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SNOWY FLOW RESPONSE MONITORING AND MODELLING PROGRAM

Scaling environmental flow releases in the Snowy River to unregulated snowmelt rivers of the Snowy Mountains

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Cover image: The Snowy River in Jindabyne Gorge (below site 2) during the 2011 spring release: Simon Williams.

Jobtrack 12275

Summary

In developing a new environmental flow regime for the Snowy River below Jindabyne Dam based on a 21% allocation of the Mean Annual Natural Flow, an alternative flow paradigm is required to re instate the health of the river. The average volume of water available for release as environmental water is five times less than average natural flow volumes, and approximately half of the lowest flow ever recorded in the Snowy River prior to construction of the Snowy Mountains Hydro-electric scheme. Such a large difference in water volumes means that it is extremely difficult to maintain or reinstate any aspect of the pre-regulation flow regime without seriously compromising other aspects of the environmental flow regime.

This report outlines the shortcomings of the previously adopted building blocks approach to environmental flow regime development for the period 2009-10 to 2012-13 and proposes instead that a naturally scaled environmental flow regime based on daily and hourly flow sequences in the Thredbo River be adopted to maximise the environmental benefits of water releases from Jindabyne Dam. The Thredbo River is a logical choice for this approach because: (i) average annual water volumes mandated for release to the Snowy River from Jindabyne Dam are very similar to average annual water volumes in the Thredbo River; and, (ii) the Thredbo River has a high degree of elevation similarity to the Snowy River and hence similar snowmelt characteristics.

The overarching objective for an environmental flow regime based on natural daily and hourly flow sequences in the Thredbo River is “to facilitate the rehabilitation and evolution of the Snowy River below Jindabyne Dam into a smaller but healthy river with a size and shape similar to the Thredbo River.” Over decadal to century long time scales, environmental water releases scaled to the Thredbo River will allow the Snowy River to slowly develop a size, shape and perhaps condition, similar to that of the Thredbo River. This overarching objective implicitly recognises that it is not possible to restore or maintain the Snowy River to its former size with one fifth of its former flow volume. Water volumes available for release as environmental flows provide a realistic and achievable rehabilitation target of a smaller montane river that would be greatly facilitated by the reinstatement of an appropriately scaled flow regime.

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Introduction

It is widely accepted that rehabilitation of regulated river systems requires flow management that emulates natural hydrological dynamics (Poff et al., 1997; Jacobson and Galat, 2008; Poff et al., 2009). The degree to which natural hydrological dynamics can be emulated, however, is often a compromise between the volume of water available for environmental flow releases, operational limitations imposed by dam infrastructure, regulatory agreements as well as community and interest group desires (e.g. Jacobson and Galat, 2008). The natural flow paradigm (Poff et al., 1997) and ecological limits of hydrological alteration - ELOHA (Poff et al., 2009) provide a framework for designing environmental flow releases to protect ecosystem integrity and aquatic biodiversity. These frameworks emphasise flow magnitude, frequency, duration, timing and rates of change as fundamental components of the natural flow regime, and advocate for re-instating flow regimes that fall within the natural bounds of variability. Poff et al. (2009) argue that “by classifying rivers according to ecologically meaningful stream flow characteristics…, groups of similar rivers can be identified, such that within a grouping or type of river there is a range of hydrologic and ecological variation that can be considered the natural variability for that type.” Clearly, identifying free flowing rivers that have similar hydrology, geomorphology and ecology, to the regulated river system forms a logical approach to designing environmental flow regimes.

Poff et al. (1997), however, dismiss the notion of restoring flow patterns proportional to natural hydrographs on the basis that few if any ecological benefits may result because many geomorphic and ecological processes show nonlinear responses to discharge. In support of this argument, Poff et al. (1997) note that half the peak discharge will not move half the sediment, half of an overbank flow will not inundate half the floodplain and that half of a migrational motivating flow will not cause half of the fish in a river system to migrate. While these ideas may be true at the instant that flow alteration commences for a regulated river system, they are not true in terms of what is naturally achieved with similar flow volumes, in natural (unregulated) analogue river systems. In such natural analogue rivers with flow volumes similar to that available for the regulated river system, the channel geometry, geomorphic processes and aquatic ecology are fully adjusted to natural patterns of flow variability across all temporal scales ranging from minutes to decades. Even for a regulated river system, the concept that halving the discharge will be less than half effective applies fully only at the instant that regulation commences as channel geometries downstream of dams do not remain static over decadal time scales. Channel contraction by vegetation colonisation and formation of inset floodplains across areas of formerly active riverbed commonly occurs in response to large scale flow reductions (Williams and Wolman, 1984; Grams and Schmidt 2002; Gilvear, 2004; Petts and Gurnell, 2005). Over decadal time scales, channel contraction serves to concentrate flows in a smaller channel (Williams and Wolman, 1984; Gilvear, 2004; Petts and Gurnell; 2005) such that flow competence within the reduced channel gradually increases with time. With regard to the example of fish migration trigger flows, Reinfelds et al. (2011) demonstrate fish migratory responses to relatively small flow pulses approximating the natural (unregulated) median daily flow. While we recognise that the release of flow pulses attaining the median daily flow alone will not maintain geomorphic and ecological integrity in regulated rivers; we simply provide the fish migratory response as an example of a positive ecological outcome that can potentially be achieved with the release of relatively small flow pulses.

In many river systems across the world that have been developed for agricultural, hydro-electric or urban water supplies, the reductions in flow volumes are so large that annual environmental flow allocations fall well below the range of natural annual flow volumes. This places such river systems at odds with the fundamental tenet underpinning the natural flow paradigm (i.e. to stay within the natural bounds of variability) and calls into question positions arguing for restoration or maintenance of unregulated geomorphic and ecological processes with environmental flow volumes that are multiples lower than natural unregulated flow volumes. Indeed, studies on the

Fitzroy, Barron and Burnett Rivers in Queensland Australia suggest that at least 80–90% of natural flows may be needed to maintain a low risk of environmental degradation (Arthington and Pusey 2003). Reinfelds et al. (2006) documented that irrigation extraction of just 7% of the mean annual flow in the Bega River NSW Australia, results in distortion of low flow hydrographs and prolongs the exposure of low flow habitats. In situations where allocations to environmental flows are multiples below the range of natural variability, it is prudent to ask whether it is appropriate to attempt to restore or maintain some components of the former flow regime with such limited water volumes, or, whether it is more appropriate to design a natural flow regime based on similar, but smaller, analogue or reference rivers. The latter position is conceptually appealing because it enables adoption of a new long term rehabilitation vision for the regulated river with a real-world analogue based on natural flow patterns.

The casual dismissal of restoring flow patterns proportional to natural flow hydrographs on the assumption that the channel geometry of the regulated river systems will remain static over decadal and longer time scales is both conceptually and empirically flawed. It is also unfounded to assume a position that restoration or long-term maintenance of unregulated geomorphic and ecological processes is possible in regulated river systems with environmental flow volumes that are multiples lower than natural unregulated flow volumes. For regulated river systems with significant water diversions, with no bulk water transfers and consequent environmental water allocations that fall well below the natural bounds of variability, the development of realistic rehabilitation objectives should encompass the following:

1. recognition of the recovery pathways and ultimate river rehabilitation states that are possible with available annual environmental flow volumes
2. that the development of such an understanding entails detailed hydrologic, geomorphic and ecological analysis of the regulated river and comparison with suitable analogue rivers on the basis of similarity in annual flow volumes and pre-regulation flow patterns
3. that the reinstatement of annually varying natural flow regimes be based on daily, and where possible hourly, flow sequences in order to facilitate the development of a smaller channel geometry scaled to available flow volumes;
4. that rehabilitation objectives are structured within a logical hierarchy (Rogers and Bestbier, 1997; Williams and Wolfenden, 2012).

The approach outlined above forms a ‘top down’ holistic approach to development of an environmental flow regime (Jacobson and Galat, 2008) by starting with an unregulated analogue river with a hydrological template, geomorphology and ecology that is already scaled to the volume of water available for rehabilitation of the regulated river. The rehabilitation process for the regulated river can then focus on reinstating a hydrological regime similar to that of the analogue river and undertaking rehabilitation works to accelerate the development of the desired channel geometry. For example, encouraging growth of native vegetation across developing inset floodplains will accelerate their development through more efficient sediment trapping. Alternative approaches such as the ‘building blocks method’ whereby hydrographs are built from the ‘bottom up’ by identifying ecological functions that should be accommodated in the flow regime (Arthington and Pusey, 2003; Jacobson and Galat, 2008) are inherently more prescriptive (King and Louw, 1998; King et al., 2003) and assume that key ecological water requirements for the river system are already adequately known. The ‘building blocks method’ forms the current environmental flow regime development approach being applied to the Snowy River below Jindabyne dam.

In situations where water volumes for the development of an environmental flow regime are limited and below the range of natural variability, a potential limitation of the building block method is that such an approach may favour particular aspects of a flow regime (King et al., 2003) to such an extent that the favoured flow component may become out-of-scale when compared to natural unregulated flow regimes. Rather than facilitating a river to develop a new channel geometry, geomorphology and ecology in equilibrium with available environmental flow volumes and natural analogue flow regimes, the building block method in such situations essentially seeks to maintain aspects of the regulated river on the hydrological equivalent of a 'life support' system. A scaled environmental flow based on an appropriate unregulated analogue river, however, provides both a hydrological template that can be used as a starting point in the development of an environmental flow regime, and a physical endpoint rehabilitation vision for the regulated river to progressively develop towards over decadal to century long time scales.

Adaptive management strategies responding to increasing knowledge of stream ecosystems, functions and processes is fundamental to effective river rehabilitation (Stanford et al. 1996; Stanford and Poole 1996; Poff et al. 2009). In this regard, managed flow regimes for regulated river systems should be regularly reviewed to assess their capacity to achieve the most natural possible flow regime, and their effectiveness in meeting targeted environmental objectives. Planned environmental water releases to the Snowy River were initially driven by the default monthly release pattern as defined in section 13.3 of the Snowy Water Licence. Since 2009 environmental flow releases for the Snowy River below Jindabyne Dam have been developed by the Snowy Scientific Committee for May-April water years. These recommendations are typically defined by February each year to be applied to the following water year, are guided by an expert panel and associated reports (Pendlebury et al., 1996) and are consistent with a building blocks approach to environmental flow regime development. Given recent increases in the volume of water entitlements recovered within the Murray-Darling River Basin that determine the volume of Snowy River Increased Flows (SRIF), it is timely to review the appropriateness of current and potential alternative environmental flow regimes in the context of available environmental water volumes and the characteristics of natural flows in the pre-regulation Snowy River and analogue rivers in the Snowy Mountains.

The purpose of this report is to:

- Review the environmental flow regime for the period 2009-10 to 2012-13, for the Snowy River below Jindabyne Dam
- Review potential alternative naturally scaled environmental flow regimes based on unregulated analogue rivers
- Assess the degree to which the current and potential alternative flow regimes accord with the natural flow paradigm and their effectiveness in meeting mandated and adopted environmental objectives.

Study area

The Snowy River, prior to flow regulation, flowed from near the summit of Mt. Kosciuszko in the south eastern highlands of New South Wales to the Gippsland coast in Victoria. Between 1955 and 1967, four major water storages were completed in the upper Snowy River as part of the Snowy Mountains Hydro-electric Scheme (SMS), the largest of these being Lake Eucumbene and Lake Jindabyne. The smaller storages of Guthega Dam and Island Bend are in the reaches above Jindabyne Dam with Island Bend providing a major pumping hub in the Scheme linking the Eucumbene, Jindabyne and Geehi Reservoirs (Morton *et al*. 2010).

