, J., Jacodson, R.B., Kennen, J.G., Merritt, D.M., O'Keefe, J.H., Olden, J.D., Rogers, K., Tharme, R.E. & Warner, A. (2010) The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology*, 55, 147-170.

Richards, K. S. (1982) *Rivers Form and Process in Alluvial Channels*. Methuen, London, UK.

Rose, T. (2017) Processes, rates and pathways to recovering river channel functions through geomorphically effective floods: a case study of the highly regulated Snowy River downstream of Jindabyne Dam, Australia. PhD thesis, School of Environmental and Life Sciences, The University of Newcastle, Ourimbah, NSW, 499 pp. http://ogma.newcastle.edu.au:8080/vital/access/manager/Repository/uon:27884

Roy, P. S. (1984) "New South Wales estuaries: their origin and evolution," in Thom, B. G. (ed.), *Coastal Geomorphology in Australia*, Academic Press, Sydney, NSW, Aust., 99-121.

Sammut, J. & Erskine, W. D. (1995) Hydrological impacts of flow regulation associated with the Upper Nepean Water Supply Scheme, NSW. *Australian Geographer*, 26, 71-86.

Sherrard, J. J. & Erskine, W. D. (1991) Complex response of a sand-bed stream to upstream impoundment. *Regulated Rivers: Research & Management*, 6, 53-70.

Stanford, J. A., Ward, Liss, W. J., Frissell, C. A., Williams, R. N., Lichatowich, J. A. & Coutant, C. C. (1996) A general protocol for restoration of regulated rivers. *Regulated Rivers: Research & Management*, 12, 391-413.

Turner, L. M. & Erskine, W. D. (1997a) Morphometry and stratification of the Bents Basin scour pool, Nepean River, NSW. *Wetlands (Australia)*, 17, 14-28.

Turner, L. M. & Erskine, W. D. (1997b) Thermal, oxygen and salt stratification in three weir pools on the Nepean River, NSW, in Riley, S. J., Erskine, W. D. & Srestha, S. (eds.), *Proceedings Science and Technology in the Environmental Management of the Hawkesbury-Nepean catchment*. Institution of Engineers Australia National Conference Publication NCP 97/01 and Geographical Society of NSW Conference Papers No. 14, Barton, ACT, Aust, 87-92.

Turner, L. M. & Erskine, W. D. (2005) Variability in the development, persistence and breakdown of thermal, oxygen and salt stratification on regulated rivers in south-eastern Australia. *River Research & Applications*, 21, 151-168.

Webb, A. A. & Erskine, W. D. (2000) *Fluvial Geomorphology of the Snowy River below Jindabyne Dam*. NSW Department of Land and Water Conservation, Cooma, NSW, Aust.

Western, A. W., O'Neill, I. C., Hughes, R. L. & Nolan, J. B. (1996) The behaviour of stratified pools in the Wimmera River Australia. *Water Resources Research*, 32, 3917-3206.

Williams, J. (2017) Water reform in the Murray Darling Basin: a challenge in complexity in balancing social, economic and environmental perspectives. *Journal & Proceedings of the Royal Society of New South Wales*, 150, 68-92.

Wayne Erskine's co-authors have written the following obituary: "Professor Wayne Erskine (1954–2017) graduated with a Bachelor of Arts (Hons 1) from the School of Geography, UNSW in 1979. He then completed his PhD at UNSW on "River metamorphosis and environmental change in the Hunter Valley, NSW" in 1986. Wayne worked as a Scientific Officer with the NSW Water Resources Commission in North Sydney from 1981–1986 before becoming a Lecturer/Senior Lecturer in the School of Geography at UNSW from 1986–1998. He was then employed by State Forests of NSW from 1998–2004, firstly as a Research Hydrologist, then as Senior Soil, Water and Fish Specialist based at West Pennant Hills. Wayne subsequently joined the University of Newcastle–Ourimbah as a Professor of Natural Resource Management from 2004–2011. He provided much advice on rehabilitating the hydro-geomorphology of Australia's iconic Snowy River. He finished his career as Program Leader and Principal Research Scientist at the Environmental Research Institute of the Supervising Scientist in Darwin from 2011 until his retirement in 2014. During his career, Professor Erskine supervised more than 30 Honours, 20 Masters and 17 PhD students. He published over 150 refereed journal papers, book chapters and conference papers and will be remembered as one of Australia's most influential fluvial geomorphologists."