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Hydrology and scaling relationships of Snowy Mountain Rivers

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Abstract

Australian rivers are generally considered to have high flow variability with large differences between baseflow and flood flows as well as large differences in the volume of floods of various return periods. This comparative study systematically assesses the hydrology of Snowy Mountain rivers to determine whether snowmelt rivers demonstrate similar discharge characteristics to their non-snowmelt counterparts. Historical and current gauging data was used to investigate flood frequency and flow scaling relationships for unregulated alluvial and semi-alluvial rivers in eighteen Snowy Mountain rivers and fifteen temperate east coast and semi-arid non-snowmelt rivers.

The results demonstrate that Snowy Mountain rivers do not exhibit the same hydrological variability as non-snowmelt rivers. By comparison, snowmelt rivers were found to have a strong seasonal discharge pattern and a higher baseflow index. The flash flood magnitude index for the snowmelt rivers (0.27) was lower than the global mean (0.28) and lower than the comparison east coast (0.74) and semi-arid (0.62) rivers. Snowy Mountain rivers demonstrated low inter-annual flow variability through low coefficient of variation values (0.38) that contrasted with those of the east coast (1.19) and semi-arid (1.41) rivers. These results were reflected by Snowy Mountain rivers having the flattest flood frequency ratio curves, the least vertical spread between predicted flow levels of varying average recurrence intervals within a given cross-section and less variability in event-based runoff coefficients. This has implications for unit-discharge relationships, which in turn affects the magnitude of flow scaling by catchment area. Floods were found to become proportionally larger (scaled to catchment area) at all recurrence intervals in Snowy Mountain rivers, but not to the extent that they did in comparison rivers. The drivers of the low inter-annual hydrological variability include a regular, seasonal climate with local conditions that keep the ground moist for months at a time. The baseflows in the Snowy Mountain rivers are higher than in the non-snowmelt settings which works to decrease the difference between mean daily and flood flow rates and volumes.

The morphology of alluvial rivers may be altered through changes in discharge and sediment supply with steeper channels being more resistant to these changes than low-gradient channels. The characterisation of mountain streams by slope enables prediction of long term channel morphology and susceptibility to change through time. The Snowy Mountain rivers vary in steepness and can be categorized as having cascade, step-pool, plane-bed and pool-riffle morphologies with intermediate classifications of cascade-pool and riffle-step also identified.

Unregulated rivers are increasingly threatened by reservoir construction, underscoring the need to extend knowledge on the behaviour of rivers in various climate regions. Comparative studies such as this one increase the ability to predict the form and function of natural systems and can provide a framework for situations where river rehabilitation or environmental flows are necessary. To be effective, environmental flow programs on regulated rivers should mimic the hydrological attributes of suitable analogue rivers and the design of those programs must be informed by analysis of the type undertaken by this study. The analyses presented were undertaken on individual rivers, at a regional and state-wide scale (New South Wales) scale and provide important perspective of how Snowy Mountain rivers fit within the Australian and global context.

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Chapter 1 – Introduction

1.1 Context

Alluvial rivers are self-adjusting systems (Huang and Nanson 2000) flowing through unconsolidated material. They are key features of a dynamic environment moving sediment, nutrients and water within the landscape and knowledge of how rivers function and how they react to changes in discharge is crucial if we are to understand and/or manage them. Many alluvial river processes demonstrate global similarities in how channels react to changes in discharge and theories such as hydraulic geometry or extremal hypotheses, such as the least action principle, seek to explain how and why rivers alter their form (Leopold and Maddock 1953; Nanson and Huang 2008). In an alluvial river, the magnitude and frequency of floods modifies the channel geometry (width and depth) to facilitate transport of water and sediment provided by the catchment.

In Australia, rivers form a part of the national psyche, with rivers such as the Snowy and the Murray featuring in the national identity. Studies have shown Australian rivers demonstrate high variability in hydrological conditions and runoff (McMahon et al. 1992; Erskine and Livingstone 1999; Nanson et al. 2002; Peel et al. 2004). These results demonstrate that for their size, large catchments produce relatively low runoff (McMahon et al. 1992), and there is a great difference in discharge between floods of various magnitudes within individual rivers (Nanson et al. 2002). To date most of the Australian research has been conducted in arid and temperate lowland settings and there has been significantly less research done on Australian mountain rivers compared with overseas equivalents, such as the USA. This study assesses Australian mountain river hydrology (flow frequency and variability) and its relationship to catchment size (flow scaling) and it will determine if these rivers demonstrate the same hydrological variability as rivers found elsewhere on the continent. The study will develop a sound knowledge of Australian mountain rivers, allowing for comparisons with national and overseas studies, potentially informing resource management agencies on issues such as environmental flows.

A region's hydrological characteristics and flow variability may be understood and compared with rivers in contrasting climatic zones using unit-less measures such as the flash flood magnitude index (Baker, 1977; McMahon et al., 1992; Erskine and Livingston, 1999), coefficients of runoff (Stewardson et al. 2005; Blume et al. 2007; Hrachowitz et al. 2013; Reinfelds et al. 2014) and variation (Chiew and McMahon 1993; Mazvimavi et al. 2007; Morton et al. 2010) and flood frequency ratio curves (Pickup, 1984; Nanson et al., 2002). Dryland rivers, for example, are typified by very large floods interspersed with years of small or zero-flow conditions resulting in steep flood frequency ratio curves (Nanson et al., 2002). In contrast humid temperate climate rivers in the UK demonstrate less inter-annual variability and therefore have low-gradient flood frequency ratio curves (Farquharson et al., 1992). Prior research has found that rivers in eastern Australia's temperate 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.

The magnitude of floods varies between climate zones and with catchment area (Segura and Pitlick 2010). 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 rivers regulated by dams need

to be able to deliver flow releases that are scaled to environmental water volumes available to the managed river, but which also 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).

1.2 Aims and objectives

Flood frequency analysis of historical and current flow data combined with long-term climatic trends such as rainfall patterns will be used to understand the traits and variability of the hydrological regime in unregulated alluvial mountain river channels in the Snowy Mountains, Australia. Field surveying and spatial analysis will be undertaken to classify channel form and flow characteristics. A comparison is then made between the Snowy Mountain river data set and a group of rivers in two non-snowmelt settings (semi-arid and temperate) to provide a broader regional context.

Specifically, this master's thesis aims to: 1) assess mountain river hydrology (flood frequency and variability) and the relationship to catchment size (flow scaling); 2) investigate mountain river geomorphology and hydraulic geometry and determine the relative differences between Australian mountain rivers and those in non-snowmelt settings.

1.3 Thesis structure

This thesis includes a literature review on the principles of hydraulic geometry and how that relates to alluvial river response to changes in discharge. A section on the least action principle explains why river channels may change their configuration and a method of channel classification is also provided so that an understanding of expected channel form is reached. The literature review continues with the impact of dams on river systems and how knowledge of unregulated river behaviour can provide baseline information for the implementation of river rehabilitation and environmental flow programs.

The study area is placed into geographical, geological, climatological, historical and cultural context in the third chapter illustrating the importance of the Snowy Mountains region to the nation of Australia. Chapter four describes the methods used to acquire and analyse data including an explanation of each hydrological technique employed. The results are presented in chapter five. Chapter six is the discussion and places the results into a national and global context through comparison to existing research. Recommendations for future work are included in this section. Chapter seven provides the conclusion.

Chapter 2 – Literature review

This chapter reviews literature relevant to the overall thesis, including the concepts of hydraulic geometry, dominant discharge and channel optimisation theories. These are presented to provide context as to how river systems respond to flow regulation. Also discussed are the effect of dams on the riverine system and the environmental flow programs necessary to preserve natural components such as longitudinal connectivity.

2.0 River response to hydrological regimes

2.1 Classifications of mountain river geomorphology

Alluvial channel morphology is influenced by discharge, local bed material, channel gradient and the amount of lateral confinement afforded by the landscape (Brierley and Fryirs 2013; Billi et al. 2014). Channel gradient in particular has been used to aid in the classification of a mountain stream where one defining characteristic is a channel slope in excess of 0.002 m/m (Wohl 2004). Channel gradient of alluvial rivers can be further used to classify these streams into the following groups: cascade, step-pool, plane-bed and pool-riffle (Montgomery and Buffington 1997). Bedforms such as cascades, steps, pools and riffles help a river dissipate energy, thereby preventing excessive erosion (Slocombe and Davis 2014). The key features of each group are listed in Table 1.

Table 1. Features of mountain stream classifications. Source: (Montgomery and Buffington 1997; Wohl and Merritt 2005)

Feature	Cascade	Step-pool	Plane-bed	Pool-riffle
Bed material	Boulder	Cobble-boulder	Gravel-cobble	gravel
Valley confinement	Confined	Confined	Variable	Unconfined
General bed form	Disorganised	Longitudinally stepped	Relatively uniform	Undulating
Channel gradient (m/m)	≥0.065	0.03-0.065	0.015-0.03	≤0.015

Stream gradient plays a significant role in a channel's ability to either transport or store sediment. Steeper channels exhibit a high transport capacity for the sediment supplied by the catchment and serve as conduits that move sediment to lower gradient reaches where storage occurs (Montgomery and Buffington 1997). Channel gradient and grain size (bed material) generally decrease in a downstream direction and Table 1 highlights that the steeper reaches of a river feature the coarsest bed material and are confined in narrower valleys where storage space is limited, while lower gradient channels are likely to feature finer material and be in unconfined valleys where storage is available on floodplains.

Cascade channels feature continuously plunging and tumbling flows over either bedrock or boulder/cobble bedforms and form when bed material is large relative to channel depth. Boulders are arranged randomly within the channel and are derived from either debris flows or mass movement from neighbouring hillslopes (Thompson et al. 2006). The boulders are immobile during all but the larger (50-100-year) floods and help create pools that are often spaced less than a channel width apart (Montgomery and Buffington 1997).

Step-pool channels are found in a wide variety of settings and so bed material may be alluvial, bedrock or large wood depending on the local conditions (Chin and Wohl 2005). In alluvial settings, they are comprised of alternating sequences of cobbles and boulders lying perpendicular to flow creating the step, and finer material aggregating to create the pools (Chin and Wohl 2005). They form in steep terrain with gradients greater than 0.03 m/m and when bed material is large relative to channel width (Thompson et al. 2006). The length to height ratio of the steps ranges between 5:1 – 17:1 (Chin and Wohl 2005) and spacing of each structure is relative to the size of the channel, with steps often one to two channels widths apart (Chin and Wohl 2005; Thompson et al. 2006). Step-pool channels are most common in narrow valleys where lateral movement such as meandering is restricted. These channels prevent excessive erosion in steep terrain because energy is dissipated in the vertical plane through plunges into the pools (Chin 2003). Energy is therefore less available for longitudinal sediment transport and erosion. Step-pool channels are stable through periods of lower flow but may be readjusted during moderate 30-50-year flood events (Chin and Wohl 2005).

The bed surface of plane-bed channels is often made of gravel and cobble providing a relatively uniform and armoured surface (Thompson et al. 2006). Plane-bed channels lack sequential bedforms or discrete features such as bars. Width to depth ratios are often low, roughness is relatively high and they occur at moderate to high slopes (Montgomery and Buffington 1997; Chin and Wohl 2005; Thompson et al. 2006).

Riffle-pool sequences are often found in mixed and gravel bedded rivers. They demonstrate variation in flow characteristics with riffles being shallow sections that flow fast over steep gradients and pools being topographic lows that feature slow moving water (Montgomery and Buffington 1997). Bed material is coarser and better sorted in riffles than it is in pools (Clifford 1993). The sequences are formed successively through roller eddies up and downstream of flow obstacles that cause local scour and deposition downstream. The initial single pool created, forms the flow irregularity that leads to creation of the next downstream pool and the process continues auto-genetically (Clifford 1993).

2.2 Hydraulic geometry principles

Alluvial channels are formed in river derived unconsolidated sediment and therefore the discharge is theoretically able to alter the form of the channel. The hydraulic geometry relationships of these rivers relate to how the physical characteristics of a stream; water surface width, channel depth, channel slope, mean velocity and channel cross-sectional area interact with a given discharge (Leopold and Maddock 1953; Rhodes 1987; Phillips 1990; Singh 2003; Wohl 2004; Agouridis et al. 2011). An appreciation of hydraulic geometry relationships is a central component to the understanding of alluvial river systems and provides use for river planning and management purposes.

Periods of both aggradation and degradation occur in alluvial rivers depending if sediment supply out-paces transport capacity or vice versa. The pace of change within the channel may be rapid, possibly throughout a single flood event (Carling 2006) or in response to anthropogenic disturbance such as in-channel sediment mining (Rinaldi et al. 2005) or changes in system boundary conditions such as changes in land-use that enable the coupling of various sediment transport modes within a catchment (Fryirs et al. 2007). Alluvial channel behaviour is also linked to channel gradient with the morphology of steeper reaches such as cascade and step-pool more resistant to changes in discharge than shallower reaches such as plane-bed and pool-riffle (Montgomery and Buffington 1997).

2.2.1 Hydraulic geometry: power functions and exponents

In hydraulic geometry, power functions are used to describe the relationship between discharge and the variables channel width, depth and mean velocity (Leopold and Maddock 1953). A power function is one where a variable base is raised to a fixed exponent or power. For example: $y = aX^b$ where a is the variable base and b is the fixed power. a serves as a scaling factor that moves the values of X^b up or down and b controls the rate of change.

Leopold and Maddock (1953) presented the following power functions as relevant to hydraulic geometry:

$$w = aQ^b$$

$$d = cQ^f$$

$$v = kQ^m$$

Where w = channel width, d = mean channel depth, v = velocity, Q = bankfull discharge, a, c and k are coefficients and b, f and m are exponents. Fluctuations in discharge may cause changes in channel width, depth or mean velocity resulting in changes in the value of the exponents. These exponents b, f and m sum to a total of 1 and allow interpretation of the rate of change of each variable as well as the contribution of each variable to the overall channel form. If any of the exponent values are modified, there must be a corresponding adjustment in the other exponents to accommodate the deviation so that unity is preserved (Leopold and Maddock 1953). Hydraulic geometry relationships may be measured at a single point along the river, known as at-a-station, or at multiple locations in a down river direction, known as downstream hydraulic geometry.

