Flood frequency and flow scaling in Snowy Mountain rivers

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Key Points

- Low hydrologic variability is demonstrated in Snowy Mountain rivrs through the combination of a seasonal discharge pattern, low flash flood magnitude index, low gradient flood frequency ratio curves and little vertical spread in flow levels of various recurrence intervals within the channel cross-section.
- Within Snowy Mountain Rivers, flood volumes increase in size as catchment area increases but not to the degree that it occurs in the comparison non-snowmelt rivers.

Abstract

Floods are a well-studied phenomenon around the globe and their impact on society and importance to geomorphology and stream ecology cannot be overstated. However, to date there has been no systematic analysis of how rivers in the Snowy Mountains of Australia adjust or scale to catchment area and precipitation-driven changes in discharge. Here, we present a hydrological analysis of 18 unregulated rivers, both currently and historically gauged, in the Snowy Mountains and compare them to 9 gauges from temperate non-snowmelt settings. We show that the alpine rivers have a strong seasonal discharge pattern and a low flash flood magnitude index which is reflected by low-gradient flood frequency ratio curves. These hydrological characteristics result in a low vertical spread between predicted flow levels of varying average recurrence intervals within a given cross-section, relative to other non-snowmelt rivers in eastern New South Wales (NSW). This has implications for unit-discharge relationships, which in turn affects the magnitude of flood scaling by catchment area. Floods were found to become proportionally larger (scale by catchment area) at all recurrence intervals in Snowy Mountain rivers, but not to the extent that they do in comparison rivers, probably due to the disproportionately large discharge volumes generated from high elevation catchment headwaters.

Keywords

Flood frequency, coefficient of variation, flash flood magnitude index, flood frequency ratio curves, Australia

Introduction

Alluvial rivers are self-adjusting systems (Huang and Nanson, 2000) flowing through unconsolidated material. The magnitude and frequency of floods within these rivers modifies the channel geometry (width and depth) to facilitate transport of water and sediment provided by the catchment. This is the first in-depth study aimed at assessing Australian mountain river hydrology (flood frequency ratio curves and flash flood magnitude index), the seasonality of discharge patterns and the relationship of flood magnitude to catchment size (flow scaling). Understanding snowmelt rivers is important because they provide water for electricity, irrigation and drinking into the dry summer months while providing habitat to the many species adapted to the seasonal signal.

Bankfull flows are those which fill the channel to the point where water begins to spill onto the floodplain. These flows engage with sediment in the bed and banks of the channel and are considered to contribute largely to alluvial channel and floodplain morphology (Wolman and Miller, 1960; Segura and Pitlick, 2010; Agouridis et al., 2011). Since, in many regions bankfull flows occur with a mean return period of 2 years (Wolman and Miller, 1960; Segura and Pitlick, 2010), we also determined flood frequency ratio curves (Qf/Qx – sensu Pickup, 1984) using flows with a return period of 2 years on the annual maximum flood series.

Normalised flood frequency ratio curves allow the comparison of rivers within or between regions and have been used in the past to investigate rivers in contrasting climatic regions (Pickup, 1984; Nanson et al., 2002). Dryland rivers, for example, are typified by rare, very large floods and many years of small or zero-flow conditions leading to steep flood frequency ratio curves (Nanson et al., 2002). In contrast humid temperate climate rivers demonstrate less inter-annual variability and therefore have low-gradient flood frequency curves (Farquharson et al., 1992). Previous research in eastern Australia has found that rivers in the region fall somewhere between these two mentioned extremes (Pickup, 1984) but until now no systematic analysis has been undertaken on the seasonal snowmelt Snowy Mountain rivers. Our results show that Snowy Mountain rivers differ from east coast non-snowmelt rivers, and we present a way to visualise the difference in how floods of various return periods fill the channel in each climate zone by plotting ARI flood levels in a channel cross-section.

The magnitude of floods varies between climate zones and with catchment area. Therefore, flood scaling analyses can differentiate one region from another and understanding this relationship is important for a variety of reasons. For example, resource management agencies seeking to implement environmental flows in dammed rivers need to be able to deliver flow releases that are scaled to environmental water volumes available to the managed river, but mimic natural variability (Reinfelds et al., 2014). Regional flood scaling studies provide an awareness of the flood characteristics of an area that may be extended to rivers lacking flow records within that zone (Farquharson et al., 1992).