A historical record for the pre-regulation Snowy River at Jindabyne (gauge no. 222501) extends from 1902-67 but construction of the Snowy Mountains Hydro-electric Scheme potentially affects this record from 1955 onwards. Flow records for the unregulated Thredbo River at Paddys Corner (gauge no. 222541) and the Murray River at Biggara (gauge no. 401012) extend back to 1985 and 1948, respectively. The Thredbo River at Paddy's Corner and the Murray River at Biggara (Figure 1) form the most suitable unregulated reference rivers to which environmental flow regimes can be compared. The Thredbo River has more similar mean and minimum catchment elevations to the Snowy River at Jindabyne than the Murray River at Biggara, as well as more similar catchment proportions above 1400 m and 1800 m elevation (Table 1). An elevation of 1400 m is defined as the nominal snow line and catchments above 1800 m elevation yield substantially greater runoff than lower elevation catchments, due in part to winter accumulation of drifting snow (Reinfelds *et al*. 2012).

The Murray River at Biggara, however, is more similar in catchment area (Table 1) and Erskine *et al.* (1999) identified the Murray River at Biggara as a suitable control or analogue station to obtain an index of natural flow in the Snowy River since completion of the SMS. On the basis of elevation similarities, the Thredbo River is clearly a suitable analogue river that can be used to guide the development of naturally scaled environmental flow regimes for the regulated Snowy River below Jindabyne Dam.

Table 1 **Catchment area and elevation characteristics (mean, maximum and minimum elevations and percentage greater than 1400 m and 1800 m above sea level) for the Snowy River at Jindabyne, Thredbo River at Paddy's Corner and Murray River at Biggara. Catchment characteristics derived from 28 m cell size Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM).**

Hydrometric station	Catchment area (km^2)	Elevation (m)				
		Mean	Max	Min	% greater 1400 m	% greater 1800 m
Snowy R. at Jindabyne(222501)	1,848	1,382	2,225	903	42.6%	7.8%
Thredbo R. at Paddys Corner (222541)	243	1,511	2,185	921	62.6%	13.8%
Murray R. at Biggara (401012)	1,256	1,100	2,185	318	17.5%	0.5%

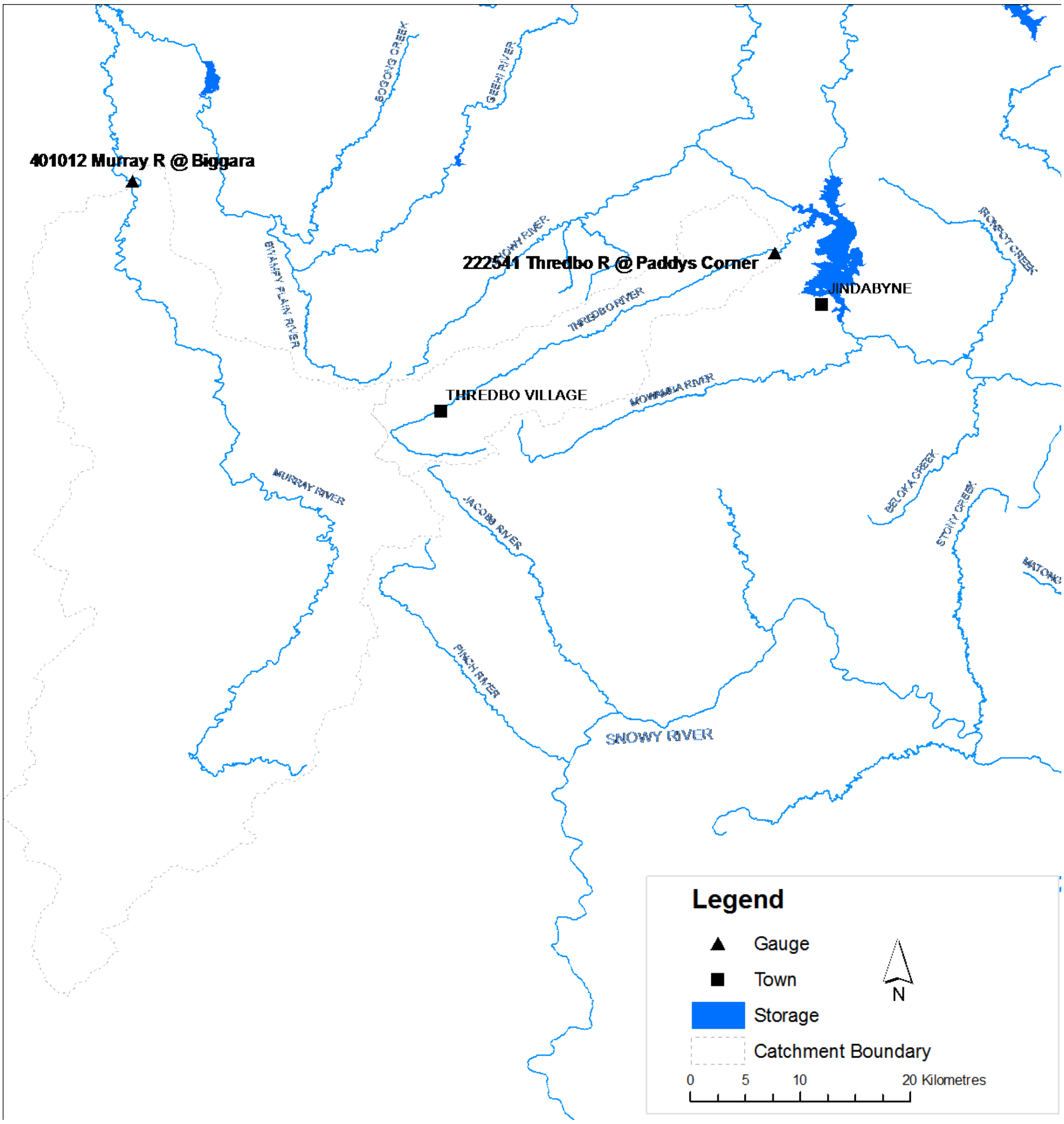

Figure 1 Location of Snowy River, Jindabyne Dam and snowmelt analogue catchments of the Thredbo and upper Murray rivers.

Flow management

Flow volumes available for environmental releases to the Snowy River are dependent on irrigation water savings achieved across NSW and Victorian parts of the Murray Darling Basin (MDB) and inflows to principal rivers and water storages. Under 2011 levels (i.e. current for this purpose) of water savings across the MDB, modelling by the NSW Office of Water indicates that the median (50^{th} percentile) annual volume of environmental flow releases to the Snowy River is 145.6 GL, increasing to 210.9 GL under a 'full water savings' scenario by 2013. In 2009-10 the annual volume allocated to the Snowy River was 43 GL (modelled 44.9 GL), rising to 69.4 GL (modelled 56.5 GL) in 2010-11. Significant rainfall across much of the Murray-Darling Basin in 2010 effectively ended the historic drought conditions being experienced in the preceding years. For the 2011-12 and 2012-13 water years, the Snowy River was allocated 159.4 GL and 162.7 GL, respectively.

Comparison of flow duration curves shows that annual flow volumes for the Thredbo River are closely comparable to Snowy River environmental flow allocation volumes for current (i.e. 2011) and projected final levels of water recovery (i.e. 2013). Average Snowy River environmental flow allocation volumes, however, are approximately 4-6 times lower than average natural pre-regulation flow volumes and two times lower than the lowest recorded annual pre-regulation flow. This flow duration analysis based on annual volumes demonstrates that it is not possible to reinstate a flow regime similar to the preregulation Snowy River with the available water volumes. It is possible, however, to reinstate a flow regime largely equivalent to the unregulated Thredbo River.

Environmental flows from Jindabyne dam to the Snowy River can be released through four structures for flow rates of up to 5,000 MLd^{-1} (Table 2), with higher flood-flow rates controlled via radial gates. The radial gate release mechanism requires water levels in Lake Jindabyne to be maintained at a much higher level than previously managed and presents a 1 in 10 year risk of unintended spilling (pers. comm. Andrew Nolan). Snowy Hydro Limited have advised the Snowy Scientific Committee and NSW Office of Water that flow releases up to 5,000 MLd^{-1} from Jindabyne Dam can be pre-programmed to change automatically on a daily basis. For selected events such as annual spring flood peaks, it is possible to vary radial gate outflows from Jindabyne Dam on a multi-hour time step so as to increase peak flow magnitudes.

The capacity for such refined flow management at a dam is rare for river systems in Australia and worldwide, and provides an unique opportunity to develop an environmental flow regime scaled to unregulated daily flow sequences of suitable analogue rivers. The similarity in SRIF volumes with the Thredbo River combined with the elevation similarity between the Thredbo River and Snowy River at Jindabyne (Table 1) draws attention to the logic of using the Thredbo River to develop an environmental flow regime for the Snowy River. Erskine *et al.*, (1999) also identified the unregulated Murray River at Biggara as a suitable large catchment analogue for the Snowy River at Jindabyne. The Thredbo and Murray Rivers therefore provide two river systems of different size that can potentially be used to develop environmental flow regimes scaled to available SRIF water volumes.

Table 2. **Release structures from the outlet works at Jindabyne Dam. (Source: Williams and Wolfenden 2012, data provided by Snowy Hydro).**

Structure	Flow range (MLd^{-1})
Mini-hydro generator	0 to 170
Submerged discharge valve	0 to 215
1.2m diameter cone valve	300 to 1,400
1.9m diameter cone valve	650 to 3,450

Jacobson and Galat (2008) identified that regulatory agreements can place constraints on the implementation of environmental release patterns. In the case of the Snowy River, current water licensing arrangements prescribe the scheduling and implementation of environmental flow recommendations. The Snowy Water Licence requires that recommendations are provided in February for the following May to April water year so as to provide certainty for electricity production. However, the licence does provide the ability to vary daily flow targets four days prior to the beginning of each month. Implementation of operational transparency/translucency rules based on daily inflows as applied elsewhere in NSW (e.g. Shoalhaven River, Hawkesbury-Nepean River, South Eastern Australia) is not possible under the existing Snowy Water Licence framework, negating such an approach as an option for refinement of environmental flow regimes. The maintenance of a minimum base flow of 90 MLd^{-1} for water supply to Dalgety township below Jindabyne Dam (SSC, 2008) was also considered as a management constraint to designing alternative environmental flow regimes. However, discussions with Snowy River Shire Council indicate that provision of water supplies to Dalgety is not impacted by flow rates as low as 15 MLd^{-1} and that existing water supply infrastructure can still be utilised well under this flow rate (Paul Lee personal communication 2012).

Methods

Environmental flow regimes for 2009-10, 2010-11, 2011-12 and 2012-13 water years are compared to naturally scaled flow regimes for the Snowy River below Jindabyne Dam developed from the Thredbo River at Paddy's Corner (gauge no. 222541) and Murray River at Biggara (gauge no. 401512). The low allocation for 2009-10 of 43 GL reflects the record low inflows to much of the Murray-Darling Basin and the Snowy Mountains catchments that occurred from 2001-07, and in particular, in 2006-07. This three year lag between broad scale Murray-Darling Basin inflows and Snowy River allocations is utilised to develop daily environmental flow regimes scaled by the ratio between the annual allocated environmental flow volume and the annual flow volume three years prior for the reference gauging stations in the unregulated Thredbo and Murray Rivers. Naturally scaled daily environmental flow regimes are calculated as:

*Eflow = reference mean daily flow * (allocated annual eflow volume / reference annual flow volume)*

Higher allocations of 159.4 GL for 2011-12 and 162.7 GL for 2012-13 reflect recovery of inflows to more normal levels, with flow duration exceedance percentiles of 40% and 10%, respectively, under the current level of entitlement. Since 2009-10, the range of SRIF allocations covering extreme drought, near median and above median allocations under the current water savings allocation scenario provides a useful test as to the performance of scaled environmental flow regimes under highly variable annual flows.