At-a-station hydraulic geometry focuses on the changes in channel form caused by changes in discharge at a single gauging site through a nominal time-period; a flood, a month, a year. Downstream hydraulic geometry includes multiple cross-sections and multiple gauging stations within a catchment and the channel response calculations use a frequency of discharge that is consistent in time, for example a flood with a 2-year recurrence interval. The reaches used in the study may be either on the same river, or on other rivers that flow into the trunk stream; however the frequency of the discharge must be consistent (Jowett 1998; Singh 2003).

2.2.2 At-a-station hydraulic geometry

Figure 1 provides an example of data from an at-a-station survey, where the variables width, depth and velocity were measured throughout a range of discharge rates within the same cross-section. The slope of the line of best fit reveals the mean rate of change of each of the variables. The channel needs to maintain adequate sediment and water transport and as discharge increases or decreases, each variable will contribute a percentage of the total change in the geometry of the cross-section to meet this goal. In the example provided by Figure 1, channel width would accommodate 41% of the change, depth 36% and velocity 23%.

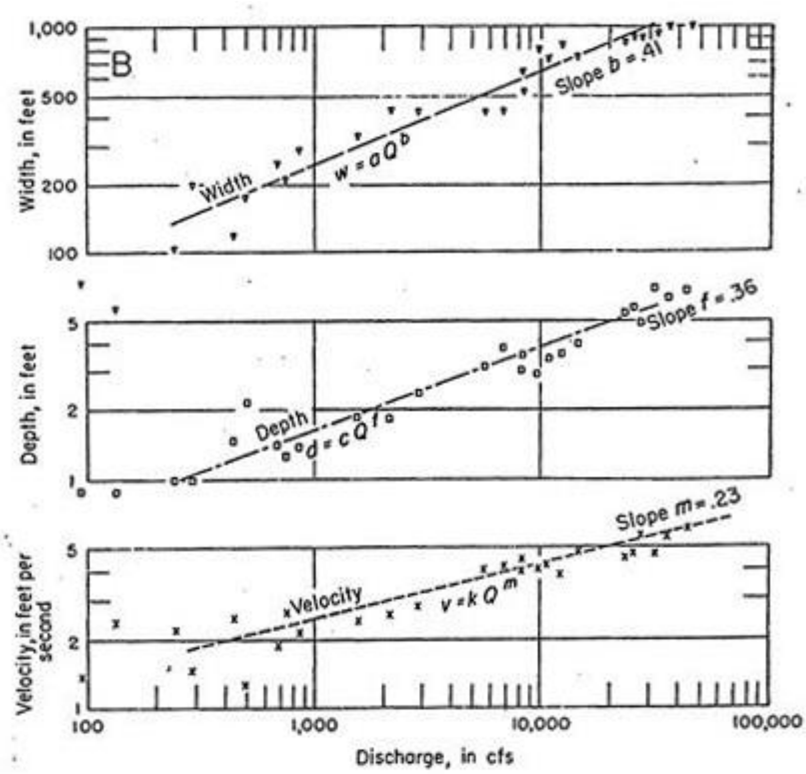


Figure 1. At-a-station hydraulic geometry relationships between discharge and width, depth and velocity. Source: (Leopold and Maddock 1953)

2.2.3 Downstream hydraulic geometry

Figure 2 shows an example of downstream hydraulic geometry data gathered at multiple gauges located within a single catchment. Data point 1 was the most upstream gauge, and data point 9 was the furthest downstream. In general, and as shown in this example, the rate of discharge rises as the contributing catchment area increases as a function of the increasing amount of water in the channel in a downstream direction. The channel needs to change its geometry to accommodate the additional water and this change occurs through the variables width, depth and velocity. The slope of the lines of best fit in Figure 2 demonstrate that the variables width, depth and velocity change with distance downstream, though at different rates. Mean channel depth increased at the fastest rate, followed by width, then velocity, as indicated by the steepness of the lines of best fit.

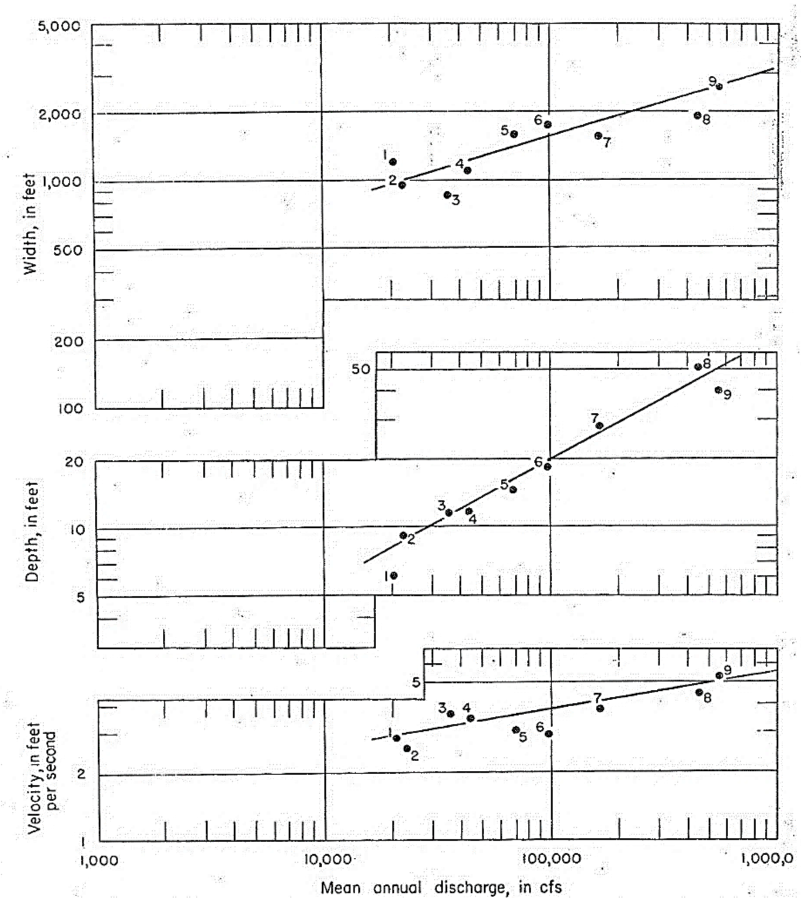


Figure 2. Downstream hydraulic geometry relations ships between discharge and width, depth and velocity to mean annual discharge. Source: (Leopold and Maddock 1953)

2.2.4 Hydraulic geometry exponents in use

The exponents provide a platform for further analysis. Knowing the strength of a rivers hydraulic geometry relationships allows confidence in channel engineering solutions and landscape evolution modelling (Ibbitt 1997; Wohl 2004). Mountain rivers whose correlation between discharge and at least two of the three variables (*w*, *d* and *v*) returned an R^2 value of a minimum of 0.5 are said to have "well-developed" downstream hydraulic geometry relationships (Wohl 2004). Therefore, understanding the expected exponent values can provide a level of assurance to predictions made for resource management assessments. In at-a-station settings, Leopold and Maddock (1953) found the average at-a-station values of the exponents for rivers in the semi-arid American west to be *b*=0.26, *f*=0.40 and *m*=0.34, and downstream values of *b*=0.50, *f*=0.40 and *m*=0.10 (Leopold and Maddock 1953). Since 1953, various papers have discussed the values and reliability of the exponents (Park 1977; Rhodes 1987; Ibbitt 1997; Stewardson 2005). To account for local and global variability, Park (1977) suggested that a range of values for the exponents should be expected. Park (1977) proposed the range for at-a-station exponents to be: *b*=0.00-0.59, *f*=0.06-0.73 and *m*=0.07-0.71, then for downstream hydraulic geometry: *b*=0.03-0.89, *f*=0.09-0.70 and *m*=-0.51-0.75 (Park 1977).

Exponent values may change through the period of a flood in an at-a-station setting. Leopold and Maddock (1953) demonstrated that as velocity increased on the rising limb of a flood, stream bed elevation also increased (Fig.3). This happened until a threshold was reached, which was seen to be when the suspended sediment concentration began to increase at a less rapid rate. When this occurred, the channel bed scoured resulting in an increase in mean channel depth and a decrease in velocity (Leopold and Maddock 1953).

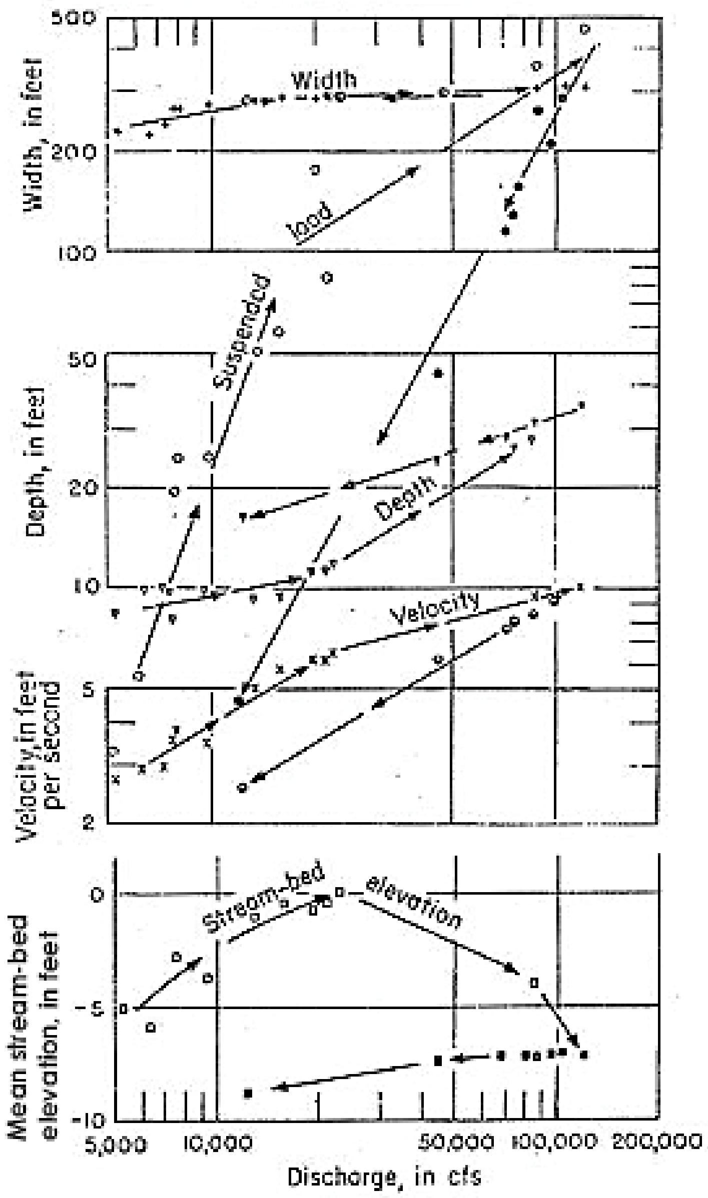


Figure 3. Changes to the at-a-station hydraulic geometry relationships through the course of a flood showing progressive changes in width, depth and velocity, and variations in stream bed elevation. Source: (Leopold and Maddock 1953)

In downstream hydraulic geometry, channel adjustment occurs most rapidly through changes in channel width, followed by depth then by velocity (Leopold and Maddock 1953). Carlston (1969) and Thornes (1970) agreed with this notion for small rivers, but noted that in larger channels, depth increases at a faster rate than channel width in response to increases in downstream discharge (Carlston 1969; Thornes 1970). Thornes (1970) also noted that small channels are less stable and therefore more geomorphologically active than their bigger counterparts.

2.2.5 Least action principle

Hydraulic geometry relationships explain *how* a river channel adjusts its morphology and flow characteristics to changes in discharge (Leopold and Maddock 1953) and extremal hypotheses such as the least action principle (Huang and Nanson 2000; Nanson and Huang 2008) provide explanations as to *why* they do so. Alluvial rivers globally demonstrate a uniformity in their characteristics (Leopold and Maddock 1953; Nanson and Huang 2008), for example, how a channel behaves throughout the time frame of a flood (Fig. 3) or the grading of sediment in a downstream direction (Table 1). This uniformity has led to the notion that channels aim toward a state of equilibrium, self-adjusting to the average conditions so that they are able to effectively transport the sediment and water provided by their catchment (Leopold and Maddock 1953; Langbein and Leopold 1966; Singh 2003; Nanson and Huang 2008).

The work of Huang and Nanson (2008) on the least action principle may be summarised as follows: a river is given energy through discharge and the difference in elevation between upstream and downstream reaches. This energy is used to do work such as transporting water and sediment within the channel. Through adjustments in channel form, alluvial rivers can expend or conserve energy as needed to maintain transport capacity. Valley gradients are often such that a river has excess energy and so the river creates features such as meander bends to lower the channel gradient to a more suitable or stable level. A river aims to reach a state of stable equilibrium, one in which the channel gradient is sufficient to move the water and sediment when the channel is straight, however a river is most often in a state of dynamic equilibrium as it meanders and seeks to slow down and use up any excess energy. Were a river to not use up surplus energy, it would be excessively erosive and the whole system would become unstable. Extra energy may be used through changes in cross-section, bedform and planform morphologies of channels. In steep, narrow valleys, excess energy is dealt with in the vertical plane, creating cascade and step-pool type rivers. In more gently sloping, wider valleys, excess energy is expended in the lateral plane where channels are adjusted through width, depth, channel slope, sinuosity, braid bars and the number of channels. Further surplus energy is used to create floodplains, erode and re-work bars. Through these changes, energy is used as heat (friction), and over time, the resulting channel is optimized to move only the amount of water and sediment provided by the catchment. When sediment supply is in demand, a channel erodes and when sediment supply is in excess, a channel aggrades.

If a state of stable equilibrium is attainable with the prevailing conditions, then through repeated flow events, the channel will find it. However, energy levels are not consistent throughout an entire river, and therefore the channel is in a constant state of change as one reach impacts another. Instability is greatest at the time of change, then over a period, rates of change will decrease as the river seeks to adjust to any newly imposed conditions. The least action principle "describes rivers as directional iterative systems where stable equilibrium offers the least opportunity for change and is therefore the attractor state and the most probable condition" (Nanson and Huang 2008).

2.2.6 Bankfull and dominant discharge

Bankfull discharge is the volume of water that fills the channel to its banks, prior to spilling onto the floodplain (Ahilan et al. 2012). This level of flow is deemed to be the one responsible for the largest contribution to channel morphology (Wolman and Miller 1960; Agouridis et al. 2011) because some rivers most efficiently move sediment and water at bankfull flow and at this level, water in the channel interacts with the greatest proportion of the bed and bank material.