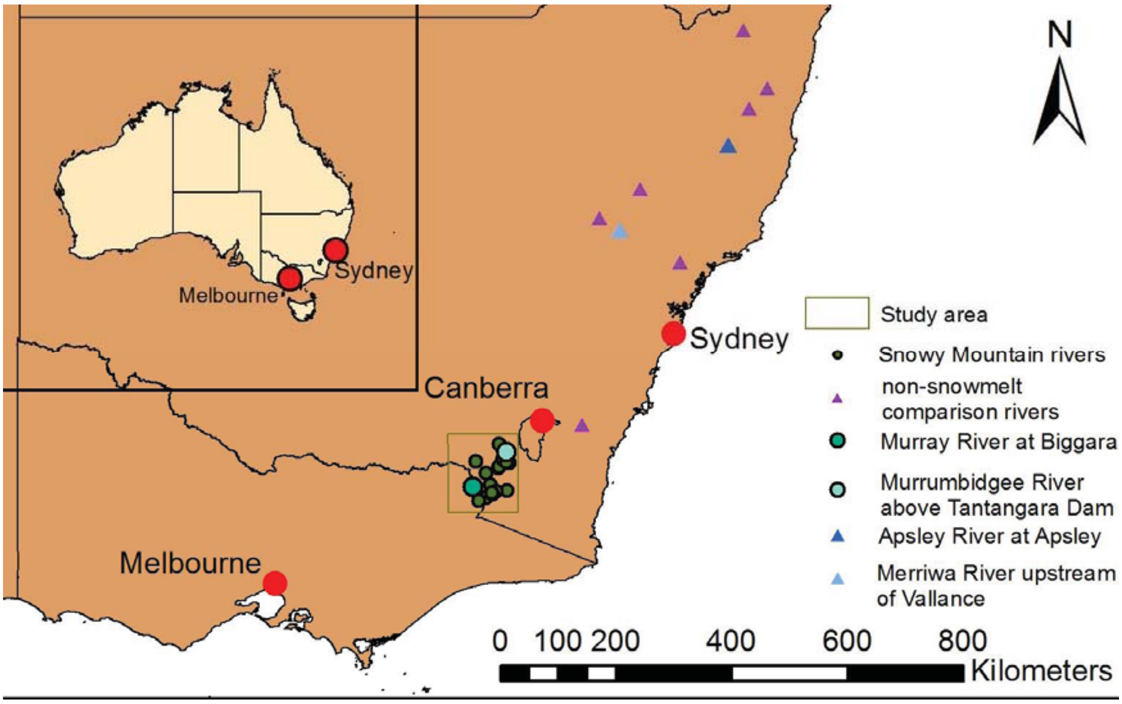
Previous studies have categorised Australia as a country whose rivers show high flow variability (McMahon et al. 1992; Erskine and Livingston 1999; Peel et al. 2004), however, these studies have focussed on rivers in non-snowmelt settings. In this study we demonstrate that the mean flash flood magnitude index (FFMI) of Snowy Mountain rivers is on par with global averages and is much lower than non-snowmelt rivers suggesting that Snowy Mountain river hydrology is significantly different to Australian rivers in other settings.

Methods

Study area

The Snowy Mountains are situated in south eastern Australia in the state of NSW (Fig. 1). Field sites for this study are located within and just outside of the Kosciuszko National Park; an area with an extensive alpine zone that includes Australia's tallest peak at 2228m. Mean catchment elevation above the field sites ranges from 850m at Maragle Creek to 2021m at Cootapatamba Creek at Ramshead and the mean catchment elevation within the entire study area is 1558m. Catchment areas of the individual gauges cover several orders of magnitude from 4.8 km^2 at Club Lake Creek at Clarke to 1256 km^2 for the Murray River at Biggara. The mean annual precipitation for all 18 field sites is 1648 mm/yr with the higher elevation locations receiving more than the lower sites (Bureau of Meteorology, 2015). Precipitation may fall as snow any time of year but this occurs mostly between the months of June and October. We chose nine other sites as representative non-regulated non-snowmelt rivers with an equivalent range in contributing areas (Fig. 1).

Figure 1. Location of the Snowy Mountain study sites and the comparison rivers (Hutchinson et al., 2008; Natural Earth, 2015)



Data acquisition and analysis

Data was provided by Snowy Hydro Limited and the NSW Office of Water database, Pinneena. From these resources, we chose 18 sites covering a range of catchment area on unregulated streams that had a minimum of 10 years stream discharge and corresponding stream water level data (metres). Further data of the same kind was accessed using Pinneena to enable comparison with nine unregulated non-snowmelt rivers with a similar range of catchment areas to those in the Snowy Mountain study zone.