Graphical comparisons of concurrent daily flow series for four years of building blocks method environmental flows and environmental flows scaled to the unregulated Thredbo and Murray Rivers as per the formula above are presented. This graphical comparison is supplemented with River Analysis Package (RAP) analyses of the scaled flows, building blocks method flows and 'as recorded' natural flow sequences. As the past decade of allocations to the Snowy River is unusually low with regard to a 114 year long modelled allocation sequence, we use the Murray River at Biggara (401012) and Thredbo River at Paddy's Corner (222541) to develop 58 and 21 year long records of scaled environmental flow regimes, respectively, for the Snowy River under current and projected final levels of SRIF. Standard and normalised flow duration curves (normalised to mean annual flow) for concurrent and multi-decadal periods of record for the naturally scaled environmental flow regimes developed from the Thredbo and Murray Rivers are compared to the building blocks method environmental flows and to the pre-regulation Snowy River at Jindabyne.

The 58 and 21 year records of scaled daily mean flow regimes for the Snowy River below Jindabyne generated from the Murray and Thredbo River daily flow records were used to develop annual maximum snowmelt flood series to assess magnitude frequency relationships for spring snowmelt floods for the scaled flow regimes. The average of ratios between mean daily and instantaneous maximum flows for the Murray and Thredbo River annual winter-spring flood series (1.16 and 2.05, respectively) were used to adjust mean daily flows to instantaneous maximum flows in the scaled annual series. The scaled flow series were compared to unscaled natural annual maximum snowmelt flood series for the Murray, Thredbo and Snowy Rivers to assess whether the scaling method produces aberrations in the annual maximum snowmelt flood series. FLIKE was used to fit log-Pearson III distributions to annual spring snowmelt flood series based on the Cunnane plotting position for the scaled flow regimes and natural sequences for the Thredbo and Murray Rivers and Snowy River at Jindabyne.

Downstream volumetric losses and flood peak attenuation was assessed for seven flood pulse releases from Jindabyne Dam since 2006. Volumetric losses were assessed at a daily time step with flood peak attenuation assessed at an hourly time step. Relationships between downstream reductions in the magnitude and duration of flood pulse releases were modelled as a function of the duration of flow releases from Jindabyne Dam.

Results

Modelled environmental flow allocation volumes for projected final levels of MDB entitlement recovery for the past 114 years demonstrate that annual environmental flow allocations to the Snowy River below Jindabyne Dam will achieve a median value approximately equal to 20% of the median natural annual flow. There is hence a five-fold difference between water volumes available to effect geomorphic and ecological recovery in the post-regulation Snowy River below Jindabyne Dam compared to the pre-regulation Snowy River.

Comparison of daily and seasonal flow patterns

The scaled Murray River and Thredbo River hydrographs (Figure 2) show alternative daily flow regimes to the building blocks method flow that can be achieved with the same annual SRIF allocations. The 2009-13 building blocks method hydrographs appear artificial when compared to the naturally scaled hydrographs for the Snowy River developed from the Murray and Thredbo Rivers (Figure 2). The building blocks method hydrographs commonly exhibit a regular periodicity, magnitude and duration of small intra-annual flow pulses that contrast with the more random and varied naturally scaled flow regimes (Figure 2a, 2c, 2d). The building blocks method minimum flows are fixed, ranging from 70 - 100 MLd^{-1}, and are greater then the minimum flows that would occur under a naturally scaled flow regime (Figure 2). The winter precipitation maximum and spring snowmelt signal contained within high winter-spring base flows are better represented by the naturally scaled flow regimes, with higher and more variable multi-peak flows over a longer duration than the produced by the building blocks method (Figure 2).

Table 3 compares River Analysis Package hydrological metrics for the building blocks method flow regime and naturally scaled alternative regimes to the pre-regulation Snowy River at Jindabyne (1903-54). Unscaled flow sequences for the Thredbo and Murray Rivers are also compared to the Snowy River at Jindabyne (1903-54) to assess the degree to which these analogue rivers reflect the flow regime of the Snowy River prior to regulation. These results show that:

1. the analogue Murray and Thredbo Rivers both have similar coefficients of variation, skewness, high flow metrics and Colwell's indices to the unregulated Snowy River at Jindabyne
2. the ratio of minimum recorded flows to the lowest tenth percentile flow for the building blocks method 2009-13 flow regime is substantially higher than for the pre-regulation Snowy River (Table 3)
3. the ratio of the highest ninetieth percentile flow to the mean daily flow for the building blocks method 2009-13 flow regime is substantially lower than for the pre-regulation Snowy River (Table 3)
4. the coefficient of variation (standard deviation divided by the mean) for the building blocks method 2009-13 flow regime is substantially higher than for the pre-regulation Snowy River (Table 3)
5. the number per year of high spell flows greater than five times the mean daily flow for the building blocks method 2009-13 flow regime is substantially lower than for the pre-regulation Snowy River (Table 3)
6. the mean duration of high spell flows greater than five times the mean daily flow for the building blocks method 2009-13 flow regime are substantially higher than for the pre-regulation Snowy River (Table 3)
7. Colwell's indices for predictability, constancy for the building blocks method 2009-13 flow regime are substantially higher than for the pre-regulation Snowy River (Table 3).

In all cases noted above, the naturally scaled alternative flow regimes for the Snowy River based on the Murray and Thredbo Rivers more closely match values for the Snowy River at Jindabyne prior to regulation.

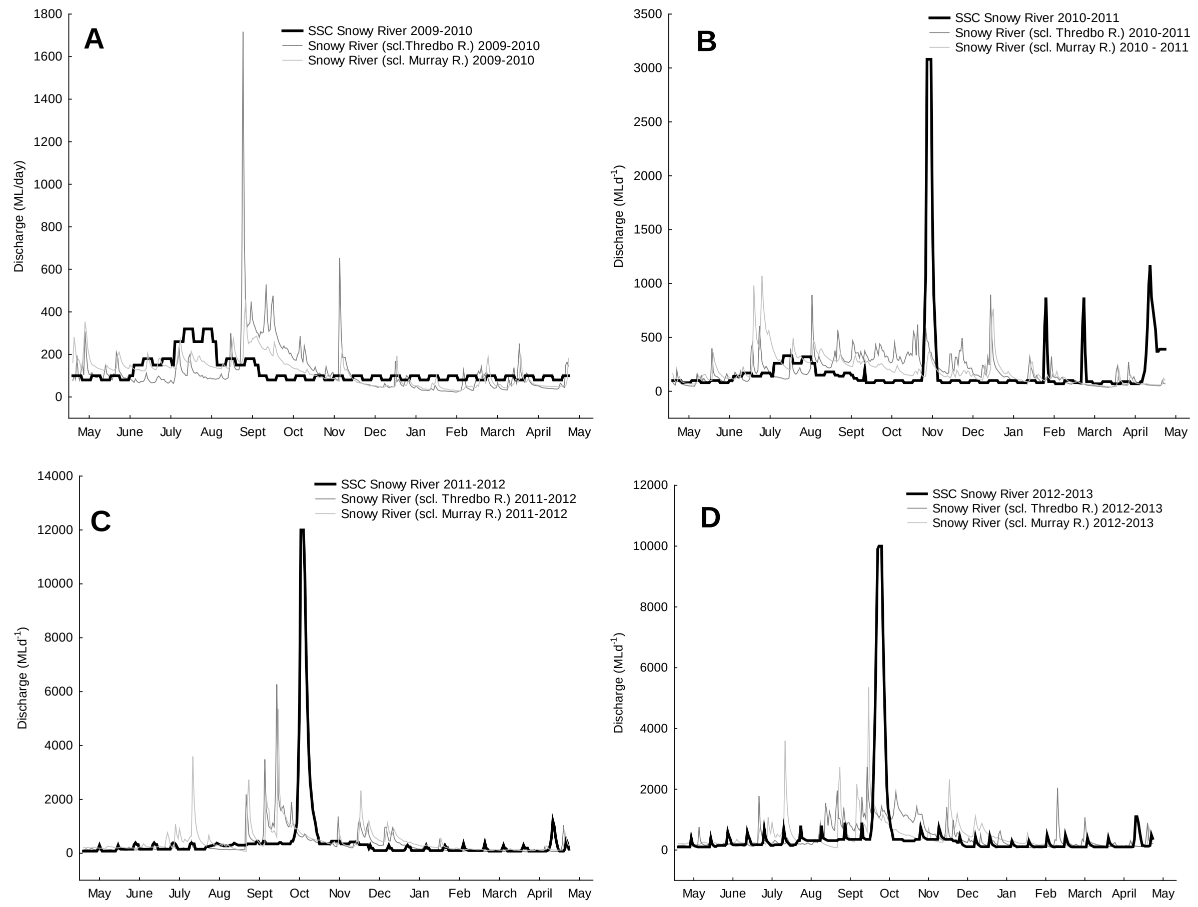

Figure 2 **Comparison of building blocks method mean daily flows (black) to scaled mean daily natural flows (grey) developed from analogue snowmelt rivers Thredbo River at Paddy's Corner and Murray River at Biggara. (A) 2009-10 water year, (B) 2010-11 water year, (C) 2011-12 water year and (D) 2012-13 water year.**

Table 3. Comparison of the hydrological metrics for the building blocks method Snowy River flow regime with the naturally scaled alternative Snowy River flow regimes for 2009-13; Murray and Thredbo River flow records from 1986-2011 and Snowy River at Jindabyne flow records from 1903-54, using the River Analysis Package.

Hydrological metric	Recommended	Naturally scaled		Observed		
	Snowy R. (building blocks) 2009-13	Snowy R. (Murray R.) 2009-13	Snowy R. (Thredbo R.) 2009-13	Murray R. 1986-2011	Thredbo R. 1986-2011	Snowy R. 1903-54
Minimum (MLd^{-1})	70	29	23	71	34	106
Maximum (MLd^{-1})	12,000	5,388	8,120	23,040	7,339	76,821
Percentile 10 (MLd^{-1})	80	64	58	235	91	416
Percentile 90 (MLd^{-1})	356	676	661	2,683	998	7,095
Mean daily flow (MDF) (MLd^{-1})	298	298	297	1,178	459	3,166
Median daily flow (Med) (MLd^{-1})	110	181	166	720	299	1,903
Coefficient of variation (CV)	3.1	1.2	1.5	1.1	1.1	1.2
Standard Deviation (MLd^{-1})	932.5	365.1	435.1	1,324.4	509.2	3,919.3
Skewness	2.7	1.6	1.8	1.6	1.5	1.7
High Spell Threshold (5 * MDF) (MLd^{-1})	1,489	1,490	1,487	5,890	2,293	15,832
Number of High Spells per year	0.75	2.00	3.75	1.64	3.16	2.14
Mean Duration of High Spell (days)	9.3	3.4	2.0	2.9	1.4	2.5
Mean period Between High Spells (days)	338	61	88	221	114	168
Colwell's predictability	0.76	0.58	0.56	0.47	0.52	0.43
Colwell's constancy	0.47	0.32	0.32	0.29	0.31	0.25
Colwell's contingency	0.29	0.26	0.24	0.18	0.22	0.19

Comparison of flow duration curves

Comparison of daily flow duration curves for 2009-13 for the building blocks method flow regime and naturally scaled flow regimes for the Snowy based on the Thredbo and Murray Rivers highlight substantial differences between the two approaches. Although only a short period of concurrent building blocks method and naturally scaled data sets are available for this comparative analysis, effects caused by the short record length and inclusion of two years with anomalously low SRIF allocation (2009-10 and 2010-11) are consistent between the data sets. The comparative analysis shows that the daily flow duration curve for the building blocks method flow regime from 2009-13 exhibits a number of artefacts that are inconsistent with flow duration curves representative of natural flow regimes:

1. the form of the building blocks method flow duration curve exhibits pronounced ‘flat spots’ and ‘steps’ representing the regular periodicity and magnitude of baseflows and pulsed flows discussed previously (Figure 3a, b)
2. flood flows that occur for less than 2% of days are over-represented in the building blocks method flow regime (Figure 3a) when compared to the scaled flow regimes (Figure 3b) and the pre-regulation Snowy River and unregulated Thredbo and Murray Rivers standardised to the mean annual flow (Figure 3a, b)
3. high flows forming recessions from flood flow peaks occurring for 2-10% of days are under-represented by the building blocks method flow duration curve (Figure 3a, b)
4. low flows with exceedance percentiles of 80-100% are over-represented by the building blocks method flow regime when compared to both naturally scaled flow regimes (Figure 3a, b) and the pre-regulation Snowy River and unregulated Thredbo and Murray Rivers standardised to the mean annual flow (Figure 3a, b).