The frequency of a particular discharge is known as the return period and Table 2 shows that the return period for bankfull discharge in the northern hemisphere is approximately 1-2 years (Harvey 1969; Dury 1959; Andrews 1980; Wohl and Merritt 2005). Research in Australia however, has shown greater range with some longer return periods; 1.4 years (Page et al. 2005), 2-5 years (Rustomji 2010) and 4-10 years (Pickup and Warner 1976). Pickup and Warner (1976) postulated that the longer interval between bankfull discharge events in Australia was due to the growth of perennial vegetation and the cohesive nature of the river bank material (Pickup and Warner 1976). Nanson (1986) suggested that in this situation, the banks resist erosion, becoming taller through overbank deposits thereby enlarging the channel cross-sectional area and decreasing the regularity with which flows greater than bankfull occur (Nanson 1986).

Table 2. The bankfull discharge return period determined by existing studies

Author	**Return Period (years)**	**Study Location**
Wolman & Leopold 1957	1-2	Eastern and Midwest USA
Dury 1959	1-2	UK
Harvey 1969	1.8-7	Southern England
Andrews 1980	1.2-3.3	Colorado and Wyoming, USA
Wohl & Merritt 2005	1-2	Western USA, NZ and Panama
Page et al. 2005	1.4	Southwestern NSW, Australia
Rustomji 2010	2-5	Northern QLD, Australia
Pickup & Warner 1976	4-10	Eastern Australia

2.3 Mountain river hydrology

Mountainous regions are important to the water security of the world's population. Globally over 700 million people live in mountain areas (Messerli et al. 2004), in the western US, mountainous areas provide water to over 60 million people (Bales et al. 2006) and in Australia, the Snowy Mountains are a significant supply of water for irrigation and electricity. Because societies rely on water sourced from the mountains, understanding the hydrology of these regions is crucial. However, the hydrology of Snowy Mountain rivers differs greatly from that of non-snowmelt dominated rivers within Australia. The differences stem from factors such as the regional climate that drives the level of flow variability of each area and physical factors that impact soil infiltration and overland flow rates. As such, understanding the impacts of flow variability on mountain rivers is an under-investigated area of research in Australia.

2.3.1 Flow variability

Flow variability is a major indicator of a river's hydrology. The hydrological response of a catchment is driven by the regional climate, local soils, topography and vegetation (Dunne 1983; Trancoso et al. 2016). Rivers demonstrate high flow variability when they exhibit a large difference in volume between the base flow and floods or if they have a large difference in volume between floods of

various return periods (Baker 1977; Pickup 1984; Farquharson et al. 1992). Flow variability may be determined on a long-term scale, or over shorter periods such as annual, seasonal, or in the case of hydro-electricity controlled rivers, hourly time frames. Unregulated rivers in regions with lower mean annual precipitation often demonstrate higher flow variability than those in wetter regions (Baker 1977). As the level of flow variability increases, a greater percentage of the annual sediment and water load is carried by less frequent flows (Wolman and Miller 1960) and because alluvial river channels are formed and reworked using sediment transported by the channel itself, channel forming flows in rivers with high flow variability tend to be high-magnitude, low-frequency events that carry proportionately large amounts of sediment (Wolman and Miller 1960). In contrast, channel forming flows in rivers with low flow variability are relatively moderate in size, and occur on an annual basis or less (Erskine et al. 1999).

The level of flow variability can be calculated using measures such as the Flash Flood Magnitude Index (FFMI, Baker 1977; McMahon et al. 1992; Erskine and Livingstone 1999), Coefficient of Variation (CV, Chiew and McMahon 1993; Mazvimavi et al. 2007; Morton et al. 2010) and Baseflow Index (BFI, Rouhani and Malekian 2013; Stewart 2015). The higher the FFMI and CV values, the higher the flow variability, while a BFI of 1 indicates uniform flow and zero indicates an intermittent or ephemeral stream (Hamilton and Bergerson 1984)

Trancoso et al. (2016) recently created a streamflow classification spectrum to describe the dominant streamflow behaviour within a catchment and BFI values were one of a list of metrics used. The spectrum began with Group A type rivers which demonstrate an ephemeral, highly erratic flow regime and ended with Group E type rivers that experience a perennial, highly regular flow regime. Higher BFI values can be expected in rivers that experience snowmelt and this has been shown to even out the flood response relative to mean flow, resulting in less variability in flow. Using this recent classification, snowmelt rivers can be expected to be classified as either Group D, perennial regular regime, or Group E.

2.3.2 The impact of snow on regional hydrology

Mountain hydrology differs from lowland, non-snowmelt hydrology because of elevation driven temperature and precipitation gradients (Bales et al. 2006) that determine the height of a rain/snow line. The coastal mountain regions of the western USA receive 70% of their annual precipitation over the winter months (Nolin 2011) and in the past 50 years, the greatest proportion of precipitation has fallen when temperatures ranged from -3^{o} to 0^{o}C (Fig. 4, Bales et al. 2006). Over the same period, temperatures have increased in the region and this has influenced the elevation at which snowfall becomes rain. The elevation of the rain/snow line is an important factor for multiple reasons. The temperature gradient impacts 1) the amount of snow-covered land acting as a source for flooding caused by rain-on-snow events and 2) the amount of water stored in the snowpack for release into river systems as spring and summer runoff.

In mountainous regions, the temperatures associated with individual storms impact the hydrology of the rivers. If a winter storm arrives with warm temperatures, the rain-snowline may rise to high elevations affecting the percentage of a catchment that receives rain, rather than snow. As the rain-snowline rises from 800 m to 2800 m, the rain-covered area of a catchment may increase from 25%, to 100%. The product of such a warm storm is significantly more runoff than if the storm had snowed at all elevations greater than 800 m (Lundquist et al. 2008). Further adding to the runoff,

snowmelt processes are accelerated through rain-on-snow events and when combined with rainfall, can lead to flooding (Sui and Koehler 2001), landslides high up in the catchments (Harr 1981; Singh et al. 1997) and changes to alluvial channel morphology (Singh et al. 1997). The amount of runoff created in this way can be substantial because in regions like the Western USA, winter storms often cover a larger area than the average summer storm (Lundquist et al. 2008). Therefore, multiple warm winter storms can form a large proportion of a rivers annual discharge.

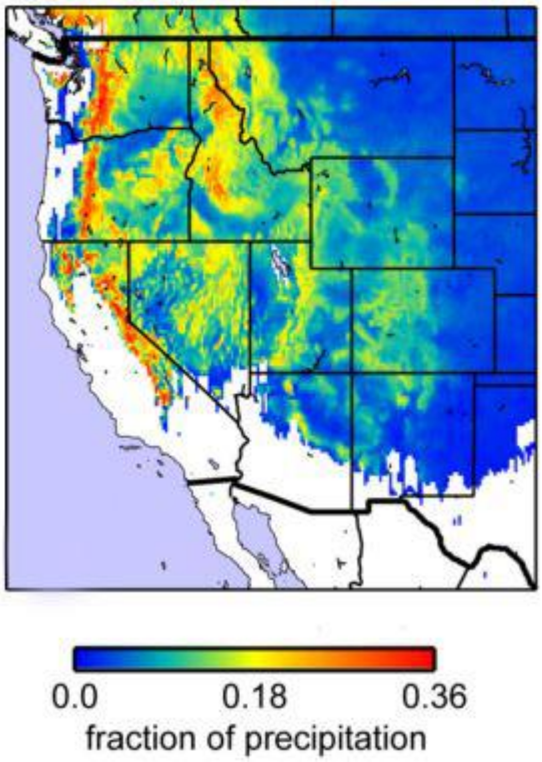


Figure 4. The percentage of annual precipitation that fell over the western USA when temperatures ranged between -3°C to 0°C over a 50-year period. Red and yellow areas coincide with elevated topography. Source: (Bales et al. 2006).

The Australian snowpack is unique in structure (Sanecki et al. 2006). Globally, a snowpack may be classified using characteristics such as thickness of layers, density, snow crystal morphology and grain characteristics, that align with six classes, those being tundra, taiga, alpine, maritime, prairie and ephemeral (Sturm et al. 1995). Although it is most like the maritime classification, the Australian climate produces a snowpack whose characteristics fall outside of the ranges proposed by Sturm et al. 1995 (Sanecki et al. 2006). Specifically, the Australian springtime snowpack is denser than elsewhere, there is little temperature variation throughout the snowpack (a condition known as isothermal) and the ground/snow interface temperature is approximately 0.6°C instead of 0°C as found in many other locations (Sanecki et al. 2006). An isothermal snowpack has implications for a region's hydrology, as when snowpacks are isothermal, little energy is required to initiate melting (Harr 1981). Cold snowpacks must first decrease their temperature gradient, moving toward being isothermal, before they melt. Cold snowpacks can become isothermal through absorbing rain water, but being that they are relatively dry, cold snowpacks can absorb substantial amounts of water. Warm snowpacks such as in maritime regions and Australia are already much wetter and will deliver rain-on-snow induced runoff sooner than colder snowpacks (Harr 1981).

Mountainous regions further differ from the lowlands because they feature a large amount of topographic variability and this heterogeneity impacts the distribution of energy exchange relationships such as solar radiation and latent heat exchanges between the land and the atmosphere (Bales et al. 2006). Solar radiation is one of the driving factors of the timing and intensity of snowmelt, and latent heat affects the phase change of snow into water, and water into water vapour. These energy exchange relationships impact a regions hydrology and are vulnerable to change through changes in climatological factors. This past century has seen mountain river runoff patterns change in the western US and Canada, with increased winter flows and decreased summer flows (Rood et al. 2008; Bales et al. 2006; Nolin 2011). Rising temperatures have contributed to a decreased amount of water in the mountain snowpack (Bales et al. 2006; Nolin 2011) and with snow melting sooner in the spring and plant transpiration also begin sooner. Through a combination of these factors, the magnitude and duration of springtime and summer flows have been reduced (Nolin 2011). The effects of climate-driven changes to seasonal snowpack demonstrate spatial variability. For example, in Mediterranean climates, such as Oregon, USA, where dry summers are the norm, the late summer low flows of surface-runoff dominated catchments are less sensitive to reduced winter snowpack than those in groundwater dominated catchments (Nolin 2011). This is because rivers in the former commonly experience late summer zero-flow conditions while those in the latter don't and rely on recharge contributions to maintain baseflow. As annual peak flows shift forward into the winter, a river becomes more likely to experience both winter flooding and summer drought within the same year (Nolin 2011).

2.3.3 Groundwater and overland flow

Hydraulic connectivity of groundwater is one of the factors that differentiates the hydrology of snowmelt rivers from arid and semi-arid region rivers. The level of hydraulic connectivity determines the ability for lateral groundwater flow to occur. Humid regions demonstrate more hydraulic connectivity and for longer periods than arid and semi-arid regions (McNamara et al. 2005). In wetter areas, sub-surface water flow is laterally connected and controlled by topography, while in arid and semi-arid areas, water movement is mostly vertical and lacks spatial connectivity. A region with a seasonal precipitation cycle can switch between having primarily lateral flow, to primarily vertical flow. Snow dominated landscapes, such as the Snowy Mountains, vary in their seasonal soil moisture content and associated hydraulic connectivity (McNamara et al. 2005). As the drier, summer period ends, rainfall increases soil moisture content, once the soil is suitably wet, lateral connectivity from ridge tops to valley bottoms can occur. Then as rain events turn to snow, soil moisture content, beyond the near-surface depth, dries out. Through spring, the snowpack becomes isothermal and primed for melting. As it does, soil moisture and lateral connectivity increase drastically (McNamara et al. 2005). Though both seasons are wet, Spring differs from Autumn in that Spring rains fall on soils saturated by snowmelt , resulting in a rapid response in streamflow (Hamlet et al. 2007). During early stages of the melt cycle, water from the snowpack is absorbed into the ground at rates linked to the dryness of the soil before it was frozen in early winter. As soil moisture increases, infiltration rates decrease so that during the latter stages of the melt, runoff rates may almost equal that of impervious surfaces (Bengtsson and Westerstrom 1992).

Storm induced precipitation is converted to stream flow through the following mechanisms as proposed by Dunne (1983); Horton overland flow, subsurface flow and saturation overland flow. The type of storm flow that feeds mountain streams differs from that of arid and semi-arid rivers. The late spring/early summer precipitation falling onto already saturated ground flows into rivers as

"saturation overland flow" (Dunne 1983). During the periods where there is no snow on the ground, permeable soils and thick vegetation enable water to flow toward topographic lows through "subsurface flow" (Dunne 1983). These delivery methods differ to rivers in arid or semi-arid regions where vegetation density is less and soil infiltration rates are often low. Here, rainfall intensity often exceeds the infiltration capacity of the soil and runoff is transported to the river as "Horton overland flow" (Dunne 1983).

2.3.4 Rainfall coefficient of variation

Spatial variation is also found in the distribution of precipitation as demonstrated by the rainfall coefficient of variation (CV) for mountainous regions. For the period 1971-2000 for catchments in Oregon (Fig. 5, Nolin 2011) the windward side of the mountains feature the lowest rainfall CV's (0.383-0.548) and the lee facing slopes feature the highest (0.549-0.714). A similar trend was found for the Rocky Mountains with rivers draining eastward experiencing a 20% decrease in summer runoff (Rood et al. 2008).

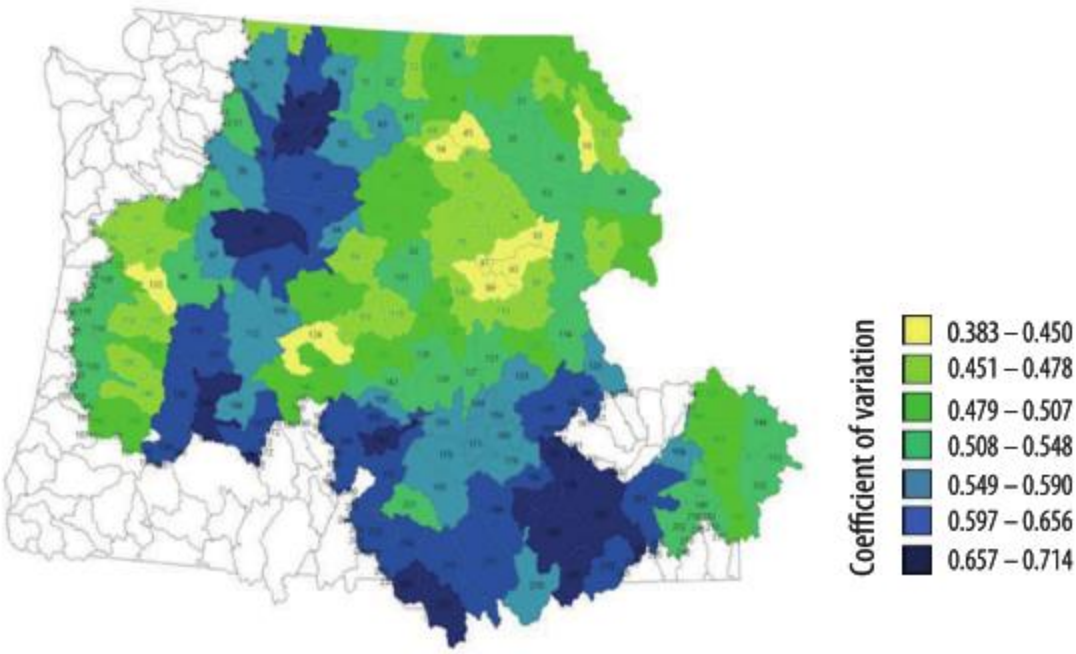


Figure 5. Precipitation coefficients of variation for the period 1971-2000 for the catchments that make up the Columbia River Basin, USA. Source (Nolin 2011).