Seasonal discharge patterns were determined by calculating the mean monthly discharge for the period of record at each site. Annual maximum series flood frequency analysis was undertaken on the instantaneous maximum discharge and stream level data using the freeware program Flike (Kuczera 2001) to calculate the magnitude of floods with average return periods (ARI) of 1.001-100 years. These data were used to calculate flood frequency ratio curves (Pickup, 1984; Farquharson et al., 1992) where the discharge for each ARI flood interval (Qf) was divided by the discharge of the two-year flood (Q2) and plotted against the full period of calculated ARI intervals. To visualise the vertical spread of floods of various ARI's within each channel, surveyed cross-sections were graphed with the location of floods derived from annual maximum level analyses. The same flood frequency analysis data was used in conjunction with catchment area to determine flow scaling.

The flash flood magnitude index (FFMI) was calculated to allow comparison of the hydrology of Snowy Mountain rivers to the NSW non-snowmelt rivers, to global rivers in previous studies (Baker 1977; Erskine and Livingston 1999) and between Snowy Mountain rivers with different mean catchment elevations. The FFMI for each gauging site was determined as the standard deviation divided by the mean of the Log_{10} of the annual maximum flood series.

Results

Seasonality

Rivers in the Snowy Mountains demonstrate a strong seasonal discharge signal (Fig. 2a). In the Snowy Mountains, the bulk of the precipitation falls during winter months as rain and snow and Figure 2a highlights that for all study rivers, peak monthly discharge occurs between August and November. The seasonal signal is most dramatic for sites on the Murray River, Eucumbene River, Spencers Creek and Cootapatamba Creek. During the 1950's, the highest elevation catchments of the Snowy River and Cootapatamba Creek achieved peak discharge in December, likely due to snow lingering at the higher altitudes, this trend has not persisted into recent years as now peak flows occur a month sooner.

Aside from the Shoalhaven River, the non-snowmelt rivers achieve their maximum monthly discharge between January and April (Fig. 2b). These rivers are located north of Sydney (Fig. 1) where the bulk of precipitation falls during summer. The Shoalhaven River is sited south of Sydney in an area where precipitation peaks are not associated with summer or winter.

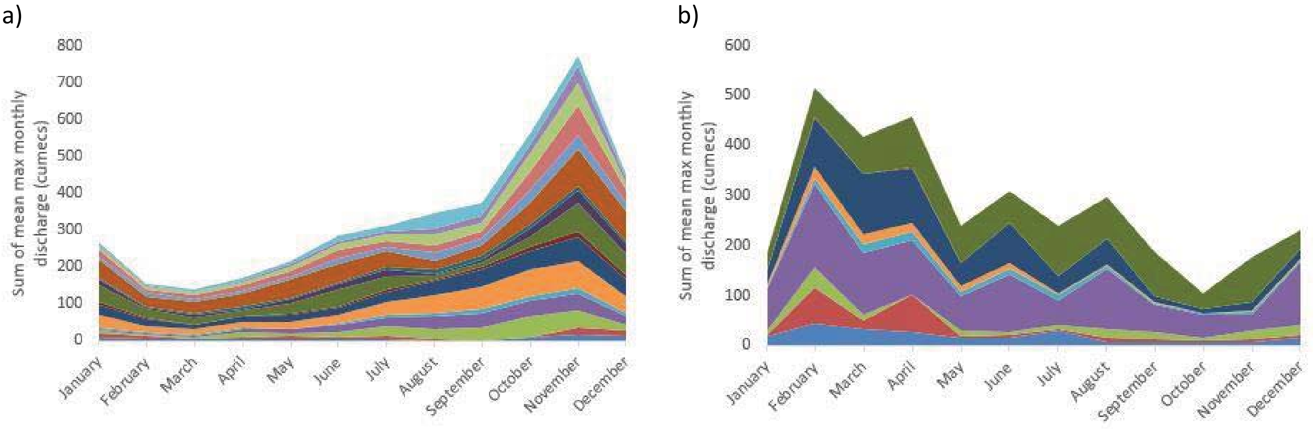


Figure 2. Seasonality trends between (a) snowmelt and (b) non-snowmelt rivers demonstrate that the Snowy Mountain rivers in this study have their highest monthly discharge in the last half of the year and the comparison non-snowmelt rivers achieve high discharge volumes in the first four calendar months of the year. Colours represent the contribution that individual rivers make to the total monthly discharge, however the goal is to represent the overall seasonal trend.

3.2 Flood frequency ratio curves – comparison between Snowy Mountain and non-snowmelt rivers

The ratio of Qf/Q2 for snowmelt and non-snowmelt rivers shows that the gradient of the regional average curve for Snowy Mountain rivers is much shallower than for the non-snowmelt rivers (Fig. 3). This demonstrates that there is a smaller difference between floods of various magnitudes in the alpine region of NSW, than in non-snowmelt rivers.