Clearly, flow regimes for the Snowy River below Jindabyne Dam scaled to patterns of natural flow in the Thredbo or Murray Rivers produce flow duration curves without the pronounced artificial artefacts that are apparent in the building blocks method flow regime. A further advantage of the scaled flow regime approach is that flow duration curves can be constructed for multi-decadal periods (flow records permitting) to better assess the degree to which environmental flow regimes match unregulated reference rivers. Multi-decadal flow duration curves for the Snowy River based on scaled Thredbo and Murray River flows match very closely with flow duration curves for both natural analogue rivers (Thredbo and Murray Rivers) as well as for the Snowy River at Jindabyne from 1903-54 prior to regulation (Figure 4c, d). No artificial artefacts similar to the ‘flat spots’ and ‘steps’ apparent in the building blocks method flow regime occur in the naturally scaled flow regimes, nor are segments of the multi-decadal scaled flow duration curve over or under representing flows when compared to flow conditions in analogue rivers (Figure 3c, d).

Comparison of flow duration curves

Comparison of daily flow duration curves for 2009-13 for the building blocks method flow regime and naturally scaled flow regimes for the Snowy based on the Thredbo and Murray Rivers highlight substantial differences between the two approaches. Although only a short period of concurrent building blocks method and naturally scaled data sets are available for this comparative analysis, effects caused by the short record length and inclusion of two years with anomalously low SRIF allocation (2009-10 and 2010-11) are consistent between the data sets. The comparative analysis shows that the daily flow duration curve for the building blocks method flow regime from 2009-13 exhibits a number of artefacts that are inconsistent with flow duration curves representative of natural flow regimes:

1. the form of the building blocks method flow duration curve exhibits pronounced ‘flat spots’ and ‘steps’ representing the regular periodicity and magnitude of baseflows and pulsed flows discussed previously (Figure 3a, b)
2. flood flows that occur for less than 2% of days are over-represented in the building blocks method flow regime (Figure 3a) when compared to the scaled flow regimes (Figure 3b) and the pre-regulation Snowy River and unregulated Thredbo and Murray Rivers standardised to the mean annual flow (Figure 3a, b)
3. high flows forming recessions from flood flow peaks occurring for 2-10% of days are under-represented by the building blocks method flow duration curve (Figure 3a, b)
4. low flows with exceedance percentiles of 80-100% are over-represented by the building blocks method flow regime when compared to both naturally scaled flow regimes (Figure

3a, b) and the pre-regulation Snowy River and unregulated Thredbo and Murray Rivers standardised to the mean annual flow (Figure 3a, b).

Clearly, flow regimes for the Snowy River below Jindabyne Dam scaled to patterns of natural flow in the Thredbo or Murray Rivers produce flow duration curves without the pronounced artificial artefacts that are apparent in the building blocks method flow regime. A further advantage of the scaled flow regime approach is that flow duration curves can be constructed for multi-decadal periods (flow records permitting) to better assess the degree to which environmental flow regimes match unregulated reference rivers. Multi-decadal flow duration curves for the Snowy River based on scaled Thredbo and Murray River flows match very closely with flow duration curves for both natural analogue rivers (Thredbo and Murray Rivers) as well as for the Snowy River at Jindabyne from 1903-54 prior to regulation (Figure 4c, d). No artificial artefacts similar to the ‘flat spots’ and ‘steps’ apparent in the building blocks method flow regime occur in the naturally scaled flow regimes, nor are segments of the multi-decadal scaled flow duration curve over or under representing flows when compared to flow conditions in analogue rivers (Figure 3c, d).

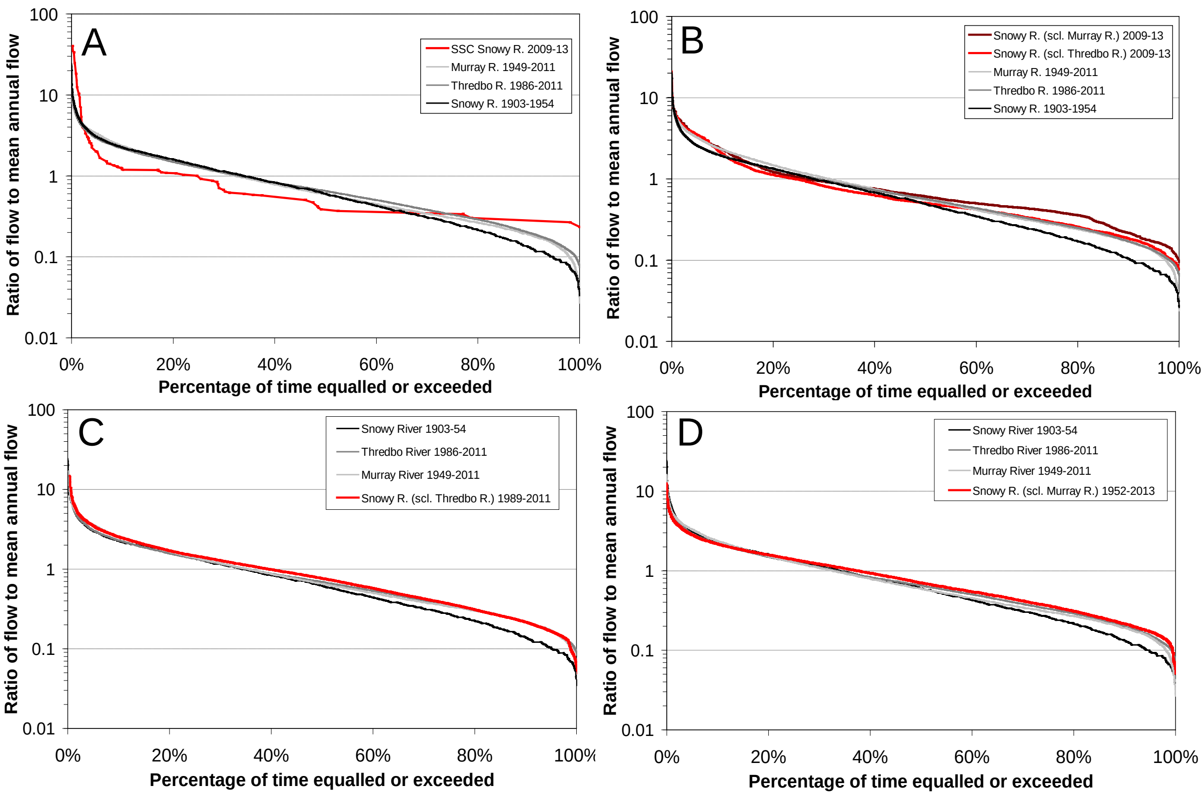

Figure 3 **Comparison of flow duration curves expressed as ratios of the mean annual flow. (A) building blocks method 2009-13 flow regime. (B) Alternative 2009-13 scaled flow regimes. (C) Multi-decadal (1986-2011) scaled flow regime developed from Thredbo River. (D) Multi-decadal (1986-2011) alternative scaled flow regime developed from Murray River.**

Note: Snowy Scientific Committee (Red), observed analogue rivers (Grey) and observed Snowy River (Black).

Comparison of annual maximum winter-spring floods

Annual maximum floods in the Snowy River at Jindabyne from 1903-54 prior to regulation by the SMS occurred most often in October (35%), September (25%), August (12%) and July (12%), with this temporal grouping the result of a winter-spring precipitation maximum and rain-on-snow events particularly during spring. Thredbo River records from 1986-2011 show a similar pattern with 26% and 22% of annual maximum floods occurring in October and September, respectively. Murray River records from 1968-2011 reflect in part a lower catchment elevation with 22% of annual maximum floods occurring in October and 71% in September.

Ratios between daily mean and daily maximum flows for annual maximum winter-spring floods (mean ± SD) in the pre-regulation Snowy River at Jindabyne (1903-54), Murray River at Biggara (1968-2011) and Thredbo River at Paddy's Corner (1986-2011) are 1.37 ± 0.23, 1.16 ± 0.13 and 2.05 ± 0.44. The difference between the ratios in these three rivers primarily reflect two processes:

1. downstream attenuation of flood peaks and declines in celerity for the larger catchment area Murray and Snowy Rivers; and,
2. differences in snowpack extent and the additional contribution to flood flows from rapid snowpack ablation events occurring in the higher elevation Snowy and Thredbo Rivers.

Annual maximum winter-spring floods in the Snowy River at Jindabyne prior to regulation are hence more muted than the peaky flood regime of the Thredbo River but are more pronounced than the flood regime for the Murray River at Biggara. The peakiness of the Thredbo River flood regime results in the 1.1 year and 1.01 year ARI flood magnitudes being larger in the Thredbo River than in the Murray River at Biggara despite the much smaller catchment area (Tables 1 and 3) and annual flow volume. Flood magnitudes for the Snowy River at Jindabyne are 3.8-4.8 times larger than the Thredbo River and 3.3-5.2 times larger than the Murray River at Biggara (Table 4) reflecting both the substantially larger catchment area, and by comparison to the Murray River, the extensive contributing area above 1800 m elevation (Table 1) which harbours extensive and deep snowpacks.

Annual maximum snowmelt flood magnitudes for the scaled flow regimes show a divergence from observed snowmelt flood regimes that is governed by the difference between modelled SRIF annual flow volumes and observed annual flow volumes in the unregulated analogue rivers. Peak flow rates for annual maximum snowmelt floods for the scaled Snowy River based on the Thredbo River show excellent agreement with observed annual maximum snowmelt floods for the Thredbo River (Table 5). Annual maximum snowmelt floods for the scaled Snowy River based on the Murray River, however, are a factor of 2-4 times lower than observed annual maximum snowmelt floods for the Murray River (Table 5).

Table 4 **Recurrence intervals and magnitude of annual maximum snowmelt (winter-spring) floods for scaled Snowy River flows, Thredbo River (natural), Murray River (natural) and Snow River (pre-regulation).**

		Scaled				Observed		
ARI (years)	AEP (%)	Snowy R. scaled to Thredbo R. 222541 (MLd^{-1})		Snowy R. scaled to Murray R. 401012 (MLd^{-1})		Thredbo R. 222541 (MLd^{-1})	Murray R. 401012 (MLd^{-1})	Snowy R. prereg 222501 (MLd^{-1})
		Current	Full	Current	Full			
1.01	99	2,340	4,110	865	1,130	1,590	1,170	6,120
1.1	90	3,595	5,565	1,410	1,970	3,180	2,890	12,185
1.25	80	4,380	6,510	1,765	2,525	4,290	4,300	16,745
1.5	67	5,125	7,450	2,110	3,060	5,395	5,840	21,570
1.75	57	5,620	8,100	2,345	3,425	6,145	6,965	25,045
2.0	50	5,995	8,610	2,530	3,700	6,720	7,865	27,815
3.0	33	6,960	9,990	3,000	4,415	8,205	10,345	35,470
5.0	20	7,970	11,550	3,505	5,165	9,750	13,155	44,270
10.0	10	9,150	13,550	4,110	6,030	11,510	16,645	55,510

Note: "Current" equates to 2011 allocations and "Full" to 2013 allocations.

The flood frequency analysis results clearly show that it is possible to replicate flood magnitude and frequency regimes of a smaller analogue river with a total annual flow similar to the allocated annual environmental flow (SRIF) volume by combining the simple daily mean flow scaling approach with a peak flow adjustment ratio. The analysis also shows that scaling to smaller catchment rivers with a similar annual flow volume will generate peakier floods than scaling to a larger catchment river with greater annual flow volumes. This difference in flood scaling performance between small and large rivers is important for environmental flow management because scaling to the Thredbo River, for example, will generate more frequent flood peaks within the range known to be geomorphically effective in the Snowy River below Jindabyne Dam. Scaling to the Murray River will generate longer duration floods with more muted peaks and quite likely, a lesser degree of geomorphic effectiveness.