River systems adapted to low interannual precipitation variability are more vulnerable to changes in climate compared to those adapted to high variability (Nolin 2011). This is because of the variance associated with the shifting of the mean in mean-annual precipitation amounts, where a one standard-deviation shift in the new mean-annual precipitation can be equivalent to a three standard-deviation shift from the original mean (Nolin 2011). To a catchment adapted to low variability, such a change is drastic and may move the river system outside its boundaries of resilience sooner than catchments adjusted for greater variability. Runoff and precipitation variability has an impact on the sustainability of river management strategies of dams and environmental flow programs. If a river is in an area with low variability, and through climate change, the runoff or precipitation regime changes to one of high variability, the viability of the strategy may become questionable (Nolin 2011). Therefore, an understanding of a catchment or regions vulnerability to such changes is a crucial component for any river management strategy.

2.3.5 Runoff coefficients

Runoff coefficients are a measure that show what proportion of precipitation over a catchment is converted to runoff and may be calculated on an annual or event basis. Mean annual runoff coefficients are mostly driven by climate factors such as mean annual precipitation (MAP) and long-term soil moisture (Merz and Blöschl 2009). Land-use and soil types were found to have only a small influence on mean annual runoff coefficients (Merz and Blöschl 2009; Norbiato et al. 2009) and geology only played a significant role in catchments receiving less than 1200 mm of annual precipitation (Norbiato et al. 2009). In Austria, the effect of MAP on mean annual runoff coefficients could be seen where mountainous catchments receiving more than 1000 mm of precipitation per year had mean annual runoff coefficients greater than 0.25, while lowland catchments receiving less than 1000 mm/y had runoff coefficients smaller than 0.25 (Merz and Blöschl 2009). MAP is therefore considered to be a good indicator of the flood response of a catchment (Norbiato et al. 2009). Mountainous regions also tend to have rain on snow events, steeper slopes, thinner soils and alpine vegetation types, all of which result in an increase in direct runoff in comparison to lowland regions (Merz and Blöschl 2009).

Event-based runoff coefficients are more effected by soil moisture conditions than event-rainfall (Merz and Blöschl 2009). In the study by Merz and Bloschl (2009), event-based runoff coefficients were higher in catchments that were already wet and the coefficients in mountainous regions were found to be highest during the winter and spring, when soil moisture content was at its annual peak. In general, mountain rivers feature higher runoff coefficients than lowland rivers because orographic precipitation ensures that mountainous regions receive more precipitation than lowland areas and so antecedent ground conditions are generally wetter with increasing altitude (Merz and Blöschl 2009). More variability was found among event-based runoff coefficients for a region if the mean annual runoff coefficient was low and the variability was thought to be caused by localized rare large runoff events that led to outliers in the dataset (Norbiato et al. 2009).

2.4 Dams, their impact on river systems and methods used to mitigate the effects

In 2000, it was estimated that 850,000 dams blocked rivers globally, with 47,000 of those dams considered to be large (Richter and Thomas 2007). Dams store and provide water for flood control, navigation, recreation, urban water and industrial needs (Bednarek 2001). Dams also contribute directly to 12-16% of global food production and provide 19% of the world's electricity (World Commission on Dams 2000). While clearly providing a benefit to society, dams can cause disruption to natural river systems that may be felt for hundreds of kilometres downstream (Williams and Wolman 1984). Forty per cent of the water in the world's rivers and more than 25% of the global land derived sediment flux is captured by large dams (Vorosmarty et al. 1997). Issues include replacing flowing rivers with lake-like reservoirs, genetic isolation caused by the loss of connectivity between upstream and downstream reaches, changes in water temperature and chemistry, changing flow regimes and channel incision (Bednarek 2001; Richter and Thomas 2007; Tena et al. 2013).

Environmental flows restore or preserve components of a natural flow regime for the benefit of the ecology and geomorphology of a river system (Graf 2006; Bobbi et al. 2014) while striking a balance between government regulation, dam infrastructure capabilities, ecological viability and economic and social desires (Reinfelds et al. 2014). Environmental flow assessments aim to understand how much the flow regime of a river may be altered while either preserving ecosystem integrity or

maintaining a justifiable level of degradation (Tharme 2003). Several methods of environmental flows have been implemented globally, with varying levels of success, including hydrological, hydraulic rating, habitat simulation and holistic methods and these will be discussed in section 2.5.

2.4.1 Morphological impacts of dams and reservoirs

There are three major types of dams; those for flood control, hydropower and water supply. Each type of dam plays a different role and therefore has a different impact on the river system. Different types of dams influence the regulated river in different ways as the discharge regime for each style of dam varies, however the reduced flows below each style of dam ensure there are shared impacts such as altered channel geometries, channel erosion and decreased sediment flux.

Flood control dams capture then release floodwaters at slow rates designed to minimize downstream flooding. Figure 6 shows that with this type of dam, small and large floods are generally eliminated and the high-flow pulse is extended over a longer time period (Richter and Thomas 2007).

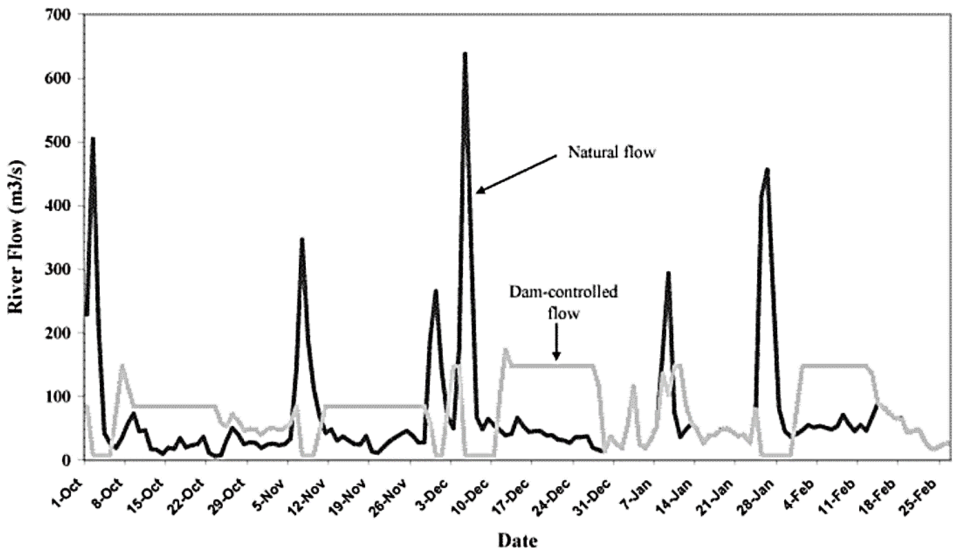


Figure 6. A flood control dam results in the river downstream having an altered hydrograph with lowered flood peaks and drawn out high flow periods through the slow release of stored flood waters. Source: (Richter and Thomas 2007).

Large hydropower dams store water for release during times when electricity needs are high and may completely turn off water supply to downstream reaches during times when electricity is not in demand. The result is a rapidly fluctuating hydrograph as shown in Figure 7 (Richter and Thomas 2007). A hydropower dam can have less impact on a rivers hydrology if it is operated on a run-of-river style (Graf 2006). In this method, approximately as much water runs into the reservoir as is released from the dam.

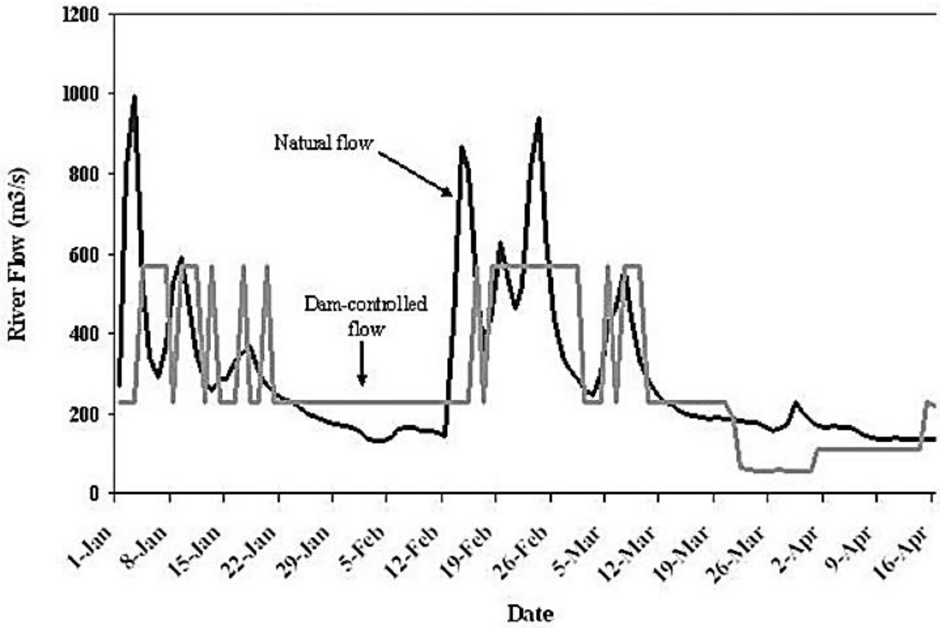


Figure 7. The hydrograph for a river controlled by a hydropower dam includes rapid and major changes in discharge when compared to the natural flow. Source: (Richter and Thomas 2007).

Storage dams capture and release water for the needs of urban, agricultural and industrial use. These dams drastically alter the seasonality of a rivers flow regime as water captured during wet periods is repurposed for human use during dry periods or constantly as in Figure 8. All flows below this type of dam are often dramatically reduced when compared to their natural flow regime (Richter and Thomas 2007).

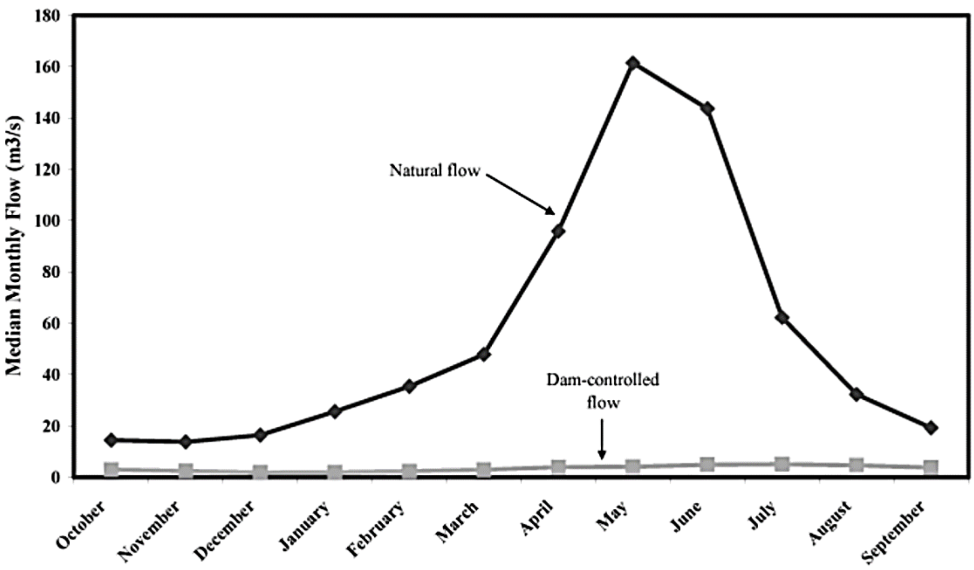


Figure 8. The hydrograph for a river controlled by an irrigation supply dam is drastically lower and less seasonal than the hydrograph for the natural flow. Source: (Richter and Thomas 2007).

2.4.2 Hydraulic geometry relationships in regulated rivers

Dam regulation impacts channel morphology and hydraulic geometry relationships in several ways. For example, if channel margins consist of uncohesive material such as silt, clay or sand, the increased carrying capacity of the clear water released from a dam may erode the river banks, resulting in re-adjustment of channel width, depth and mean velocity (Williams and Wolman 1984).

The combined effect of clear water erosion and reduced sediment supply below a dam may result in the lowering of stream bed elevation (Bednarek 2001; Poff and Hart 2002; Draut et al. 2011; Kondolf et al. 2014), as shown in Figure 9. Over time, channel degradation results in a flatter mean gradient, a reduction in velocity and reduced stream competence (Williams and Wolman 1984). Through these effects the channel below a dam may become stabilized and as stream velocity decreases, vegetation will find it easier to colonize geomorphic features such as emergent bars (Graf 2006; Bejarano et al. 2013). The overall result is a reduction in channel size.

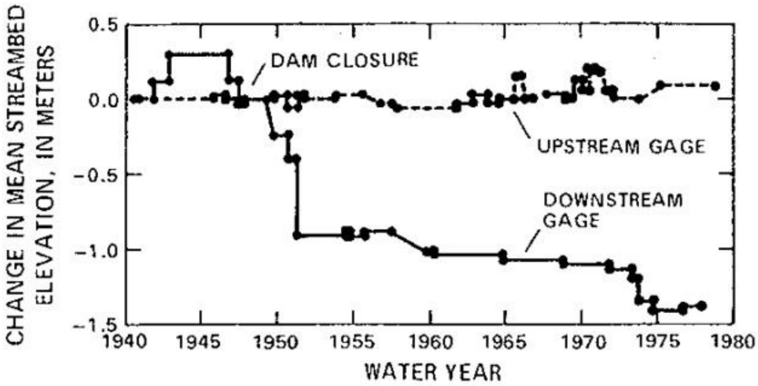


Figure 9. A comparison of the difference in streambed elevation upstream and downstream of a dam. Highlighted is the amount of streambed elevation lost over time that was caused by sediment capture through dam regulation. Source: (Williams and Wolman 1984).