Figure 3. Regional average flood frequency ratio curves for Snowy Mountain rivers and comparison non-snowmelt rivers. Flood frequency ratios calculated against 2-year annual maximum flood discharges and then averaged across the two regions.

Flood scaling by catchment area

Floods in Snowy Mountain rivers scale in volume by catchment area (Fig. 4a), as catchment area increases the size of each corresponding calculated ARI flood also increases. When plotted, the R^2 values for the logarithmic trendlines in the model highlight the strong correlation between the data, with values of 0.97, 0.96, 0.99 and 0.98 for catchments with areas of <10km^2, 10-100km^2, 100-1000km^2 and >1000km^2 respectively. In their respective regions, both Snowy Mountain rivers and the comparison non-snowmelt rivers have floods that scale by catchment area, however, the magnitude of scaling relationships in Snowy Mountain rivers are much smaller than in non-snowmelt rivers (Fig. 4b). Scaling is more pronounced in both data sets in catchment areas greater than 10km^2.

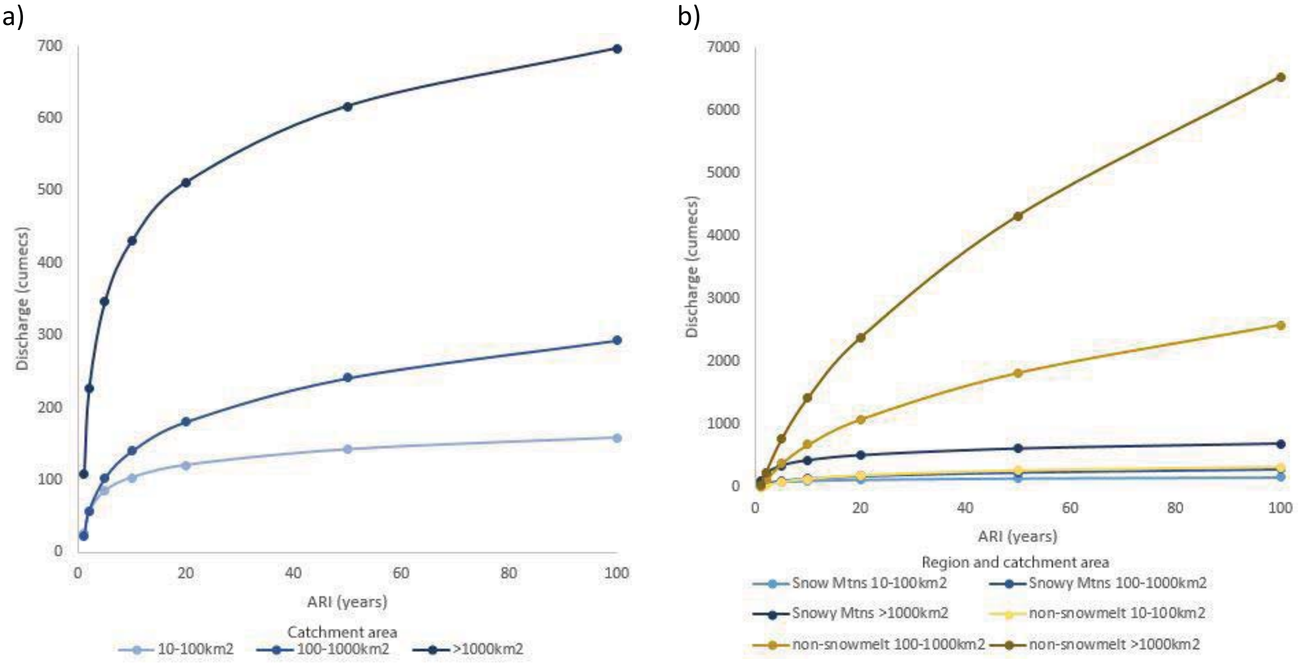


Figure 4. Mean discharge values for floods with up to a 30 year return interval, scaled by catchment area for a) Snowy Mountain rivers and b) for Snowy Mountain rivers and non-snowmelt rivers. The values plotted are the mean annual series ARI discharge volumes in cumecs for each catchment scale.

Correlation between cross-sections and annual series ARI events

For each of the gauges, surveyed cross-sections have been graphed with the level of floods of various ARIs. In the Snowy Mountains (Fig. 5a, b), there is less vertical spread in predicted water levels for the 2 to 20-year ARI flows (~ 1 m) in comparison to the non-snowmelt NSW rivers (~ 5 m) (Fig. 5c, d). Whilst not shown, the largest flood on record at each of the gauges shows the same trend with a mean of 1.45 m difference between the Qmax and the Q2 on the Snowy Mountain Rivers and a mean of 7.23 m on the non-snowmelt systems. The location of the cross-sections used as an example are shown in Figure 1.