The building blocks method flow regime for the Snowy River aims to reconstruct an annual spring snowmelt flood as a channel maintenance flow on the basis of recommendations from an expert panel (Pendlebury *et al*., 1996). It has been suggested that "…channel maintenance flows of about 12,000 MLd^{-1} should occur every year and last for about one week during the spring snowmelt period" (SSC, 2008), differing slightly from the original "base length" recommendation of 3-5 days by the expert panel (Pendlebury *et al*., 1996). A flow rate of 12,000 MLd^{-1} has a recurrence interval of 1.1 years on the annual maximum winter-spring (snowmelt) flood series in the pre-regulation Snowy River at Jindabyne and approximately 5.0 and 10.0 for the unregulated Murray and Thredbo Rivers, respectively (Table 4). There are insufficient years of building blocks method releases to undertake flood frequency analyses but SSC (2008 p. 27) recommended that "fluvial disturbance by flows of between 12,000 and 20,000 MLd^{-1} should be planned for all years in which water is available." When combined with the 2012-13 recommendation of a spring flood with a four day 10,000 MLd^{-1} peak, it would appear that the minimum flow rate for flood releases developed under the building blocks method for channel maintenance is approximately 10,000-12,000 MLd^{-1} with a peak flow duration of 3-4 days.

Three snowmelt flood events in the Snowy River below Jindabyne Dam (station no. 222501) prior to regulation with magnitudes approximating the 1.1 year recurrence interval event are compared against the building blocks method 2011-12 snowmelt flood recommendation in order to assess the degree to which the building blocks method approximates these natural pre-regulation events (Figure 4a). The 1918, 1919 and 1938 floods have recurrence intervals based on the Cunnane plotting position of 1.09, 1.17 and 1.07 years, respectively. In all three cases, natural durations for peak flow rates were 1-2 days as opposed to the three days for the building blocks method 2011-12 event (Figure 4a), indicating that the duration of peak flows for the building blocks method spring flood events can be decreased by 1-2 days without detriment to replication of natural events of similar magnitude. Of greater divergence from natural pre-regulation flow characteristics, however, is the fact that pre-regulation winter-spring high flows are characterised by complex multi-peak flow sequences as opposed to the building blocks method single peak (Figure 4a). Further divergence from natural pre-regulation flow characteristics are evident in a comparison of 15 day event volumes for the building blocks method and similar magnitude pre-regulation events illustrated in Figure 4a. Over a 15 day period covering the flood peaks, the building blocks method 2011 spring flood event accounted for 81.2 GL or 50.9% of the total annual discharge, whereas 15 day totals for the three natural events accounted for 9.7-12.1% of total annual discharges. By comparison with pre-regulation Snowy River flows, even the single peak building blocks method 2011 spring flood event is out of proportion with available annual environmental flow volumes.

Comparison of the building blocks method 2011 spring flood event with hourly mean and daily mean flows for a 10 year recurrence interval winter-spring event in the unregulated Thredbo River highlights the much shorter duration of flood peaks in the Thredbo River (Figure 4b). Similar to the Snowy River, however, winter-spring snowmelt sequences in the Thredbo River are characterised by multiple peaks representing multiple rain-on-snow events and elevated baseflows before and after the largest snowmelt peak (Figure 4b). The 15 day volume for the Thredbo River 10 year ARI September 1998 flood event accounts for 16.5% of the total annual discharge, a value similar to the 9.7-12.1% range for the smaller 1.1 year ARI floods assessed for the Snowy River, but again, substantially lower than the 50.9% for the building blocks method 2011 spring flood event. The much shorter duration of flood peaks characteristic of the Thredbo River, together with the similarity in annual SRIF allocations and Thredbo River annual discharges, make it volumetrically feasible to develop a flood regime for the Snowy River based on the Thredbo River. Key considerations in developing such a flood regime then include:

1. knowledge of downstream peak flow attenuation for flow pulses and small flood releases from Jindabyne Dam;
2. with information from the above, develop scaled flood peaks of suitable duration and magnitude that are geomorphologically and ecologically effective, operationally implementable.

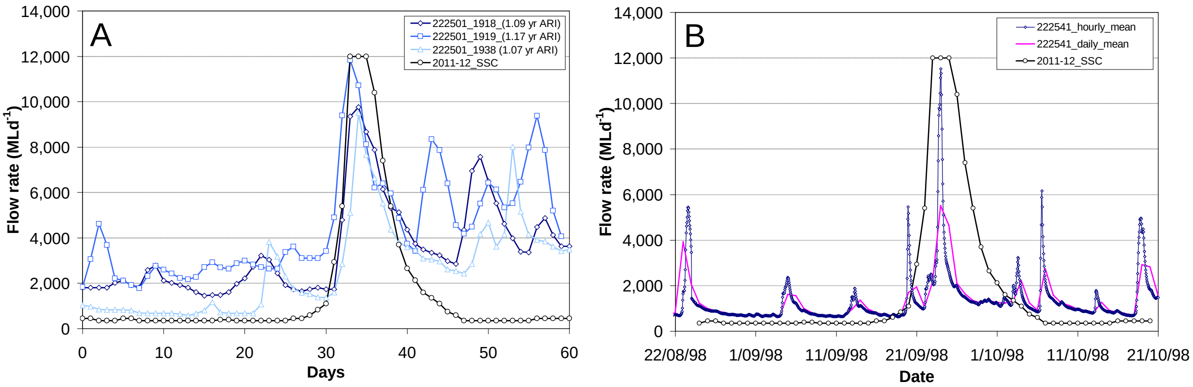

Figure 4. **Comparison of building blocks method spring 2011 flood release with (A) Snowy River (222501) pre-regulation ca. 1.1 year recurrence interval winter-spring floods, and (B) the 10 year recurrence interval Thredbo River (222541) winter-spring flood.**

Downstream volumetric losses and flood peak attenuation for releases from Jindabyne Dam

Volumetric losses and flood peak attenuation for seven flow pulses and small floods released from Jindabyne Dam between September 2006 and October 2011 are assessed to interpret likely downstream transmission changes for short duration flood pulses released from Jindabyne Dam as a part of any future environmental flow regime for the Snowy River (Table 5). Only the first peaks and leading 'shoulders' of complex, long duration hydrographs released since 2006 are included in the analysis (Figure 5), to better reflect likely transmission changes for any future release of short duration flood pulses from Jindabyne Dam.

Daily flow totals for the Snowy River at Cobbin Creek gauge (222020) immediately downstream of Jindabyne Dam and the Dalgety gauging station (222026) indicate volumetric losses of 9-12% for flow pulse releases totalling 2,070-2,290 ML such as occurred from September-October 2006 to February-March 2010 (Table 5). Larger volume releases with higher peak flow rates from November 2010 to October 2011 show smaller volumetric losses ranging from 5-9% (Table 5). For all seven events, unregulated tributary inputs downstream of Dalgety (primarily Delegate River, Maclaughlin River and Bobundara Creek) caused event volumes at Burnt Hut Crossing (gauge no. 222013) to increase beyond volumes recorded immediately downstream of Jindabyne Dam (gauge no. 222020) and at Dalgety (gauge no. 222026). Similarly, unregulated tributary inputs downstream of Dalgety also aid in maintenance or augmentation of peak hourly mean flows such that flow rates at Burnt Hut Crossing (gauge 222013) and Willis (222023) for 5 of 7 events match or exceed those recorded at Dalgety (Figure 5a, c, e, f, g).

The degree of downstream attenuation of peak discharges and reductions in the duration of flood peaks between Jindabyne Dam and Dalgety is dependent primarily on the duration and magnitude of flow releases from Jindabyne Dam, and to a lesser degree, on baseflow rates in the river system in the days prior to the release event, and hydrograph shapes for the release event. For example, an hourly mean flow of 23 m^3s^{-1} released from Jindabyne Dam (incorporating a flow peak of 38 m^3s^{-1} sustained for four minutes) generated a peak hourly mean flow of only 4.5 m3s-1 at Dalgety, equivalent to approximately 20% of the peak hourly mean flow at Jindabyne (Table 5; Figure 5d).

The duration (in hours) of peak flow releases from Jindabyne Dam can be used to estimate the magnitude of peak hourly mean flow rates at Dalgety (as a percentage of peak hourly mean flow rates released from Jindabyne Dam) from a logarithmic relationship between duration and magnitude (Figure 6a). This relationship indicates that a release from Jindabyne Dam with a peak flow sustained for eight hours will generate a peak flow at Dalgety that is approximately 72% of the magnitude of the peak hourly mean release rate (Figure 6a). This 72% estimate from the trend line may prove conservative as peak flow rates at Dalgety for all releases with peak durations greater than three hours ranged from 74-92% (Figure 6a). Similarly, a linear trend line fitted to event peak flow durations at Jindabyne and Dalgety indicates that a release from Jindabyne Dam with a peak flow sustained for eight hours will result in a flow peak sustained for approximately three hours at Dalgety (Figure 6b).

This analysis of volumetric losses and flood peak attenuation downstream of Jindabyne Dam indicates that release of flow events with peak flow magnitudes scaled to the Thredbo River, but with peak flow durations extended to approximately eight hours, will result in the effective transmission and maintenance of flood peaks to Burnt Hut Crossing approximately 83 km below Jindabyne Dam. By Burnt Hut Crossing, unregulated tributary inputs, notably from the Delegate River, Maclaughlin River and Bobundara Creek, contribute baseflows and pulse flows to the Snowy River such that peak flow magnitudes for releases from Jindabyne Dam are often maintained or augmented. The release of flow pulses from Jindabyne Dam scaled to the Thredbo River, but with durations extended so as to maintain effective downstream transmission of flood peaks, circumvents a problem inherent in the building blocks approach of trying to maintain aspects of the pre-regulation Snowy River flow regime with an environmental flow allocation that is well below the natural bounds of variability. Release of about 50% of the total annual environmental flow allocation in a single flow pulse event as per the building blocks approach is completely out of proportion with natural snowmelt flow sequences in both the pre-regulation Snowy River and smaller unregulated snowmelt streams. Such a high allocation to a single event seriously compromises flow volumes available to maintain other hydrological components of natural snowmelt rivers within an environmental flow regime.