The loss of sediment impacts a river for considerable distance downstream of a dam. Channel degradation was measurable 120 km below the Colorado River's Hoover Dam, and on the Missouri River suspended sediment loads were measured at 30% of the pre-dam amounts at a distance of 1300 km downstream of the Gavins Point Dam (Williams and Wolman 1984). The length of river affected by loss of sediment through damming expands with time and the channel reacts with a lag to dam closure as the degradation moves downstream; for example, it took 30 years for the degraded area to extend 120 km below the Hoover Dam on the Colorado River (Williams and Wolman 1984). Rates of degradation were found to be greatest soon after closure of the dam. Initial rates within the first 5-10 years were as high as 42 kilometres per year (km/y), tapering off over time to 0-29 km/y due to the flattening out of the channel gradient and armouring of the bed.

Clear water erosion below a dam can cause the channel to incise and become disconnected from its floodplains (Poff and Hart 2002; Schmidt and Wilcock 2008; Draut et al. 2011; Ma et al. 2012). The result is a smaller sized river flowing in a confined channel with floods that are no longer large enough to spill over the banks onto the floodplains. With this issue comes a loss of lateral connectivity between the river and the landscape. A study of large rivers in the US by Graf (2006) noted that regulated reaches had 3.6 times more inactive floodplain area than unregulated reaches (Graf 2006). Clear water erosion will also cause a channel to become armoured through the winnowing out of fine material resulting in better sorting as coarse sediment is left behind. A progressive fining of sediment calibre occurs that is in contrast to the naturally poor sorting of sediment above reservoirs (Draut et al. 2011). Channel degradation occurs at the greatest rate directly below a dam (Fig. 10) and once a bed is armoured, it can lose its ability to adjust its depth in response to changes in discharge.

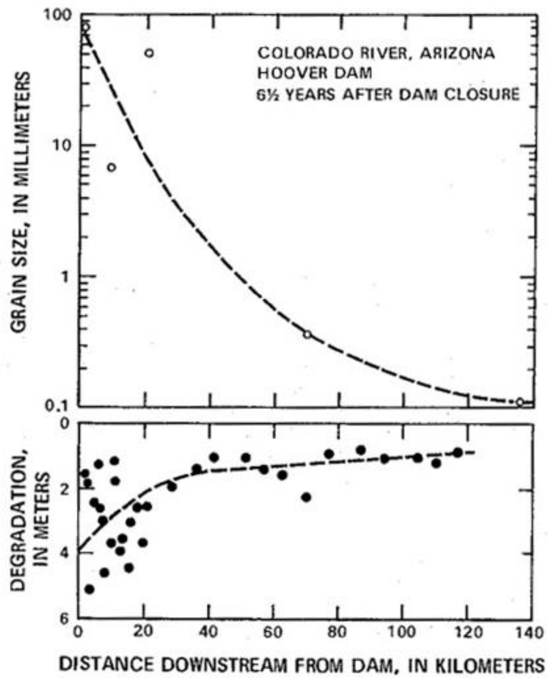


Figure 10. Bed armouring and channel degradation with distance downstream on the Colorado River below the Hoover Dam. Source: (Williams and Wolman 1984).

Hydraulic geometry relationships above and below a dam are likely to be different and may even become unstable, due to the overall and/or periodic changes in water volume and sediment load (Graf 2006; Ma et al. 2012; Bejarano et al. 2013). In large rivers, the order of sensitivity of the downstream hydraulic geometry variables to changes in discharge were found to be depth, then width followed by velocity. For smaller channels the order of sensitivity of adjustment was width, depth then velocity (Carlston 1969; Pietsch and Nanson 2011). Were a river to become dam-regulated, the downstream hydraulic geometry relationships would change once flows were reduced and the channel below the dam shrank in size. A once large river would become a smaller river with a new set of hydraulic geometry relationships. An example of such channel reduction is the Snowy River in Australia (Fig. 11) where flows were reduced by approximately 99% of their pre-dam volume for a period of more than 30 years before the second image was taken (Rose and Erskine 2011).

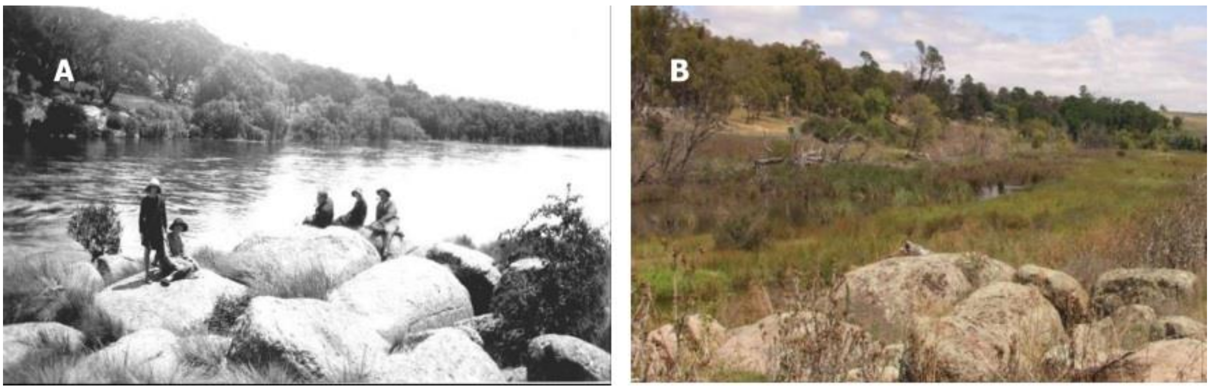


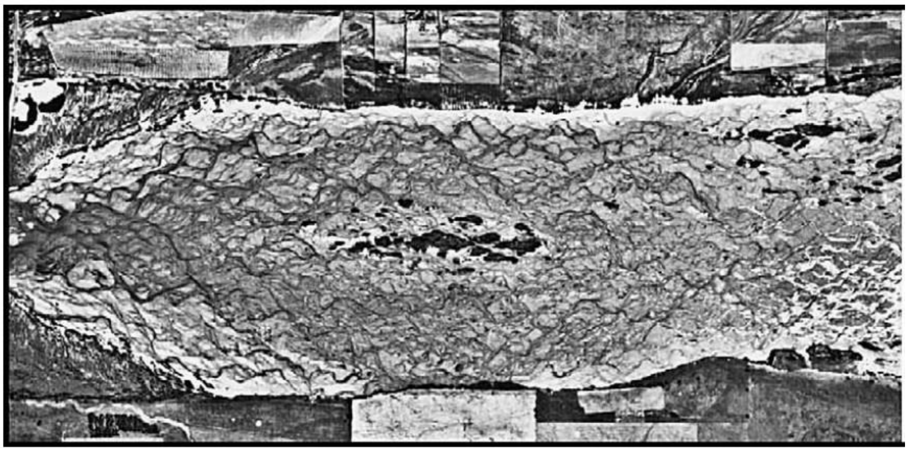
Figure 11. Two images taken at the same location on the Snowy River in Australia prior to (A) and after (B) dam regulation. Source: (Rose and Erskine 2011).

Instability of hydraulic geometry relationships may be caused below a dam by flushing flows aimed specifically at transporting sediment from the reservoir into downstream reaches. For example, a study on the Yellow River in China found that at-a-station hydraulic geometry exponents would change rapidly and range between 0.16 - 0.76 for width, 0.01 - 0.49 for depth and 0.22 - 0.49 for velocity when high volumes of sediment were flushed from the Sanmenxia Dam (Ma et al. 2012).

2.4.3 Channel metamorphosis

Alluvial river channels have been shown to undergo transformation in form in response to changes in water discharge and sediment load, termed channel metamorphosis by Schumm (1969). Channel form complexity may be reduced through decreases in discharge, for example, anabranching rivers may become single threaded (Gendaszek et al. 2012), or morphological features such as islands in braided rivers may become vegetated and thereby stable (Graf 2006). Graf (2006) suggested that regulated rivers are "shrunken, simplified versions of former unregulated rivers" (Graf 2006). Examples were found in a comparison between the unregulated and regulated reaches of multiple rivers where the reaches downstream of each dam were shown to have larger low flow channels, smaller high flow channels, reduced bar formation, smaller islands, smaller active floodplains and larger inactive floodplains than their upstream counterparts (Graf 2006).

a



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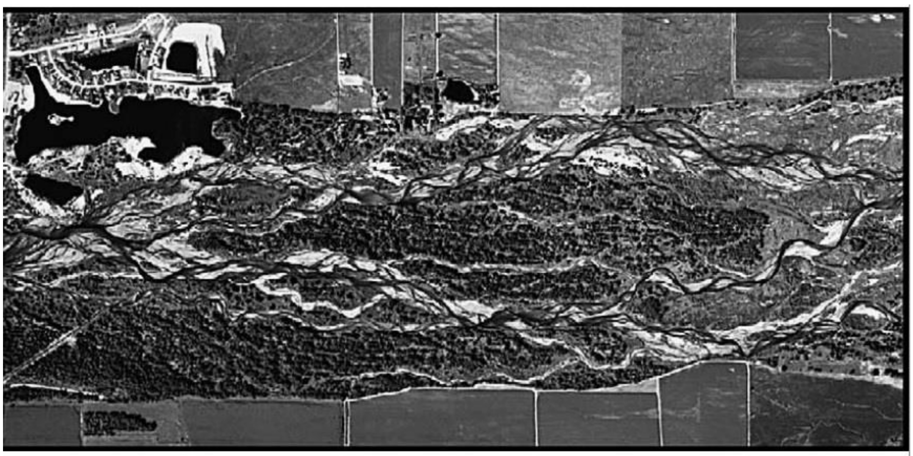


Figure 12. Two images of the Platte River in Nebraska, a) was taken in 1938, prior to the construction of the Kingsley Dam, b) was taken of the same location in 1998, 57 years after the dam was commissioned. Channel complexity has decreased through decreased discharge as islands became stabilized through colonization by vegetation Source: (Graf 2006).

2.4.4 Disrupted sediment flux: channel to landscape scale

Dams trap both suspended and bed-load sediment, limiting or preventing its passage downriver, thereby reducing the amount of channel forming material available (Williams and Wolman 1984; Dai et al. 2008; Kondolf et al. 2014). Global transport of sediment and water has been so drastically altered through the damming of rivers that earth surface processes have been measurably altered (Graf 1999; Poff and Hart 2002). Estimates show that rivers flowing in the period pre-human disturbance brought approximately 15-20 Bt/y of sediment to the ocean (Walling 2006), now in more modern times, entrapment behind dams has reduced the amount of sediment reaching the ocean by 1.4-5 Bt/y (Vörösmarty et al. 2003; Syvitski et al. 2005; Kondolf et al. 2014) and this reduction occurred during a period when human activities such as mining, deforestation and poor farming practices have increased the amount of sediment introduced to river systems by approximately 10%.

While all sediment flux is impacted by a dam, the calibre of the sediment determines the nature and duration of storage. Coarse sediment such as gravel and cobbles move through the river as bed load and are completely caught by a dam. Coarse sediment is crucial to the geometry of the river channel; this sediment is what builds features such as the bed, bars, banks and riffles and requires higher shear stress to be mobilized (Mueller and Pitlick 2014), thereby providing some protection from erosion. Fine sediments provide nutrients and silts and clays to downstream reaches and build alluvial landforms such as floodplains and benches (Kondolf et al. 2014). These sediments travel as suspended load and the amount captured by a dam depends on the type of infrastructure. However, the more time that these sediments spend in a reservoir, the less likely they are to be remobilized (Kondolf et al. 2014). After the Three Gorges Dam was completed, suspended sediment loads decreased downstream of the dam by 91% and total phosphorous by 77% (Kondolf et al. 2014). The Nile River once transported an estimated 10 x 10^7 t/y of suspended sediment to the delta, but the Aswan Dam has now reduced that amount to almost zero (Walling and Fang 2003). Figure 13 provides a further example of the effect dam regulation has on suspended sediment flux. In the period leading up to dam closure, suspended sediment measurements on the Colorado River at the Grand Canyon and Topock stations followed the same trends and had similar values. After the Hoover Dam was commissioned, suspended sediment rates at Topock station, downstream of the dam dropped off dramatically while readings upstream of the dam at Grand Canyon station continued in a similar cycle to before (Williams and Wolman 1984).

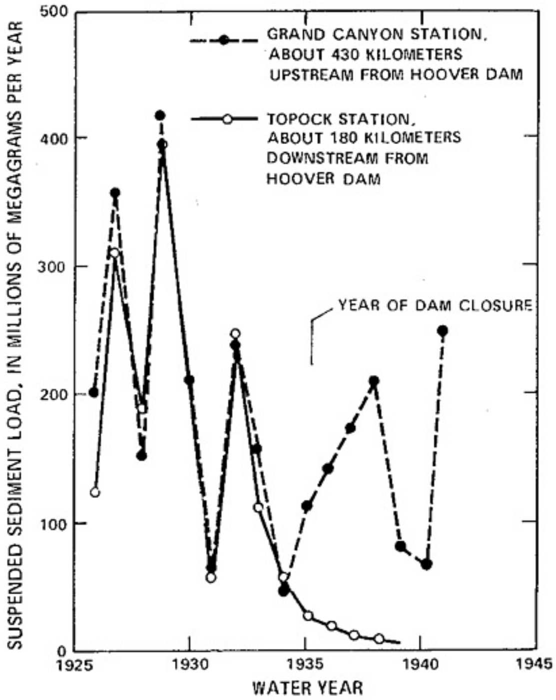


Figure 13. The Effect of the Hoover Dam on annual suspended sediment loads at gauges upstream (Grand Canyon) and downstream (Topock) of the dam. Source: (Williams and Wolman 1984).

Sediment entrapment by dams does more than just rob downstream reaches of vital nutrients and channel building capabilities; the long-term security of water resources also become diminished as the reservoir is filled by sediment. An example is the Sanmenxia Dam on the Yellow River which took only two years to become 90% filled with sediment (Ma et al. 2012). This dam is located by the Loess region in China and had extremely high sedimentation rates due to poor farming practices through the period of its construction.