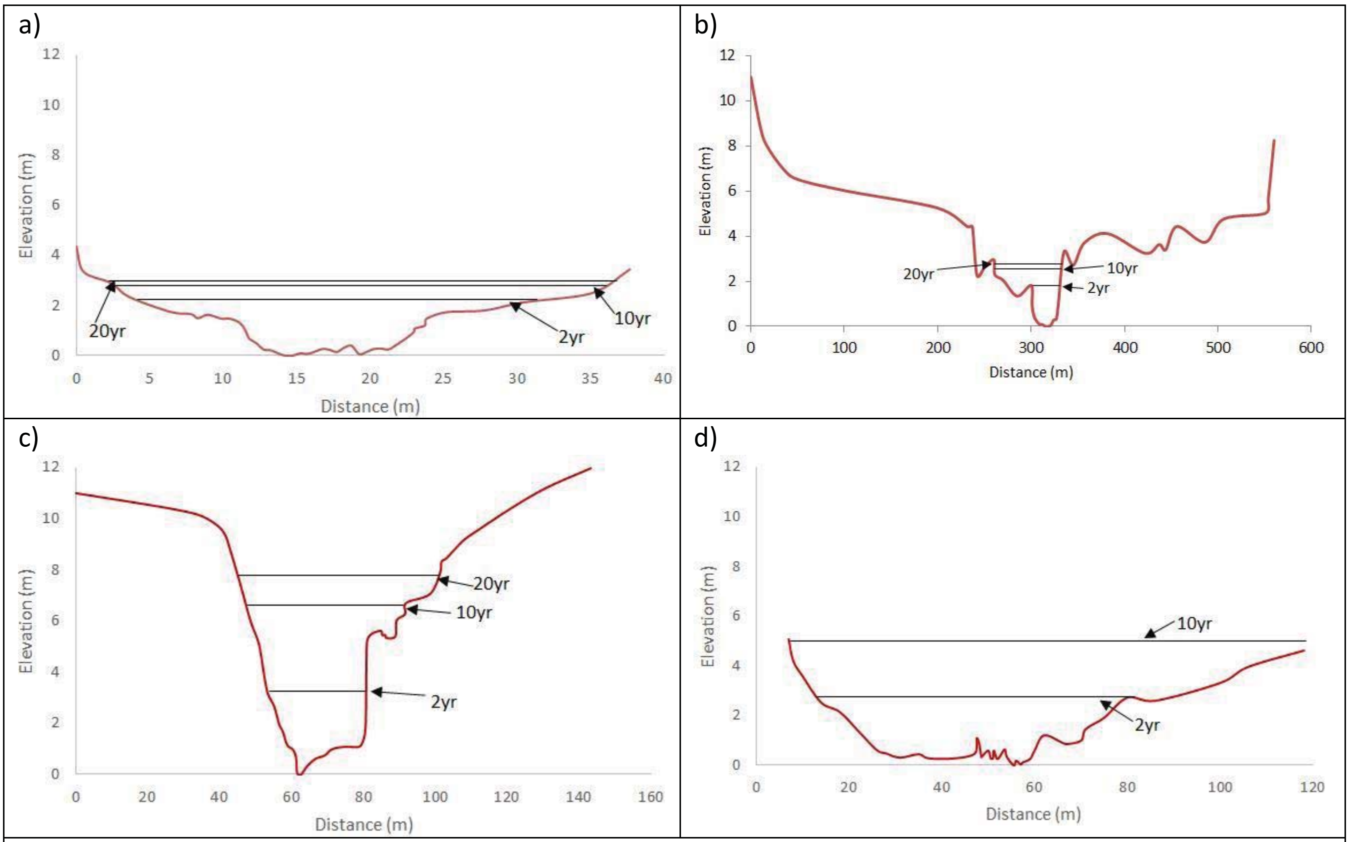


Figure 5.a) Cross-section of the channel at the Murrumbidgee River above Tantangara Dam; b) Murray at Biggara; c) Merriwa River upstream of Vallance and d) Apsley River at Apsley with heights of the 2, 10 and 20 year ARI floods .

Flash Flood Magnitude Index

The mean FFMI calculated for Snowy Mountain rivers was 0.27 and 0.74 for the comparison non-snowmelt rivers, with Warrah Creek proving to be an outlier in the non-snowmelt dataset. With Warrah Creek removed, the FFMI for the non-snowmelt rivers was calculated to be 0.67 (Fig. 6).