Table 5 **Downstream volumetric losses and hourly mean peak flow attenuation from Jindabyne Dam (gauge no. 222020) to Dalgety (gauge no. 222026).**

Event	Jindabyne duration of peak (hours)	Jindabyne maximum discharge (m^3s^{-1})	Dalgety event volume (ML) and loss as % of 222020	Dalgety peak discharge m^3s^{-1} and (% of 222020)	Dalgety peak duration hours and (% of 222020)	See Fig. 6
Sep-Oct 2006	23	11.9	2002.2 (-12.6%)	15.0 (74.3%)	8.8 (65.2%)	a-a'
Jan-Feb 2010	13	14.2	1726.4 (-16.7%)	11.2 (78.7%)	5.0 (38.5%)	b-b'
Feb-Mar 2010	9	14.4	1874.1 (-8.8%)	10.5 (74.6%)	4.0 (44.4%)	c-c'
Sep 2010	1	23.0	(N/A)	4.5 (19.7%)	1.0 (N/A)	d-d'
Nov 2010	3	36.9	15848.8 (-8.6%)	30.3 (82.1%)	1.0 (33.3%)	e-e'
Apr 2011	15	14.2	7166.6 (-5.8%)	12.4 (86.9%)	8.0 (53.0%)	f-f'
Oct 2011	23	39.1	79858.4 (-5.0%)	36.1 (92.3%)	19 (82.6%)	g-g'

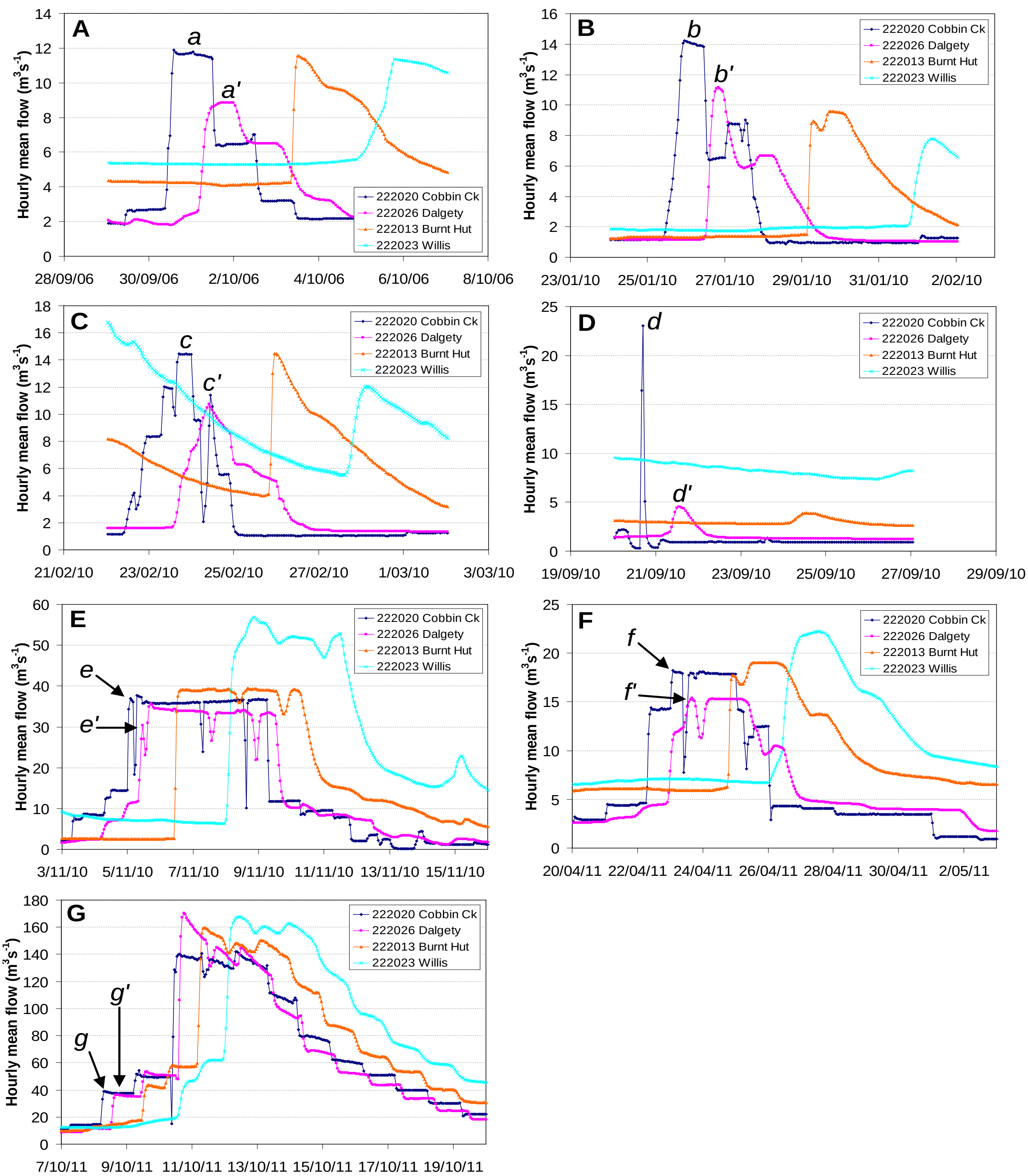

Figure 5 **Hourly mean flow hydrographs from four consecutive downstream gauging stations for seven flow pulses released from Jindabyne Dam. Paired letters (e.g. a a') indicate first flow peaks and leading shoulders analysed for peak flow rate attenuation and duration reduction from Jindabyne Dam to Dalgety.**

Note: Cobbin Creek refers to the Snowy River at the junction with Cobbin Creek (i.e. below Jindabyne Dam)

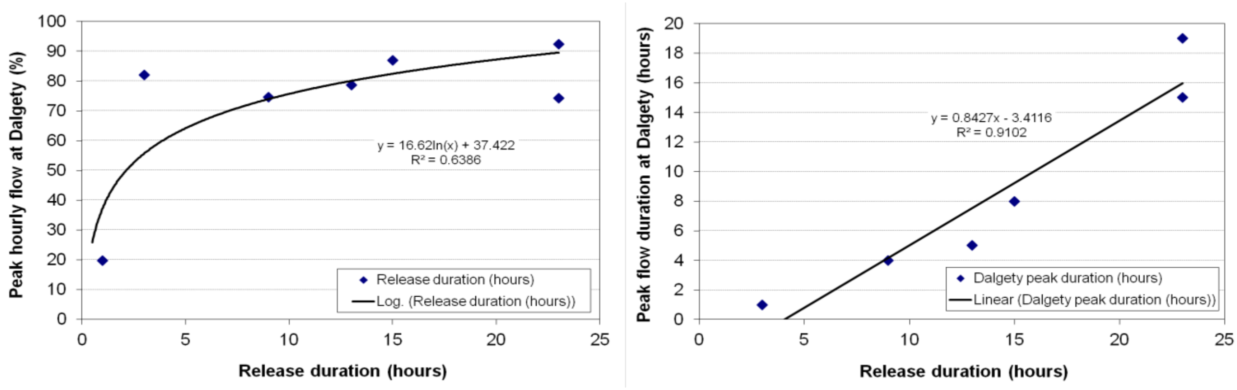

Figure 6 **The relationship between the (A) peak hourly flow rate (%) and (B) peak flow duration (hours) for flood pulses at Dalgety.**

Discussion

Under current levels of water entitlement recovery in the Murray Darling River Basin, annual environmental flow allocations to the Snowy River below Jindabyne Dam will have a median value approximately equal to 20% of the median natural annual flow. There is hence a five-fold difference between water volumes available to reinstate geomorphic and ecological recovery in the post-regulation Snowy River below Jindabyne Dam and water volumes that were available to maintain geomorphic and ecological processes in the pre-regulation Snowy River. A comparison has been undertaken of the daily flow patterns, flow duration, flood frequency and flood peak attenuation for flow regimes developed through application of the 'building block' methodology as per the building blocks method flow regime for 2009-13, and flow regimes based on scaling daily and hourly flow patterns from natural analogue rivers. In order to evaluate which flow allocation method best meets the management objectives and rehabilitation vision adopted by the Snowy Scientific Committee, we address the following questions:

1. which flow allocation method, the 'building blocks' approach used over 2009-13, or the 'natural scaling' approach, delivers a flow regime most consistent with the recommendations of the independent expert panel (Pendlebury et al., 1996)?
2. which flow allocation method delivers a flow regime most consistent with the pre-regulation Snowy River at Jindabyne and natural analogue snowmelt rivers as per the internationally recognised 'natural flow paradigm'?
3. which flow allocation method delivers a flow regime most consistent with management objectives for the Snowy River below Jindabyne Dam as outlined in the Snowy Water Inquiry Outcomes Implementation Deed (SWIOID, 2002) and by the Snowy Scientific Committee?

Consistency with independent expert panel recommendations

The independent expert panel assessment of environmental flow regimes for the Snowy River below Jindabyne Dam included recommendations for minimum flows, seasonally varied baseflows and flood flows (Pendlebury *et al*., 1996). These flow recommendations form the "...basic overall vision for delivery of environmental flows" adopted by the Snowy Scientific Committee (SSC, 2009 p. 3).

The expert panel (Pendlebury *et al*., 1996) recommended that a minimum flow of 200 MLd^{-1}, or natural catchment inflows (whichever is the lesser), was required to provide adequate wetted habitat area and to prevent the development of thermal stratification and anoxic conditions. The minimum flow recommendation of 200 MLd^{-1} requires 73 GL per year (Williams and Wolfenden 2012) or approximately 50% of the median SRIF allocation under current levels of entitlement recovery. Neither the building blocks method flow regime for 2009-13 nor the naturally scaled alternative flow regimes meet the 200 MLd^{-1} expert panel minimum flow recommendation. The basis of the 200 MLd^{-1} minimum flow recommendation in light of climate change effects on water yields in the Snowy Mountains (Reinfelds *et al*., 2012) and the appropriateness of this recommendation with regard to recent scientific advances in the understanding of minimum flow requirements since the 1996 expert panel report needs to be further assessed. Internationally recognised minimum flow modelling approaches (e.g. Reinfelds *et al*., 2004; Brooks *et al*., 2005) are required to address this information gap and are currently underway.

The prevention and breakdown of thermal stratification can not be addressed by the 200 MLd^{-1} recommended minimum flow for the Snowy River or by typical minimum environmental flow releases in regulated rivers within NSW and worldwide (Bevitt *et al*. in prep; Reinfelds and Williams, 2011). Discharge rates required to breakdown thermal stratification are dependent on local hydraulic, climatic and water temperature conditions, but typically flow rates in the range of natural (pre-regulation) median to mean daily flows are sufficient to break down thermal stratification over multi-kilometre river reaches in bedrock controlled pool-riffle type rivers in temperate NSW (Reinfelds and Williams, 2011). For the Snowy River below Jindabyne Dam, thermal stratification has been demonstrated not to be a significant issue. Stratification is restricted to a small area within a single pool within Jindabyne Gorge and minimum overnight air temperatures that regularly drop below surface water temperatures provide an additional water column mixing mechanism unrelated to flow that helps to break down thermal stratification (Bevitt *et al*., in prep; Williams and Wolfenden 2012). However, flow magnitudes of approximately 1,000 MLd^{-1} are required to mix the water column in the pool (Bevitt *et al*., in prep).

The expert panel recommended that a seasonally varied baseflow based on the pre-regulation 95th flow duration percentile for each month is provided to the Snowy River below Jindabyne Dam in order to help stimulate biological and reproductive processes of fish and macroinvertebrates (Pendlebury et al., 1996). This recommendation requires approximately 300 GL per year or 1.4 - 2.0 times SRIF volumes (Williams and Wolfenden 2012) under future and current entitlement recovery estimates. Clearly it is not possible to meet this recommendation with current and future available SRIF volumes. However, with regard to replicating seasonal flow patterns, the scaled flow regime alternatives based on the Thredbo and Murray Rivers provide a much clearer pattern of natural seasonal flow variations than the building blocks method flow regime for 2009-13 (Figure 2). Indeed, the naturally scaled flow regimes replicate natural daily and seasonal patterns of flow variability, and inter- annual as well as decadal scale variations in these patterns, that cannot be achieved by the building blocks approach.

The expert panel (Pendlebury *et al*., 1996) recommended that a flood flow event be released to the Snowy River below Jindabyne Dam between May and October each year with a minimum peak of 12,000 MLd^{-1} and a flood base length of 3-5 days so as to exceed thresholds of motion for stabilised sediment and to rehabiltate and maintain channel morphology. The SSC (2008) further note that the purpose of the channel maintenance flow is to: mobilise substrate sediments to flush interstitial fines and strip biofilms; trim encroaching sediment and vegetation in order to reverse channel shrinkage; strip fine sediment infilling pools and replace the fines with coarser sediment; scour pools and fill riffles so as to maintain pool-riffle sequences; fully mix pools by turbulent flows; and rework marginal bars and benches so as to reverse recent terrestrialisation of the riparian corridor.