Further issues relating to the discontinuity of sediment flow include coastal erosion caused by the reduction in sediment supply from rivers. Sixty percent of the sediment transported to coasts around the world is derived from catchments draining mountainous areas with headwaters above 3000 m (Syvitski et al. 2005). These rivers are also the most dam regulated and suffer the greatest reductions in sediment flux (Syvitski et al. 2005). Africa and Asia are most affected by the reduction of sediment supply to the coast, with rivers like the Nile, Zambezi, Yangtze, Yellow and Indus seeing drastic changes in sediment flux since dam control (Syvitski et al. 2005). Rates of coastal erosion on Damietta peninsula, near the mouth of the Nile, have ranged between 20 and 30 m per year in the period 1990-2014 (Abd-El Monsef et al. 2015).

Dams also impact subsidence rates in river deltas. Deltas subside via the compaction of sediment through loading, as well as through isostatic adjustment, faulting, unconsolidated sediment flow (Stanley 1988) and removal of underlying oil and gas reserves (Syvitski 2009). Delta subsidence is intensified through reduced sediment supply because the addition of new sediment to fill the space left by the compacting process is impaired (Becker and Sultan 2009). Average subsidence rates for the Nile delta through the Holocene have been measured at 0.5-4.5 mm/y, since the commission of the Aswan Dam, subsidence rates have increased to 8 mm/y (Becker and Sultan 2009). Implications of delta subsidence in the region are large, sea levels are predicted to rise in the area at a rate of 1.8-5.9 mm/y, 50 million people live on the Nile delta and it is Egypt’s agricultural hub (Becker and

Sultan 2009). This problem extends beyond the Nile as 24 of the world's 33 major deltas are subsiding (Kondolf et al. 2014). A combination of subsiding deltas and rising sea levels will have major impacts on coastal populations in the future.

2.4.5 Flood magnitude/frequency relationship

Dam regulation impacts the flood magnitude/frequency relationship of a river with floods of the pre-dam magnitude no longer occurring at the same frequency. These impacts affect channel forming flows such as those that fill the channel to bankfull level. In many free flowing rivers the return period for such flows is approximately two years (Wolman and Leopold 1957; Dury 1959; Harvey 1969; Andrews 1980; Wohl and Merritt 2005; Gendaszek et al. 2012). Dam regulation has changed the frequency of bankfull flows on the Murrumbidgee River, Australia. Here, natural bankfull flows occurred every 1.4 years, since regulation, the return period has increased to 2.2 years (Page et al. 2005). In the USA, floods with a two-year return interval on the Green River in Utah, decreased in magnitude by 57% after construction of the Flaming Gorge Dam (Grams and Schmidt 2002) and those on the Cedar River in Washington were found to decrease in size by 47% (Gendaszek et al. 2012). The resulting changes affect the geometry of the channel, for example, the change in the flood magnitude/frequency relationship is one of the factors that contributed to the plan form of the Cedar River changing from a wide, anabranching river to a 50% narrower single threaded channel with slower migration rates (Gendaszek et al. 2012).

2.5 Environmental flows

Environmental flows are becoming increasingly common given the scale of biophysical impacts of dams on river systems. To mitigate or reverse some of the environmental damage done, environmental flow programs have been implemented to restore or preserve components of a natural flow regime for the benefit of the ecology and geomorphology of a river system (Bobbi et al. 2014). Programs vary, from sporadic flushing flows that target a specific issue, to holistic basin wide approaches (Alfredsen et al. 2012; Reinfelds et al. 2014).

Environmental flow programs are often based on ecological goals (Graf 2006). For example, Australia's Snowy River environmental flow objectives can be quoted as follows (NSW Office of Water 2010):

- To protect endangered/threatened species
- To maintain natural habitats
- To maintain wilderness and national park values

The goal was to meet these objectives through an environmental flow regime that would achieve "channel maintenance and flushing flows within rivers". Through this program water temperatures would improve through the breakdown of thermal stratification in pools below the dam, habitat connectivity would be regained, triggers for fish spawning would be met and the riverine environments would become more aesthetically pleasing (NSW Office of Water 2010).

Environmental flow programs that include ongoing sporadic flooding have the following social and ecological benefits: water is filtered of pollutants, sediment and nutrients as it flows through floodplain forests and wetland areas, ecological habitat complexity is increased through bank erosion and sediment deposition, cultural traditions may be regained and fishing opportunities can be increased (Richter and Thomas 2007).

There are a variety of techniques currently used for determining environmental flow programs. Four categories of methods will be discussed, those being hydrological, hydraulic rating, habitat simulation and holistic. Holistic methods are the most complex and so the conversation will go into more depth here. Each method in the four categories begins with an assessment of the regulated river system. Understanding the flow regime of the pre and post-regulation river system is vital to the assessment and management of an environmental flow program. Ideally, current and historic daily flow data is available so that comparison of the magnitude, frequency, duration and timing between pre and post-regulation flow regimes can be made (Zhang et al. 2012).

2.5.1 Hydrological methods

Hydrological methods are the simplest technique for calculating environmental flows. They use historical flow data such as monthly and daily records to determine the proportion of flow needed over an annual or seasonal time frame to maintain river and ecosystem health at an acceptable level. The simplicity of hydrological methods make them suitable for initial planning level stages for water resource development (Tharme 2003).

The Tennant (Montana) method has been a popular hydrological method used globally (Richter et al. 1997; Tharme 2003). In this technique, ecological, hydraulic and morphological data are gathered and correlated with different percentages of the post-dam mean annual flow. According to the Tennant method, a discharge reaching 10% of the mean annual flow (MAF) enables most aquatic life to survive, 30% provides a good habitat, 60-100% provides an excellent habitat and 200% is determined as a flushing flow (Richter et al. 1997). This type of desktop hydrological method has been used in Zimbabwe (Mazvimavi et al. 2007) for water resources planning throughout the entire country.

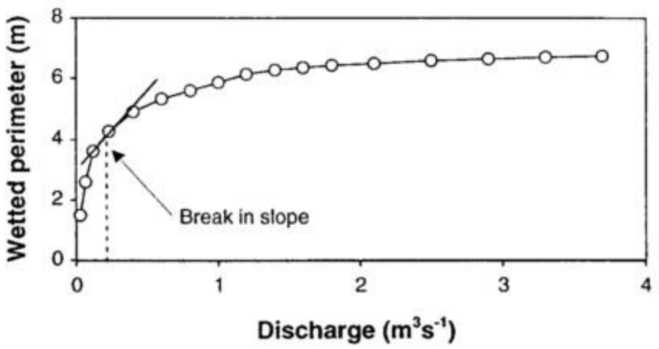
The flaw with hydrological methods is that environmental flow allocations are often drastically less than pre-dam flows and so it is not possible to restore the river system to the same conditions as the original river (Reinfelds et al. 2014). The Montana method also fails in that it does not consider the timing nor the extremes of flows, thereby neglecting to address natural variability (Richter et al. 1997). Further, desktop hydrological methods address the relationships between hydrologic data and ecological processes without consideration for ecological needs on a site by site scale (Mazvimavi et al. 2007).

2.5.2 Hydraulic rating and habitat simulation methods

Hydraulic rating methods are simple and fast, site specific techniques used to determine the minimum flow needed to achieve certain goals. For example, how much habitat is created by a certain level of discharge (Gippel and Stewardson 1998; Tharme 2003). The notion is that by preserving features such as riffles, low flow habitats in the overall river system will be protected. Figure 14a highlights the change in the curve on a wetted perimeter-discharge plot, this marks the point at which the riffle in the cross-section meets the minimum level required for ecological connectivity (Gippel and Stewardson 1998). There are links between hydraulic rating methods and the Tennant hydrological method. Tennant (1976) found that at 10% of the MAF, 50% of the maximum wetted perimeter was available, and at 30% of MAF almost the entire wetted perimeter was provided (Tennant 1976; Gippel and Stewardson 1998).

The viability of the wetted perimeter method was assessed on two rivers near Melbourne, Australia (Gippel and Stewardson 1998) and was found to be inconsistent. Channel geometry was shown to impact the location of the breakpoint on the wetted perimeter-discharge curve; rectangular channels resulted in a more sharply defined breakpoint than triangular channels. A supplementary biological study at the site of the cross-sections surveyed found the minimum flows calculated using the breakpoints were inadequate for maintaining macroinvertebrate habitat. A further issue with the wetted perimeter method is that it is only able to recommend a minimum flow and so at most should form a component of a more in depth environmental flow assessment (Gippel and Stewardson 1998).

a



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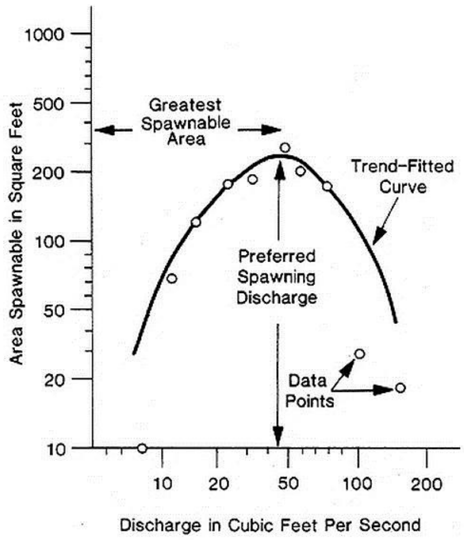


Figure 14. a) The breakpoint on a wetted perimeter-discharge curve is where a marked change in the curve of the slope occurs. Source: (Gippel and Stewardson 1998). b) An example of a habitat discharge curve showing the level of discharge that corresponds with the most suitable habitat for spawning. Source: (Stalnaker 2015).

Habitat simulation methods are similar to hydraulic rating methods as they link the quality and quantity of instream habitat for target species to a variety of discharge levels (Tharme 2003; Belmar et al. 2011). Variables commonly used to calculate physical habitat suitability include channel depth, velocity, shear stress and substrate composition. A range of suitability is produced in a habitat-discharge curve so that an optimum flow can be determined (Fig. 14b). The instream flow incremental methodology (IFIM) is an example of a widely used habitat simulation method (Tharme 2003) and was used on the Silverstream River in New Zealand (Campbell and Scott 1984) to determine levels of habitat quality for brown trout (*Salmo trutta* L). The study found good correlation between velocity and discharge and could tie in the percentage of mean monthly flow needed to categorize habitat suitability levels in a way modelled on the Tennant hydrological method (Table.3) (Fraser 1978) in (Campbell and Scott 1984).

Table 3. Modification of the categories used by the Tennant method as proposed by Fraser (1978) in (Campbell and Scott 1984)

% of mean monthly discharge	**Protection level**
100	Optimum
75-99	Acceptable
30-74	Fair-poor
<29	Unacceptable

Habitat simulation models focus on specific species and assume that by protecting one species, the river will maintain a suitable level of function and health. However, rivers are complex systems, with many interacting variables such as climate, catchment elevation, lithology and interspecies relationships. Through this need for more comprehensive environmental flow assessments holistic methods were created.

2.5.3 Holistic methods

Holistic methods have been used for several decades and have proven to be popular in Australia where lack of detailed information on river biota has made it more sensible to protect a whole river. This way everything in and related to the system is covered. This contrasts with the previous methods where specific flow levels are targeted for individual species. Holistic approaches may be bottom-up or top-down and the discussion below includes a comparison between the two holistic methods along with examples and an analysis of the strengths and weaknesses of each.

Bottom-up holistic method – building block

The building block method has been the most widely used holistic method for determining environmental flows (Tharme 2003). The building block method is a bottom-up approach designed to address the ecological and physical processes of a river system (Alfredsen et al. 2012). It works as follows (Tharme 2003):

1. Interest groups for the river in question are consulted to learn their needs
2. Each need then constitutes a "building block" and has an optimum range of magnitude and duration of flow
3. The building blocks are added together to determine the total flow regime

An example of the use of the building block method is shown in Figure 15. In this study by Alfredsen et al., (2012), the interest group most strongly considered for the water allocation was the Atlantic salmon. For this species, smolt migration is triggered by water temperature and higher discharge, while hatching requires a reduction in flow. The research suggested that summer discharges needed to be enlarged so that there would be increased space in the river for the increased fish numbers due to hatching. To attain an element of variability, summer flows were to have periods of higher and lower flows. The resulting flow regime is demonstrated by the hydrograph in Figure 15 (Alfredsen et al. 2012). The aim of the project was to ensure the environmental flow regime included natural variability, Figure 15 however, highlights the unnatural "blocky" hydrograph and is one of the

problems with the building block method. In this example, completely uniform flows are interspersed with sudden and dramatic increases in water level. Further problems with the building block method may include bias in the planning stages. When one interest group dominates the consideration process, subjectivity is introduced that may come at the expense of another species (Alfredsen et al. 2012; Bobbi et al. 2014; Reinfelds et al. 2014). By unduly favouring one aspect of the rivers flow regime, other ecosystem components whose needs are less well known or recognized may be inadvertently unduly disfavoured under a bottom-up building blocks approach to environmental flow development.

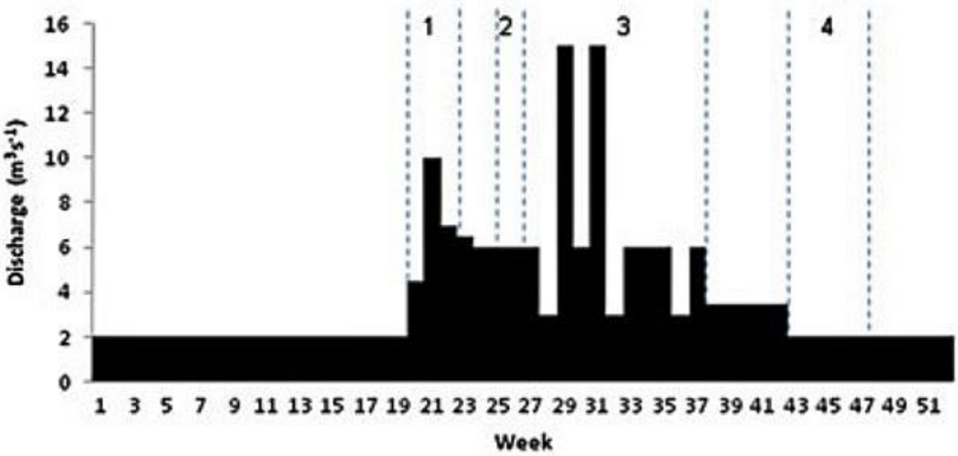


Figure 15. The hydrograph associated with the building blocks method proposed by Alfredsen et al (2012). Important events for the rivers Atlantic salmon are graphed as follows, 1. Smolt migration occurs in weeks 19-22, 2. Hatching occurs in weeks 25-26, 3. Summer flexible flow period, 4. Spawning occurs in weeks 43-47. Source: (Alfredsen et al. 2012).