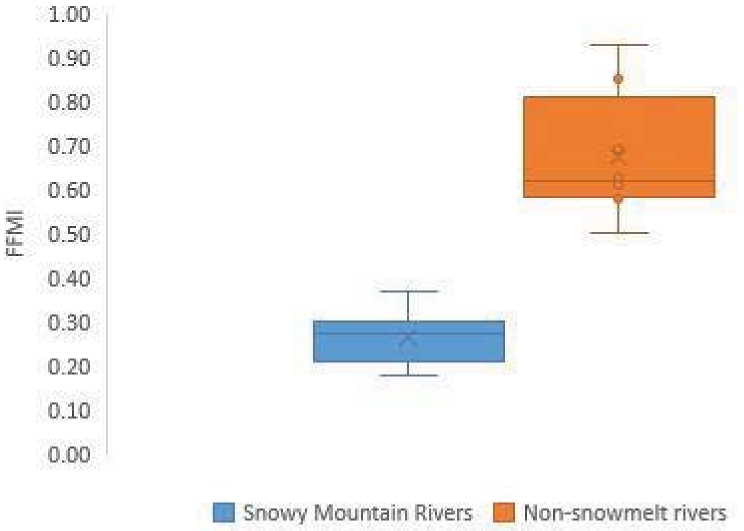


Figure 6. The flash flood magnitude index for Snowy Mountain rivers and comparison non-snowmelt rivers (including Warrah Ck).

Discussion

The results of this study show that alpine and non-snowmelt rivers with the same range of catchment areas have vastly different hydrology. Within the Snowy Mountains region, we found the flood variability to have a low figure of 0.27, similar to the global mean FFMI value of 0.28 calculated by McMahon et al. (1992), while the non-snowmelt rivers in this study showed an FFMI value of 0.67 that is consistent with Erskine and Livingston's (1999) standard of 0.60 for high flood variability. Previously it has been thought that Australia has high hydrologic variability driven by inconsistent precipitation and runoff when compared to other continents in the same climate zone (Peel et al., 2004), however, this study demonstrates that Snowy Mountain rivers do not conform with Australian rivers in non-snowmelt settings because the alpine climate is reliably seasonal. The results of this in-depth analysis of Snowy Mountain rivers agree with Erskine et al. (1999) whose study of the pre-dam Jindabyne River returned an FFMI of 0.2, from which they surmised that due to the low flow variability of the historic river, the channel forming flows were relatively frequent in occurrence and moderate in volume (Erskine et al., 1999).

Steep-gradient flood frequency ratio curves indicate a large difference in volume between the maximum and minimum volumes of gauged floods, while the opposite is true for low-gradient flood frequency ratio curves. Pickup (1984) suggested that low-gradient flood frequency ratio curves are caused by small inter-annual variability, most likely a function of a regular and predictable seasonal climate. Similarity between the flood frequency ratio curves of different regions suggest similarity in the runoff characteristics of each area (Farquharson et al., 1992). As with Snowy Mountain rivers, the rivers studied by Pickup (1984) featured low-gradient flood frequency ratio curves yet these examples were located in tropical Papua New Guinea (PNG). While the Snowy Mountains receive significantly less mean annual precipitation than PNG, 1,648mm vs 8,000-11,000mm, and wet season humidity levels are 85% in the Australian highlands compared to 100% in PNG (Pickup, 1984; Bureau of Meteorology, 2015), the runoff coefficients are similarly high in both regions, 88% in the Snowy Mountains and 70-85% in the area where the Purari River is located (Pickup & Chewings, 1983). These large runoff coefficients demonstrate that the great majority of runoff enters the rivers in both locations. For his PNG sites, Pickup (1984) surmised that local conditions ensure ample moisture is available for prolonged periods throughout the year and so losses through infiltration and evaporation are low before runoff begins. Our work suggests that a similar process may be occurring in the Snowy Mountains where soggy ground caused by the insulating snowpack and by the slow release of water through the melting of snow maintains a regular input of water to the river making the overall flood frequency ratio trend much less dramatic than for arid region rivers.

In the rivers studied by Pickup (1984), the 100-year flood was approximately twice the size of the 2-year flood (Fig. 7). In comparison, the data in the flood frequency curves (Fig. 3) show that in Snowy Mountain rivers, the 100-year flood is 4.6 times as large as a 2-year flood, where in the non-snowmelt NSW rivers, the 100-year flood is 22.9 times larger than the 2-year flood. While the gradient of the flood frequency curves for Snowy Mountain rivers aren't as low as those from Pickup (1984) for rivers such as the Fly and Purari, the results suggest that Snowy Mountain rivers share some commonality to the Papua New Guinean rivers and that a combination of the factors discussed may be the driver between the difference in flood frequency ratio curve gradients in NSW rivers and for the similarity between the curves from the Snowy Mountain rivers and the Papua New Guinean rivers.