The building blocks flow regime released a spring flood event in October 2011 with a 12,000 MLd^{-1} peak flow continuing for three days over a base length of eleven days with flows exceeding 2,000 MLd^{-1} (Figure 2). The October 2011 spring flood release replicated peak flow rates associated with a natural pre-regulation winter-spring flood event of approximately 1.1 years ARI but the peak flow duration was 1-2 days longer than that of natural events with similar recurrence intervals (Figure 4). The post-peak hydrograph shape after the October 2011 event, however, was inconsistent with natural pre-regulation hydrographs which show that natural snowmelt sequences are complex multi-peak events with multi-week durations (Figure 4). Replication of the natural multi-peak snowmelt flow sequences presents a conundrum as water volumes allocated by the building blocks approach to achieving a single peak of 12,000 MLd^{-1} are already disproportionally large (50.9% of annual flow volumes) when compared to water balances in the pre-regulation Snowy River for small recurrence interval spring flood events (9.7-12.1% of annual flow volumes). Such a disproportionally large allocation to replication of a single flood pulse event clearly demonstrates that replication of even small pre-regulation Snowy River flood events comes at the expense of being able to effectively replicate natural seasonal patterns of flow variability and the complex multi-peak characteristics of natural spring mixed rainfall - snowmelt hydrographs. Indeed, our analyses of four years of building blocks method flows, pre-regulation spring flood versus annual water balances and water volumes required to implement the expert panel seasonal baseflow recommendations confirm that it is impossible to replicate virtually any aspect of the pre-regulation Snowy River flow regime with approximately one fifth of the pre-regulation water volume without seriously compromising other aspects of the flow regime. This gives rise to the question as to whether the geomorphic and ecological role ascribed to the annual spring flood event be accomplished by release of shorter duration, peakier flood events characteristic of the analogue Thredbo River.

The natural flow scaling approach proposes to deliver annual spring floods with peak magnitudes that vary from year to year in accordance with natural patterns of variability in the Thredbo or Murray Rivers. As such, a Snowy River flow regime based on the Thredbo River will have annual spring flood peak flow magnitudes that vary from 3,595–9,150 MLd^{-1} for 1.1 year to 10.0 year recurrence interval events under current levels of entitlement savings, and 5,565–13,550 Mld^{-1} under projected final levels of entitlement savings (Table 4). The geomorphic effectiveness of small flow pulse and flood events in facilitating the recovery of the Snowy River below Jindabyne Dam was assessed by Rose and Erskine (2011) who investigated sediment deposition on the developing inset floodplain as a result of three environmental flow releases and one natural tributary flood event during 2010. Their results and those of Williams *et al.* (2011) show that flow pulses and small floods with peak flow magnitudes ranging from 1,240-3,270 MLd^{-1} are highly effective in scouring silt to sand size sediment from the current Snowy River low flow channel and depositing it onto the inset floodplain developing across the abandoned sections of the pre-regulation Snowy River bed. These relatively small flow pulses produced rapid floodplain sedimentation rates of up to 4.0 cm yr^{-1}, with predictions that future environmental flow releases with exactly the same magnitude and duration as the 2010 events will deposit up to 66 cm of sediment by 2025. Importantly, Rose and Erskine (2011) cautioned that release of larger floods may exceed thresholds for floodplain deposition and cause floodplain stripping and re-working, thereby slowing or reversing the positive river recovery trajectory achieved by the relatively small flow pulses released in 2010.

Unpublished data by Williams *et al.* (in prep) of suspended sediment concentrations at three sites in close proximity to gauging stations at Jindabyne Dam (Site 1), Dalgety (Site 4) and Burnt Hut Crossing (Site 5) shows that the October 2011 flood mobilised, and commenced to deplete, different sediment sources as flows were progressively increased to the flow peak (Figure 7). At each of the three sites, the first rising shoulder of the flow release generated large increases in total suspended sediment concentrations from 2.5 mgL^{-1} to 59-190 mgL^{-1} as the flow release increased from approximately 1,250 MLd^{-1} to 3,300 MLd^{-1} (Figure 7). After an approximate 50% decline in total suspended sediment concentrations as flows were maintained at about 3,300 MLd^{-1} during the first shoulder of the release (Figure 7), suspended sediment concentrations again increased from 18-52 mgL^{-1} to 81-110 mgL^{-1} as flows increased from about 3,300 MLd^{-1} to 4,375 MLd^{-1} to form the second rising shoulder of the event (Figure 7). Suspended sediment concentrations again declined as the flow release was maintained at about 4,375 MLd^{-1} for the second shoulder before increasing substantially to a maximum of 130-730 mgL^{-1} during the final rising limb of the flow release which peaked at 12,080 MLd^{-1} (Figure 7).

The suspended sediment data collected for the October 2011 flow release demonstrates mobilisation, and then partial depletion, of different sediment sources contributing to suspended loads as release rates from Jindabyne Dam increased in a step-wise fashion from 1,250 MLd^{-1} to 3,315 MLd^{-1}, 3,315 MLd^{-1} to 4,375 MLd^{-1} and then 4,375 MLd^{-1} to 12,080 MLd^{-1}. While suspended sediment concentrations were about 6-7 times greater at Dalgety and Burnt Hut Crossing, a peak flow release rate of 12,080 MLd^{-1} then at flow release rates ranging from 3,315-4,375 MLd^{-1}, the proportion of sediment mobilised from the floodplain developing on the abandoned Snowy River bed as opposed to sediment mobilised from within the current low flow channel under the range of flows discussed above is not known and forms an important information gap. This is currently being investigated through detailed assessment of overbank shear stress versus in-channel shear stress from HEC-RAS and River2D models and forms an important area of investigation because of the floodplain erosion concerns of Rose and Erskine (2011). The suspended sediment results at three Snowy River sites show clearly that the majority of sediment is mobilised on the rising limbs of flow pulses and that sediment concentrations decline rapidly by a factor of 2-9 within 24 hours of the flow peak. These results support Stanford's *et al* (1996 p. 404) discussion of protocols for the restoration of regulated rivers where they note that very high flows are not required every year, nor are historical durations for flood events likely to be required to maintain in-stream and floodplain habitats, as the majority of sediment is moved on the rising limb of flow events.

The study of floodplain sedimentation rates in the Snowy River below Jindabyne Dam by Rose and Erskine (2011) and suspended sediment results from the October 2011 event (Figure 8; also Williams *et al*. in prep) support a case for release of more frequent, shorter duration and variable magnitude flood pulse events as part of an environmental flow regime in order to maximise rates of sediment deposition across the developing inset floodplain. Over decadal time scales, positive feedback effects resulting from progressively increasing flow confinement due to sediment deposition across the inset floodplain will lead to continually increasing in-channel geomorphic effectiveness of environmental flow releases from Jindabyne Dam. The natural scaling approach based on the Thredbo River flow record provides regular floods and flow pulses within the range of flow rates reported as being geomorphically effective in progressing recovery of the Snowy River below Jindabyne Dam (Figure 3) without producing artificial distortions in flow duration curves and compromising other aspects of the flow regime that result from the 'building blocks' approach (Figure 4). The natural scaling approach delivers flood pulses with peak flow rates equivalent those advocated by the expert panel (Pendlebury *et al*., 1996), but with average annual recurrence intervals (frequencies) commensurate with available water volumes. It hence provides a demonstrably more natural flood regime to the Snowy River below Jindabyne Dam than the current 'building blocks' method and delivers flood pulses that are demonstrably geomorphically effective in progressing the recovery of the Snowy River.

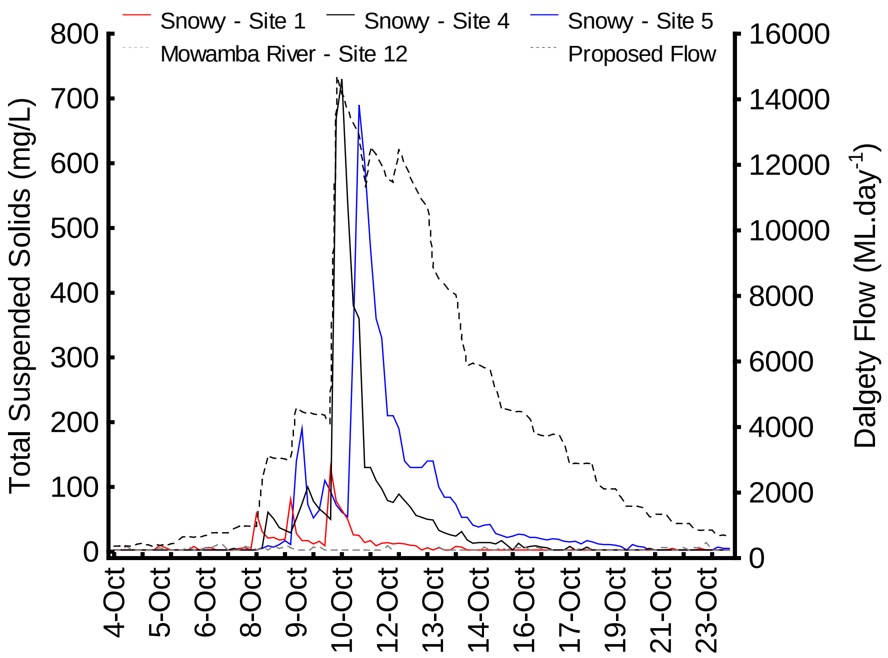

Figure 7. **Total suspended solids concentrations (mg/L) measured 4-6 hourly at three Snowy River sites during the October 2011 environmental water release from Jindabyne Dam (source: Williams *et al*. in prep).**

Consistency with pre-regulation and natural analogue flow regimes

The Snowy Water Inquiry Outcomes Implementation Deed (SWIOID, 2002 p. 13) states that "… the arrangements and actions contemplated under this deed are intended to ensure that water releases will to the extent possible mimic seasonal natural flows under prevailing climatic conditions." The Snowy Scientific Committee (SSC, 2010 p. 6) considers this to mean that "in the case of rivers being considered here, respecting the natural flow regime means comparing river flows before the Snowy Mountains Scheme with flows since dam construction."

Our study has compared pre-regulation Snowy River flow characteristics to environmental flow regimes developed by a 'building blocks' approach and a 'natural scaling' approach. Flow duration analyses, River Analysis Package analyses, flood frequency analyses and flood pulse volumetric analyses all unequivocally demonstrate that the natural scaling approach based on analogue snowmelt rivers (i.e. Thredbo River) delivers an environmental flow regime to the Snowy River much more in keeping with the pre-regulation Snowy River than the 'building blocks' approach.

The Murray River at Biggara was considered by Erskine et al. (1999) to be a suitable unregulated analogue river to the Snowy. Detailed analysis of digital elevation models demonstrate that while the Murray River is substantially closer in catchment size to the pre-regulation Snowy River, the Thredbo River has much more similar elevation characteristics to the Snowy. The elevation similarities between the Snowy and Thredbo Rivers, in particular catchment proportions above 1800 m elevation, are important as Reinfelds et al. (2012) demonstrate that elevation is the primary control on catchment runoff across the Snowy Mountains with steep increases in catchment yields for mean elevations greater than 1800 m. Comparison of flow characteristics for these natural analogue rivers with the pre-regulation Snowy River and the 'building blocks' flow regime demonstrates that both of these analogue rivers, and any scaled flow regimes derived from them, are much more in keeping with pre-regulation Snowy River hydrological characteristics than the current building blocks approach. In short, the naturally scaled flow regimes are unequivocally closer to the hydrological characteristics of the pre-regulation Snowy River at Jindabyne than the current 'building blocks' flow regime.

Consistency with management objectives

Williams and Wolfenden (in prep) review the environmental objectives for the Snowy River to develop more contemporary hydro-ecological objectives, however, the Snowy Water Inquiry Outcomes Implementation Deed (SWIOID, 2002 p. 39) mandates environmental objectives for the Snowy River as follows:

"...to improve the habitat for a diverse range of plant and animal species through a combination of:

1. improving the temperature regime of river water
2. achieving channel maintenance and flushing flows within rivers
3. restoring connectivity within rivers for migratory species and for dispersion
4. improving triggers for fish spawning
5. improving the aesthetics of currently degraded riverine environments."

The Snowy Scientific committee (SSC, 2010 p. 11) interprets the mandated and implied environmental objectives for the Snowy River into the following target:

"...to rehabilitate the Snowy River so that the upland and gorge reaches resemble a montane river, characterised by: high and seasonally predicable patterns of (flow) disturbance; clear, cool and low-nutrient (oligotrophic) water; biota characteristic of such a river."