Another problem with the building block method example is the magnitude of flood pulses as demonstrated in the Snowy River, Australia. Under the 1961 original operating license, water allocated for environmental flows was 1.2% of pre-dam mean annual discharge. This amount was increased through re-licensing in 2002 with aims of gradually increasing environmental flow discharges to 28% of the mean pre-regulation flow (Rose and Erskine 2011). However the plan developed by the Snowy Scientific Committee called for 51% of the total annual environmental flow allocation to be released in a single pulse (Reinfelds et al. 2014). The fault with this strategy was that the magnitude of the environmental flow pulse was grossly out of proportion with the volume of water allocated for environmental purposes. Pre-regulation floods with a 1.1-year return period were four times as large as the mean daily flow. The flood pulse planned under the building block method was designed to mimic a 1.1-year flood but was 34-40 times greater than the mean daily post regulation flow (Reinfelds et al. 2014). This drastically increased magnitude would likely serve to erode channel features rather than deposit new sediment (Rose and Erskine 2011). The environmental flow program on the Snowy River has since been re-evaluated and is now based on the top-down natural flow scaling approach.

Top-down holistic method – natural flow scaling

Natural flow scaling is a top-down holistic approach to determining environmental flows. This method has been implemented on the Snowy River in Australia in recent years. Here, channel degradation and negative ecological impacts caused by flow reduction, resulted in a reassessment and subsequent increase in the volume of water allocated for environmental flows (Rose and Erskine 2011).

With the natural flow scaling method, the allocated environmental flow is scaled proportionally to the hydrograph of a suitable unregulated analogue river (Reinfelds et al. 2014). By mimicking the hydrograph of an unregulated river (Fig. 16), the natural flow scaling technique smooths out the blocky nature of the building block method, and spreads the allocated environmental flow out over the whole year in a more natural way by basing the timing and magnitude of environmental flow releases on those of the analogue river.

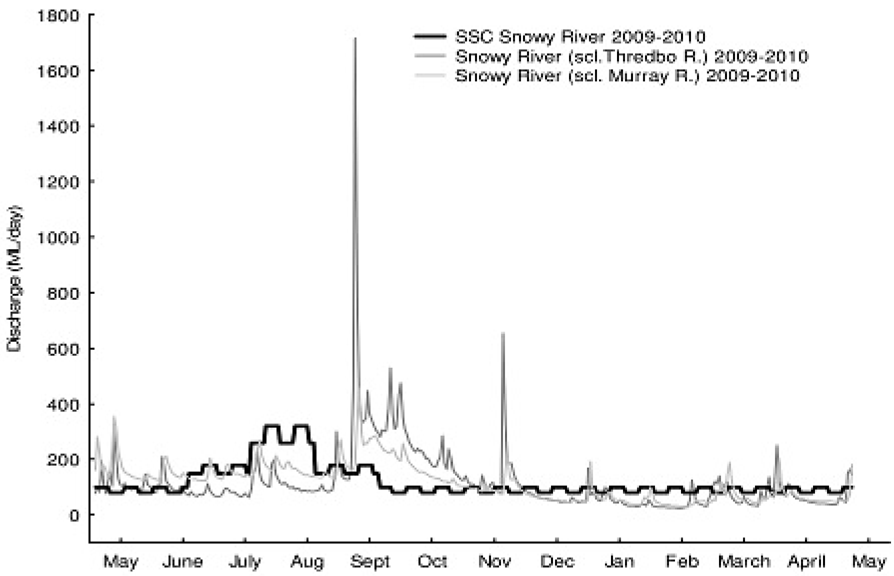


Figure 16. A comparison between the hydrographs of the natural flow scaling method (grey lines) and the previously used building blocks method (black line). Two potential unregulated analogue rivers were assessed for use on the Snowy River environmental flow program, the Thredbo and the Murray. The Thredbo River was deemed more suitable due to similarities in mean annual discharge and mean catchment elevation with those of the regulated Snowy River below Jindabyne. Source: (Reinfelds et al. 2014)

The natural flow scaling approach offers several more advantages over the building blocks method; there is no bias toward specific interest groups and because the flow regime is scaled appropriate to the discharge allocated for the environmental flow program, and the hydrograph reflects a natural variability that is proportional to the volume of water allocated for environmental purposes, therefore reflecting what may be found in nature. An added advantage is that an example or physical template of how the regulated river may look and adjust in the future is provided by the analogue river.

2.5.4 Morphological responses to environmental flows

The Snowy River was once Australia's greatest snow-melt river, with maximum historical discharges of up to approximately 100,000 ML/d downstream of Jindabyne at Dalgety (Erskine et al. 1999). Since it was dammed for the Snowy Hydro Scheme, flows were reduced by 99% for a period of 35 years (Rose and Erskine 2011). Increased flows were reintroduced to the Snowy River below Jindabyne Dam beginning in 2002 and the plan was to ramp up the annual discharge allotment to 21% of historical mean annual flows over a time frame of 10 years (NSW Office of Water 2010) then up to 28% after that period (Rose and Erskine 2011). The value of 28% was determined to be the "minimum environmental flow required to restore ecological health to the severely degraded Snowy River" (Crisp and Gallard 2009). Flushing flows of 12,000 ML/d were introduced in 2011 (NSW Office of Water 2010) and annual flows increased from 10.5 GL in the 2002-03 water year, to 147.9 GL for 2015-16 (NSW Office of Water 2015).

In the period after dam closure, the channel below the Jindabyne dam became filled with fine sediment through the combination of readily erodible granitic soils, drought, bush fires and agricultural practices that caused land degradation (NSW Office of Water 2015). One of the goals of the flushing flows was to remove the fine sediment from pools and there has been a measurable morphological change since the enlarged flow program began (Fig. 17). Research has since demonstrated that flows in excess of 1000 ML/day are sufficient to remove fine sediment and sand from the channel and that most of the work is done during the first day of the flood event (NSW Office of Water 2014). This led to suggestions that the magnitude of the flood is more important than duration, a notion that's in line with Leopold and Maddock (1953) who found that the bulk of sediment is moved on the rising limb of the hydrograph (Leopold and Maddock 1953). The risk in replicating the duration of pre-dam floods is that the time spent in the rising limb is prolonged thereby eroding channel and floodplain features that were on their way to some level of restoration (Reinfelds et al. 2014). Pre-dam channel geometry was naturally scaled and adjusted temporally to move the water and sediment provided by the catchment. The post regulation floods released as part of an environmental flow program carry less water and sediment and thus must be scaled to the new regime so as not to cause excessive erosion.

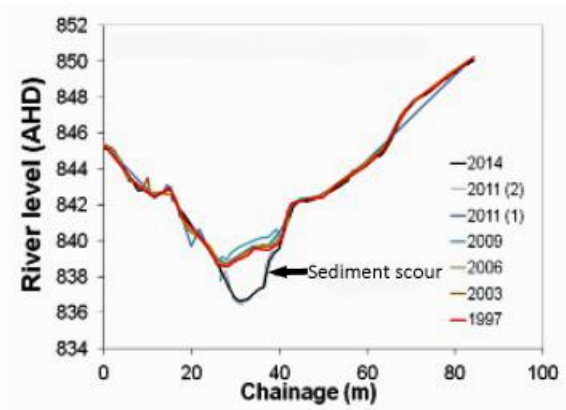


Figure 17. Changes in the cross-section of the Snowy River channel through the impact of higher flows. Source: (NSW Office of Water 2015).

Further effects of the increased flows on the Snowy River can be seen in Figure 18. Morphological features such as benches have become inundated and the channel has become wider (NSW Office of Water 2010). A willow removal program forms a component of the objectives for the rehabilitation of the Snowy River and to date over 180km of willows have been removed.

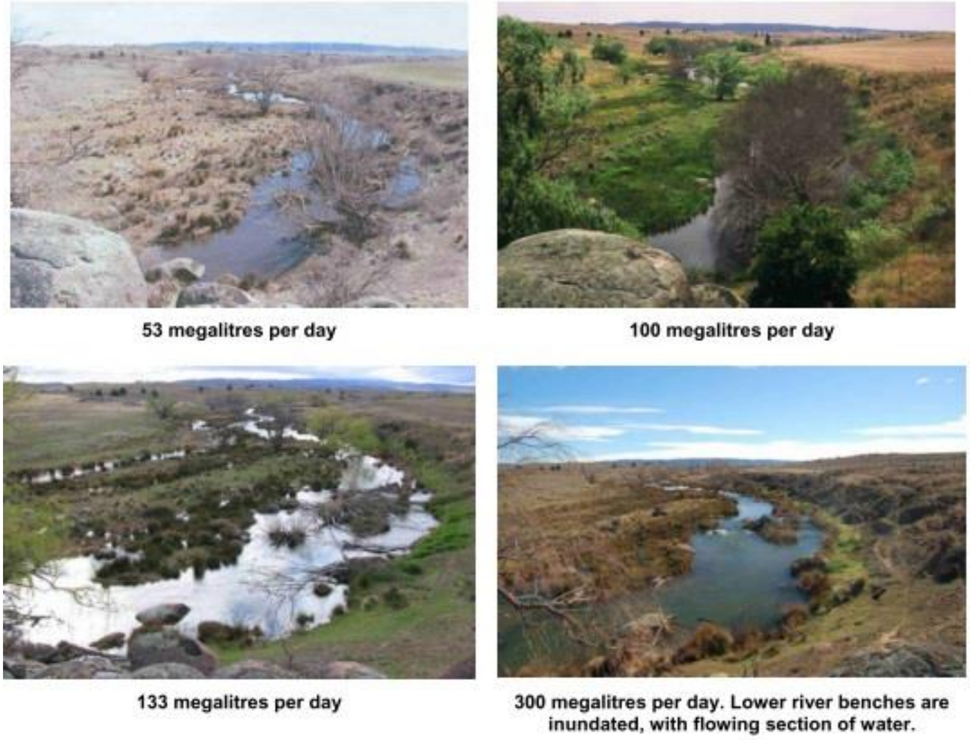


Figure 18. The impact of increased flows and willow removal on the Snowy River below the Jindabyne Dam through the revised environmental flow program. Source: (NSW Office of Water 2010).

2.6 Identifying knowledge gaps in mountain rivers

Comparative studies allow scientists and managers to use the knowledge of one area to further the understanding of a different area with similar characteristics (Slocombe and Davis 2014; Sobkowiak and Liu 2015). In comparison to overseas locations such as the USA, significantly less work has been done on Australian mountain rivers and so there are research questions that remain. What are the baseline morphological and hydrological characteristics of Australian mountain rivers and do they differ from elsewhere? How will the mountain rivers respond to changes in climate and discharge and how important are elevation to runoff relationships? Factors that drive mountain river hydrology include the influence of the mountains on the local climate through temperature and precipitation gradients. Mountain rivers in regions that experience low variability in precipitation patterns are vulnerable to changes in hydrology through changes in climate. For example, as temperatures rise, the elevation of the rain/snow line will change and this has implications for winter flooding, summer drought and water storage. These changes may move a river system outside its boundaries of resilience and this can impact any river management strategy. How variable is the hydrology of Snowy Mountain rivers and what are the implications for environmental flows and other water use strategies? This thesis will investigate the differences in magnitude frequency relationships, runoff variability and the implications on channel morphology in south eastern Australia.

Chapter 3 - Regional setting

3.1 Study area

The Snowy Mountains are situated in south eastern Australia, in the state of New South Wales (NSW). 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 peaks at 2228 m (Fig. 19). Two iconic Australian rivers have their headwaters in this region, the Snowy River and the Murray River. Before its flows were extensively altered by a large engineering project, the Snowy River was once Australia's largest snowmelt river. Since operation began in 1955, the Snowy Hydro Scheme has ensured that the flow down the Snowy River is regulated for irrigation and water supply security. Regulation occurs through dams and diversions that cause a portion of the Snowy River's discharge to flow west rather than east, into the Murray and Murrumbidgee catchments (Fig. 19). Below the dam at Lake Jindabyne, the Snowy River currently receives approximately 20% of the pre-Snowy Scheme natural discharge (Reinfelds et al. 2013). At 2520 km in length, the Murray is Australia's longest river. It flows north then west from the Snowy Mountains, through some of Australia's prime agricultural land toward its mouth in South Australia. The Murray River naturally receives an average of 1270 GL of water per year, with an additional 850 GL of water supplied through the Snowy Scheme. A third major river, the Murrumbidgee also has its headwaters in the Snowy Mountains and initially flows east before turning north where it runs along the outskirts of Australia's capital city, Canberra. The river then heads west, eventually flowing into the Murray. The Murrumbidgee River is also important for the purposes of agriculture and water supply.

Eighteen unregulated river sites, both currently and historically gauged, comprise this study (Fig. 19 and Appendix 1). Eight sites are in the Snowy River catchment, six of these are above Lake Jindabyne and two are on the Eucumbene River, a tributary that enters the Snowy at Lake Jindabyne (Fig. 19). Six sites are within the Murray River catchment and four in the Murrumbidgee catchment. The straight-line distance from the northernmost field site at Yarrangobilly to the southernmost site at Tom Groggin is 100 km.

Mean catchment elevation above the field sites ranges from 850 m at Maragle Creek to 2021 m at Cootapatamba Creek and the mean catchment elevation within the entire study area is 1558 m. 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.