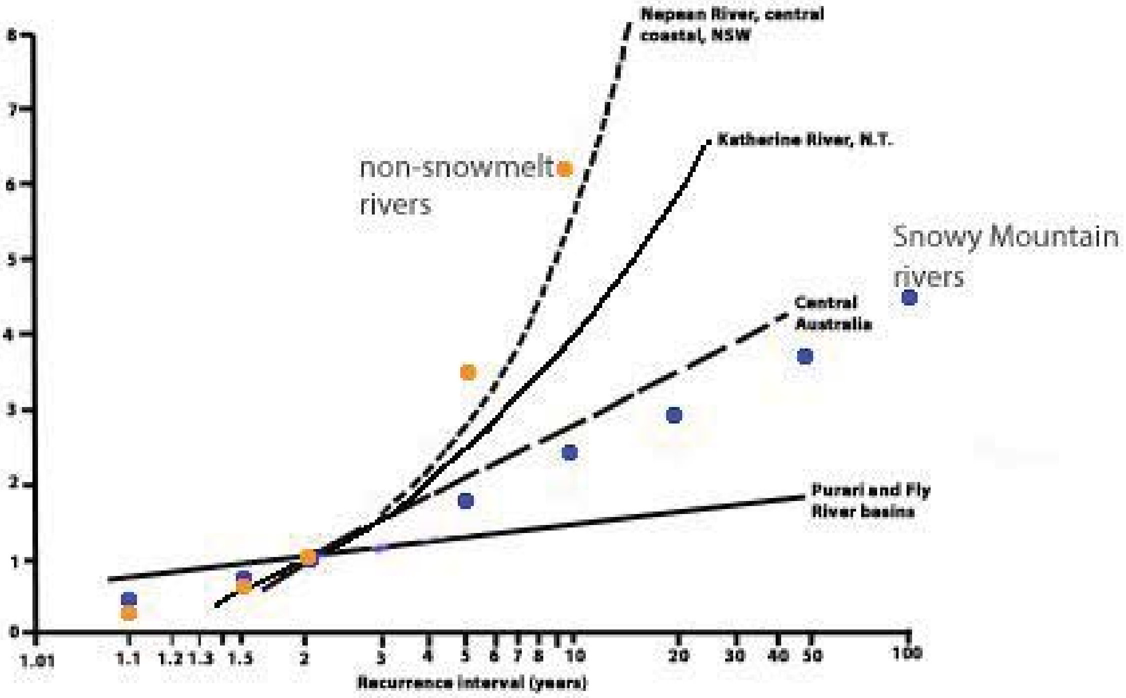


Figure 7. Flood frequency ratio curves for Australian and Papua New Guinea rivers from prior research by Pickup (1984) alongside rivers from the Snowy Mountains and the comparison non-snowmelt rivers used in this paper. Data source: (Pickup, 1984).

Similar to the flood frequency ratio curves, the Snowy Mountain river cross-sections with the stage of floods of various ARI's plotted (Figs.5.a-b) show that there is little vertical difference between larger and smaller magnitude floods. This demonstrates that in Snowy Mountain rivers, floods are more similar in stage across ARI intervals from 2-20 years ARI when contrasted with NSW rivers that have no alpine influence (Figs.5.c-d). This data correlates with Figure 4b which highlights that when compared to non-snowmelt NSW rivers, those of the Snowy Mountains have less variability in flood magnitude at a catchment scale.

Conclusion

The results of this study show that Snowy Mountain rivers do not exhibit the same hydrologic variability that non-snowmelt Australian rivers do. The drivers behind the differences in variability include a regular seasonal climate in the alpine region as well as local conditions that keep the ground within the catchment area wet for months at a time leading to less loss through infiltration and evaporation before runoff begins. The flash flood magnitude index of Snowy Mountain rivers was found to align with mean world values and was significantly lower than for non-snowmelt rivers in eastern NSW. Future work could include a comparison with snowmelt rivers in other regions to determine if this trend holds true.