The previous sections of this report have demonstrated that the natural scaling approach to environmental flow development is superior to the building blocks approach with regard to overall consistency with the natural flow paradigm, pre-regulation flow characteristics and expert panel recommendations (Pendlebury et al., 1996). This section addresses the question as to which approach best meets the mandated and implied environmental objectives and targets outlined in the Snowy Water Inquiry Outcomes Implementation Deed (SWIOID, 2002) and adopted by the Snowy Scientific Committee.

Improving the temperature regime of river water

Flow related improvements to the temperature regime of river water downstream of Jindabyne Dam can be achieved through the release of flow pulse events sufficiently large to effect turbulent mixing of deep pools (Turner and Erskine, 2005; Reinfelds and Williams, 2011; Bevitt et al. in prep). Independent hydrodynamic assessments (Erskine unpublished cited by SSC

2008;) and continuous temperature monitoring of destratification events in the Snowy River below Jindabyne Dam (Bevitt et al., in prep) have found that flow pulses with magnitudes of 850-900 MLd-1 will result in turbulent mixing and destratification of the deepest pools downstream of the dam. Flow duration analyses show that these flow rates are equalled or exceeded for 3% and 8% of the time, respectively, by the building blocks regime and the alternative naturally scaled flow regimes. Moreover, River Analysis Package results show that a naturally scaled flow regime based on the Thredbo River would deliver five times the number of high flow pulses (about 1,490 MLd^{-1} or greater) per year than was delivered by the building blocks flow regime over 2009-13. The naturally scaled flow regimes are clearly superior to the building blocks regime with regard to delivering flow pulse related temperature improvements to the Snowy River below Jindabyne Dam.

Achieving channel maintenance and flushing flows

The purpose of channel maintenance and flushing flows released from Jindabyne Dam is to: exceed thresholds of motion for stabilised sediment and to partially restore and maintain channel morphology (Pendlebury et al., 1996); mobilise substrate sediments to flush interstitial fines and strip biofilms; trim encroaching sediment and vegetation in order to reverse channel shrinkage; strip fine sediment infilling pools and replace the fines with coarser sediment; scour pools and fill riffles so as to maintain pool-riffle sequences; fully mix pools by turbulent flows; and rework marginal bars and benches so as to reverse recent terrestrialisation of the riparian corridor (SSC, 2008).

Flow regimes developed by both the‘building blocks and the natural scaling method, will give effect to the geomorphic processes listed above as both flow regimes will deliver flows with similar maximum flow rates. The magnitude, frequency and duration flood pulse releases, however, varies substantially between the two approaches. Rather than delivering a flood of 10,000-12,000 MLd^{-1} with a peak flow duration of 3-4 days every year, the natural scaling approach will deliver occasional floods with the same peak flow rates as the building blocks approach (10,000 to 12,000 MLd^{-1} peak flows have recurrence intervals of 1 in 3 to 1 in 10 years under full entitlement recovery) within an annual magnitude-frequency distribution closely replicating that for natural snowmelt river flood regimes. This has significant advantages over a flood regime with comparatively static annual flood magnitudes as it facilitates the development of landforms and ecosystems adjusted to a variable range of flood magnitudes that closely replicate natural analogue flood regimes.

A major disadvantage of the building blocks approach is that the single flood pulse release accounted for 50.9% of the total 2011-12 environmental flow allocation to the Snowy River below Jindabyne Dam, a figure substantially out of proportion with similar recurrence interval natural flood pulses that account for 9.7-12.1% of annual flow volumes. A further disadvantage to replicating the long duration of pre-regulation Snowy River flood pulses is that the majority of sediment is mobilised on the rising limb of flood pulse events, and as such, the need for replication of the duration of pre-regulation flood pulse events to facilitate the rehabilitation of regulated rivers has been questioned (Stanford et al., 1996). Suspended sediment results at three sites in the Snowy River over the October 2011 flood pulse release recorded declines in sediment concentrations by factors of 2-9 within 24 hours of each of the three primary rising hydrograph limbs forming the flood pulse event (Figure 8; also Williams et al. in prep). These results support the observations and reasoning of Stanford et al. (1996), and attest to the advantages of releasing more frequent, shorter duration flood pulses to more regularly mobilise accumulated fine sediment from within the current low flow channel and deposit this sediment onto the developing inset floodplain.

An additional concern with regard to releasing flood pulses of the magnitude and duration suggested by the building blocks approach is that events of this magnitude and duration have the potential to reverse, through floodplain stripping and re-working, the positive recovery trajectory achieved by the release of smaller flood events (Rose and Erskine, 2011). The peak flow for the building blocks 2011-12 and 2012-13 annual flood pulse is 34 to 40 times greater than the mean daily flow, whereas for the pre-regulation Snowy River this ratio was 4:1 for a 1.1 year recurrence interval event. The magnitude of the 'building blocks' annual flood is clearly out of proportion to the magnitude of more frequent flows, a situation conducive to eroding parts of the developing inset floodplain that would otherwise stabilise under a flood regime with a more natural magnitude/frequency distribution.

Williams et al. (2011) also demonstrated that the spring 2010 event with a maximum discharge rate of 3,080 MLd^{-1} was also capable of scouring the bioflims from riffles in the Snowy River below Jindabyne. These magnitude events are regularly achievable using the natural scaling method and will ensure maintenance biofilms in riffles with the current water allocation.

Restoring connectivity within rivers for migratory species and for dispersion and improving triggers for fish spawning

Restoration of longitudinal and lateral connectivity for migratory species and for dispersion through flow manipulation can be achieved through provision of flow pulses, where significant barriers do not occur. Flow pulses are one of a range of environmental stimuli (e.g. water temperature, photoperiod, moon phase etc.) that are well known to trigger migratory and movement responses for dispersion and spawning in fish (e.g. Lucas and Baras, 2000; Reinfelds et al., 2011). The naturally scaled flow regime is superior to the building blocks regime in this regard as it demonstrably provides a four times greater frequency of small flow pulses (5 times the mean daily flow or greater) that are likely to trigger local scale flow-related movement for dispersal and/or spawning responses in fish.

Gilligan and Williams (2008) identified four significant natural barriers in the Snowy River below Jindabyne, and demonstrate significantly different fish assemblages above and below these natural waterfalls. Haeusler and Bevitt (2008) have undertaken hydraulic analysis of one of the smaller barriers (Pinch Falls) to show that the conditions for Australian Bass passage (selected only due to the availability of information on swimming ability) occurs at flow rates greater than 12,000 Mld^{-1} and require significant water allocation. Williams et al. (in prep) show that even when 50.9% of the total 2011-12 environmental flow allocation is released as a single flood pulse, it still may not be possible to ensure large scale longitudinal upstream fish movement due to the presence of large water falls (Figure 8). Thus the 'building block' method is not particularly applicable for large scale fish movement in the Snowy River. Fish movement through these reaches, if it does occur, is likely to be dependent on larger natural flood events.

Pre-spring release September 2011 | During spring release October 2011

Figure 8. Hydraulic conditions in the Snowy River at the Snowy Falls, pre and post the spring 2012 release. A, B and C show significant water falls (Source: Williams *et al.* in prep).

Improving the aesthetics of currently degraded riverine environments

A number of non-flow related management activities can substantially improve the aesthetics of degraded riverine environments, for example weed control, fencing and stock exclusion and erosion control provide opportunities for immediate improvement of the visual appeal of degraded areas.

Williams and Wolfenden (2012) review the aesthetic objectives as they relate to environmental water allocations to the Snowy River. Typically, many of these aesthetic objectives in the literature are related to low flow conditions and are not particularly relevant to hydrologically flashy montane rivers such the Snowy River. However, in terms of flow related aesthetic objectives the natural scaling approach is superior to the building blocks approach because:

1. Implementation of a flow regime for the Snowy River below Jindabyne Dam scaled to the Thredbo River will cause the hydraulic geometry of the Snowy River, over decadal to centuries time scales, to adjust towards that of the Thredbo River. With complementary management actions to expedite this process, the development of the Snowy River towards the aesthetic Thredbo River, provides a realistic and tangible rehabilitation vision and target.
2. The release of floods that are so disproportionally large to the remainder of the flow regime as per the building blocks method has the potential to erode the developing inset floodplain, thereby reversing the positive recovery trajectory achieved by the release of more moderate magnitude flow pulses (Rose and Erskine, 2011).

Conclusion

This report has compared two approaches to environmental flow regime development for the Snowy River below Jindabyne Dam: (1) the ‘building blocks’ approach whereby components of pre-regulation flow regimes considered to be important are used to construct a pattern of environmental flow releases; and, (2) a ‘natural scaling’ alternative where environmental flow regimes are developed from daily and hourly flow sequences for hydrologically similar analogue rivers.

1. ‘Naturally scaled’ flow regimes were developed from two analogue rivers (the Thredbo and Murray Rivers) that differed in catchment area and catchment elevation characteristics. The ‘naturally scaled’ flow regimes developed are superior in overall achievement of mandated and adopted objectives ascribed to the release of environmental flows for the Snowy River below Jindabyne Dam. Additionally, the adoption of a naturally scaled flow regime based on the smaller catchment and higher elevation Thredbo River holds two significant advantages over one based on the larger catchment but lower elevation Murray River.
2. The Thredbo River is more similar in catchment hypsometry (elevation) to the Snowy River with similar catchment proportions above 1800 m in elevation, an elevation threshold where Reinfelds et al. (2012) documented a significant increase in catchment yield above the trend apparent for lower elevation catchments. As a result of this elevation similarity, snowmelt sequences in the Thredbo River are likely to more closely reflect snowmelt sequences in the Snowy River.
3. Long-term modelled annual flow volumes available as an environmental flow release to the Snowy River closely approximate long-term annual flow volumes in the Thredbo River. With regard to flow scaling at daily and hourly time steps, peak flow magnitudes for flood events are not ‘down-scaled’ as occurs for the larger catchment Murray River, hence preserving a natural flood magnitude frequency distribution over decadal time scales.

In simple terms, adoption of a naturally scaled environmental flow regime for the Snowy River below Jindabyne dam based on the Thredbo River at a daily (and for specific events, hourly) time step, provides an opportunity to facilitate over decadal time scales, the rehabilitation, and ultimate evolution, of the Snowy River below Jindabyne Dam into a smaller montane river with a form similar to the Thredbo River. Such an approach implicitly recognises that neither the grandeur, nor the original ecosystems of the pre-regulation Snowy River can be restored with 20% of the unregulated flow volume but instead, provides a realistic rehabilitation vision for the development of a healthy, functioning and arguably aesthetic, smaller monatne river. The opportunity to develop an environmental flow regime where environmental flow release patterns can be altered across a wide range of flow rates on such a fine time scale to match a natural, unregulated analogue river is rare, and perhaps unique, for management of regulated rivers world-wide.

Recommendations

Based on this assessment the following is recommended:

- Adoption of a naturally scaled environmental flow regime for the Snowy River below Jindabyne Dam based on:
    - daily pattern of flows in the Thredbo River from 2-3 years prior and scaled to available SRIF volumes.
    - hourly pattern of flows that will double the mean daily flow rate for a spring flood event for a period of eight hours. An eight hour flood peak release from Jindabyne Dam is predicted to provide a flood peak with a duration of approximately three hours at Dalgety and a peak magnitude approximately 72% of that of the release.
- Develop an operational environmental flood release strategy in conjunction with the operator of Jindabyne Dam (Snowy Hydro) that incorporates the analogue daily/hourly flow sequence.
- Provide further assessments of water balancing options across yearly, seasonal or event based hydrographs to account for the additional water volumes required for release of annual flood peaks.
- Provide further assessments, in conjunction with the operator of Jindabyne Dam (Snowy Hydro), regarding opportunities and limitations for increasing the number of flood peak releases in a year.
- Continuation of the Snowy Flow Response Monitoring and Modelling program in the Snowy River below Jindabyne dam to optimise environmental water releases via a clear adaptive management framework.

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