Snowy Mountain rivers were found to scale their discharge by catchment area, and the magnitude of each flood increases in size as the annual return interval increases. However, when compared to non-snowmelt rivers elsewhere in NSW, the magnitude of the increases in discharge through time and space in Snowy Mountain rivers was small. Knowledge of how floods scale by catchment area within a region is useful for land managers so they can predict how large a flood in a particular catchment may be. This information may also be used to better understand the frequency of channel forming flows (Segura and Pitlick, 2010) and may be used in determining environmental flow regimes for regulated rivers below dams using a "natural flow scaling" approach (Reinfelds et al., 2014).

It is assumed that the size and regularity of floods determine the dimensions of the channel (Huang and Nanson, 2000), however as we demonstrated, some of the Snowy Mountain cross-sections surveyed are so large that they only rarely fill to the level in which they overtop and inundate the dominant alluvial surface. Future work at these sites could determine how long this current trend has been in place by investigating the nature, age and mode of deposition of the alluvial units inset within the dominant alluvial surface. Future results may show that the paleo-flood frequency curves and flood scaling relationships differ from those of today.

Acknowledgments

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References

Agouridis, C. et al., 2011. Bankfull hydraulic geometry relationships for the Inner and Outer Bluegrass regions of Kentucky. *Water*, 3(3), pp.923–948.

Baker, V.R., 1977. Stream-channel response to floods, with examples from central Texas. *Geological Society of America Bulletin*, 88(8), pp.1057–1071.

Bureau of Meteorology, 2015. Climate Data Online. Available at: http://www.bom.gov.au/climate/data/index.shtml?bookmark=136&zoom=3&lat=-32.5355&lon=147.74&layers=B00000TFFFFFFFTFFFFFFFFFFFFFFFFFFFFFTTT&dp=IDC10002-d [Accessed August 4, 2015].

Erskine, W.D. et al., 1999. River rehabilitation from the hydrogeomorphic impacts of a large hydro-electric power project: Snowy River, Australia. *Regulated Rivers: Research & Management*, 15(1999), pp.3–24.

Erskine, W.D. and Livingston, E., 1999. In-channel benches: the role of floods in their formation and destruction on bedrock confined rivers. In A. L. Miller & A. Gupta, eds. *Varieties of Fluvial Form*. John Wiley & Sons, Ltd, pp. 445–475.

Farquharson, F.A.K. et al., 1992. Regional flood frequency analysis in arid and semi-arid areas. *Journal of Hydrology*, 138(3-4), pp.487–501.

Huang, H.Q. and Nanson, G.C., 2000. Hydraulic geometry and maximum flow efficiency as products of the principle of least action. *Earth Surface Processes and Landforms*, 25, pp.1–16.

Hutchinson, M.F. et al., 2008. Geofabric. Available at: https://www.ga.gov.au/products/servlet/controller?event=GEOCAT_DETAILS&catno=66006.

Kuczera, G., 2001. FLIKE. *Department of Civil, Surveying and Environmental Engineering. University of Newcastle, Callaghan, NSW, 2308*, V4.50.

McMahon, T.A. et al., 1992. *Global runoff: continental comparisons of annual flows and peak discharges*, Catena Verlag.

Nanson, G.C. et al., 2002. A global perspective on dryland rivers: perceptions, misconceptions and distinctions. In L. J. Bull & M. J. Kirkby, eds. *Dryland Rivers: Hydrology and Geomorphology of Semi-arid channels*. John Wiley & Sons, Ltd, pp. 17–54.

Natural Earth, 2015. 1:50m Cultural Vectors. Available at: http://www.naturalearthdata.com/downloads/50m-cultural-vectors/ [Accessed August 3, 2015].

Peel, M.C. et al., 2004. Continental differences in the variability of annual runoff-update and reassessment. *Journal of Hydrology*, 295(1-4), pp.185–197.

Pickup, G., 1984. Geomorphology of tropical rivers 1. Landforms, hydrology and sedimentation in the Fly and Lower Purari, Papua New Guinea. *Catena*, (Supplement 5), pp.1–17.

Pickup, G. and Chewings, V.H., 1983. The hydrology of the Purari and its environmental implications.pdf. In T. Petr, ed. *The Purari - Tropical environment of a high rainfall river basin. Monographiae Biologicae*. The Hague/Boston/Lancaster: Dr W. Junk Publishers, pp. 123–139.

Reinfelds. et al., 2014. *Natural flow scaling: a paradigm shift in environmental flow development for rivers subject to large reductions in flow*, Wollongong; Cooma.

Segura, C. and Pitlick, J., 2010. Scaling frequency of channel-forming flows in snowmelt-dominated streams. *Water Resources Research*, 46(W06524), pp.1–14.

Wolman, M.G. and Miller, J.P., 1960. Magnitude and Frequency of Forces in Geomorphic Processes. *The Journal of Geology*, 68(1), pp.54–74.