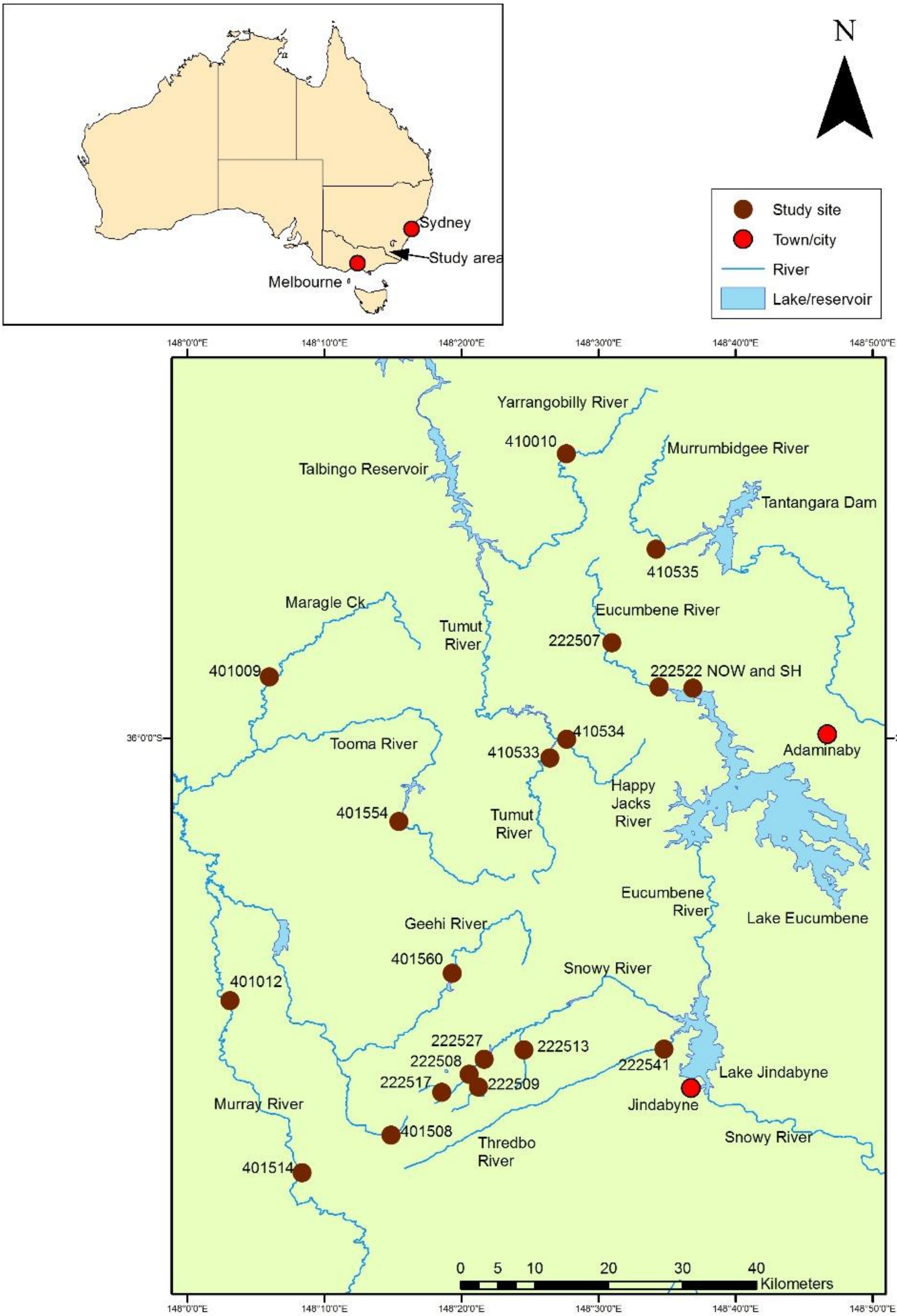


Figure 19. The location of the field sites in south eastern Australia. Data from the Geofabric (Hutchinson et al. 2008) and Natural Earth (Natural Earth 2015).

3.2 Geological setting

The Snowy Mountains are the roof of Australia. They are a series of undulating plateaus with large amounts of land above 1500m (Fig. 20) and stand in contrast to the ragged peaks and deep valleys of overseas mountain ranges. The Snowy Mountains form part of the Great Dividing Range which runs in a north/south orientation and extends the length of the east coast of Australia, reaching its highest point at Mt Kosciuszko (2228 m) in NSW. In the Snowy Mountains region, the Great Dividing Range is approximately 160 km wide (Gill and Sharp 1956).

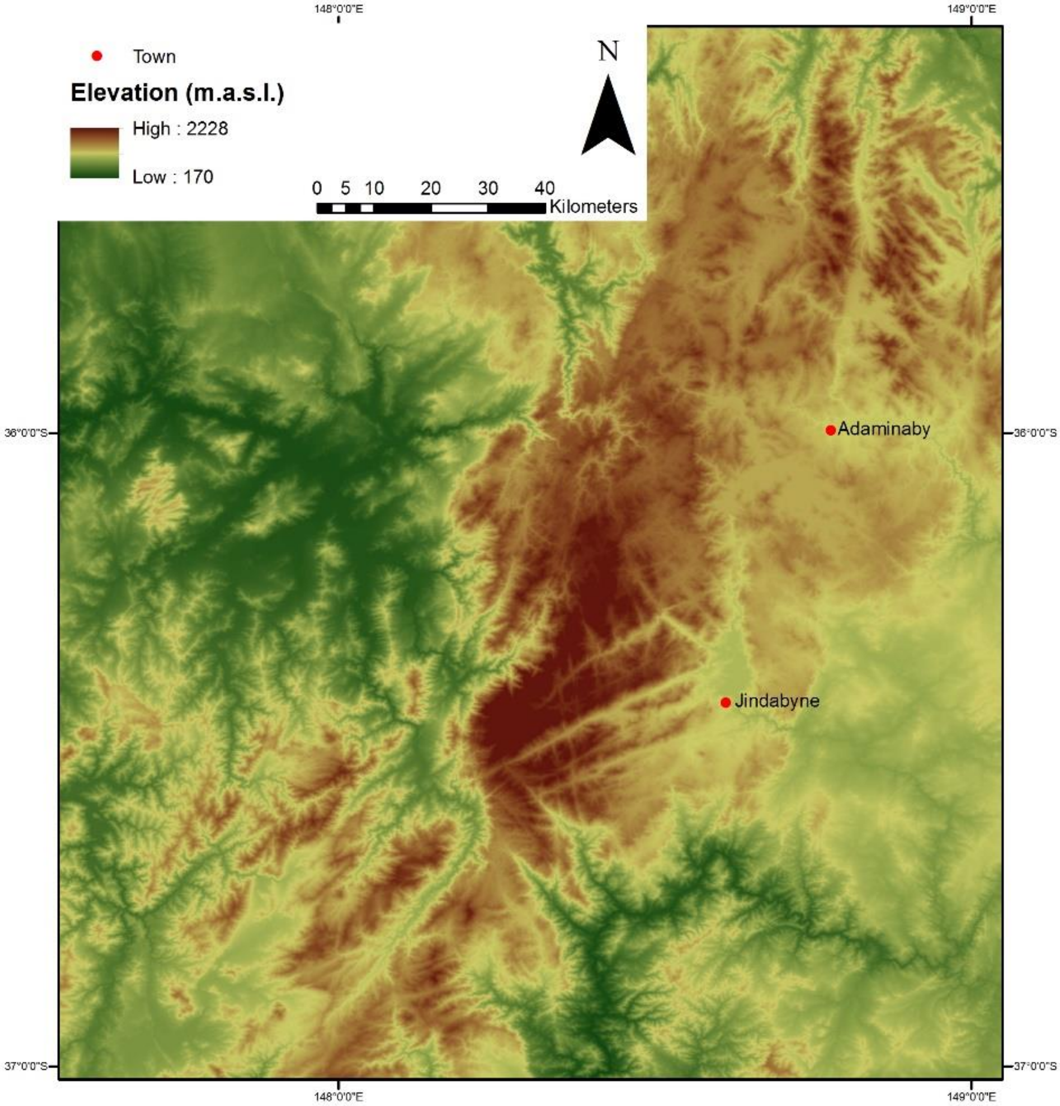


Figure 20. A DEM of the Snowy Mountains showing the large amount of elevated land (Geoscience Australia 2011b)

Surface geology of the Snowy Mountains (Fig. 21) consists of Ordovician to Devonian (487-416 Ma) sedimentary rocks (Sharp 2004), Silurian and Devonian (444-416 Ma) granodiorites (Barrows et al. 2001; Sharp 2004) and a belt of Ordovician meta-turbidites (Barrows et al. 2001). Neogene and Paleogene basalts as well as metamorphic rocks such as amphibolite and intrusive igneous rocks such as diorite and monzonite can be found in the northern section of the study area, as can areas of limestone (Fig. 21, Gill and Sharp 1956).

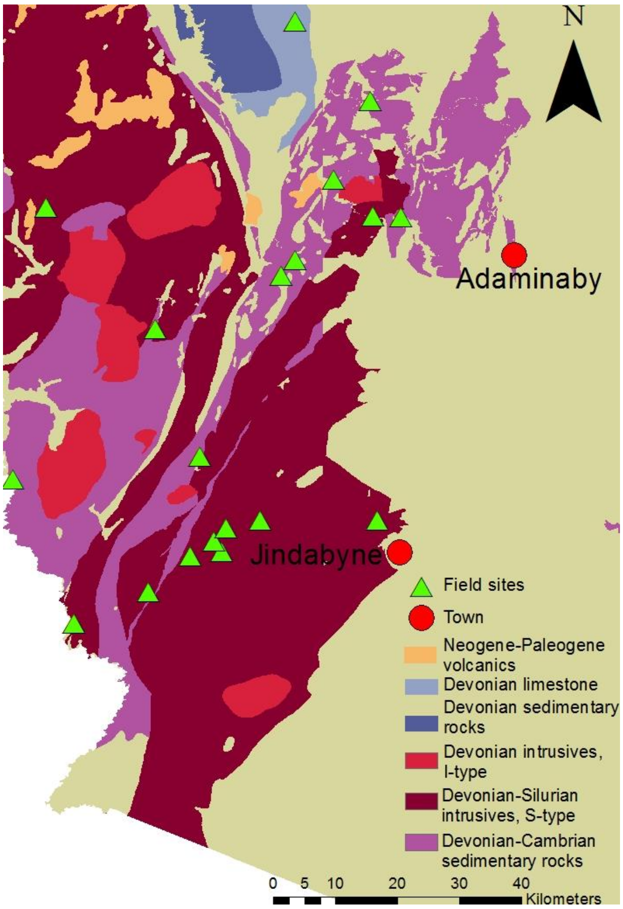


Figure 21. Surface geology map of the study area. Data source: (Scheibner 1998; Geological Survey of NSW 2003)

In Australia, uplift of the current highland areas occurred somewhere around the mid-Cretaceous, either between 120-90 Ma (Müller et al. 2016) or around 80 Ma (Van Der Beek et al. 1999), approximately the same time that the Rocky Mountains were pushed into existence in the USA (Maxson and Tikoff 1996). The uplift of the Snowy Mountains occurred during a time when rifting of the Tasman Sea and Bass Strait caused a lowering of base level leading to a re-energizing of river systems and carving of river valleys (Van Der Beek et al. 1999). By the mid to late Cretaceous (~100 Ma), subduction of eastern Gondwana ceased. This lead to further periods of tectonism linked to the dynamic rebound of eastern Australia in the Cenozoic (Müller et al. 2016), specifically during the Paleogene (65-23 Ma) (Van Der Beek et al. 1999) and again during the Neogene (23-2.588 Ma) (Webb et al. 2011). The various periods of uplift and denudation caused drainage diversion and river reversal leading to the current circuitous drainage pattern of rivers such as the Snowy and the Murrumbidgee (Van Der Beek et al. 1999). What is clear is that the Snowy Mountains were already old when the Southern Alps of New Zealand were born 25 million years ago (Grapes and Watanabe 1992; Coates 2002).

During the Neogene uplift rates of 0.18-0.25 mm/y raised the Snowy Mountains to their current height (Webb et al. 2011) which is rapid for a passive margin situation. In comparison, uplift rates in the Transantarctic Mountains are 0.095-0.105 mm/y (Gleadow and Fitzgerald 1987), and along the Atlantic coast of the US are 0.002-0.13 mm/y (Pazzaglia and Gardner 1994), but they are slow compared to the tectonically active Southern Alps of New Zealand which are rising at 6-9 mm/y near Franz Josef Glacier (Little et al. 2005).

Erosion rates are slow in the Snowy Mountains, 0.003 mm/y (Barrows et al. 2001), compared to the Rocky Mountains in the US at 0.075 mm/y (Dethier et al. 2014) and 5-7 mm/y in Taiwan (Siame et al. 2011). Erosion occurs slowly because Australia is relatively tectonically inactive, has low relief and was only subjected to minimal glaciation throughout the late Quaternary (Barrows et al. 2001). In the Snowy Mountains, areas with granite lithology have weathered producing the deepest soils and those with quartzite lithology have the shallowest soils (Kirkpatrick et al. 2014).

3.3 Climate and vegetation

The Snowy Mountains study area is an alpine region located in a temperate climate zone (Fig. 22). The comparison east coast rivers are in the same temperate zone, and the comparison semi-arid rivers are in the semi-arid grassland climate zone. The Snowy Mountains receives the bulk of its annual precipitation during the winter when humidity is also at its highest (Fig. 23.b-d). Snow is possible at any time of year, but mostly falls between the months of June and October. The summer months occur December through February (Fig. 23.a), when afternoon thunderstorms bringing periods of intense rain are possible. Mean daily temperatures at the top of the Thredbo ski area in the southern portion of the study area range from -5 to 16^{o}C, while in the north at Cabramurra, they range from -1 to 22^{o}C (Australian Bureau of Meteorology 2015).

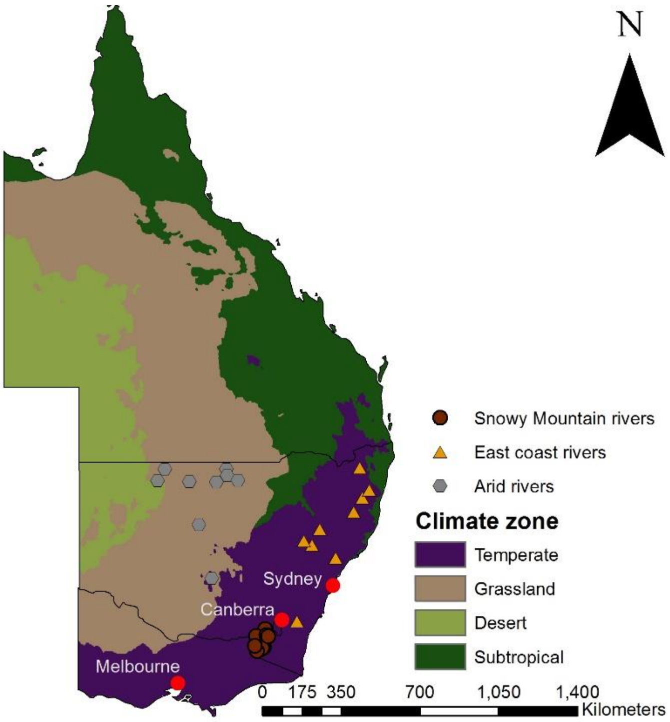


Figure 22. A map of the Köppen climate zones of New South Wales (Australian Bureau of Meteorology 2001)

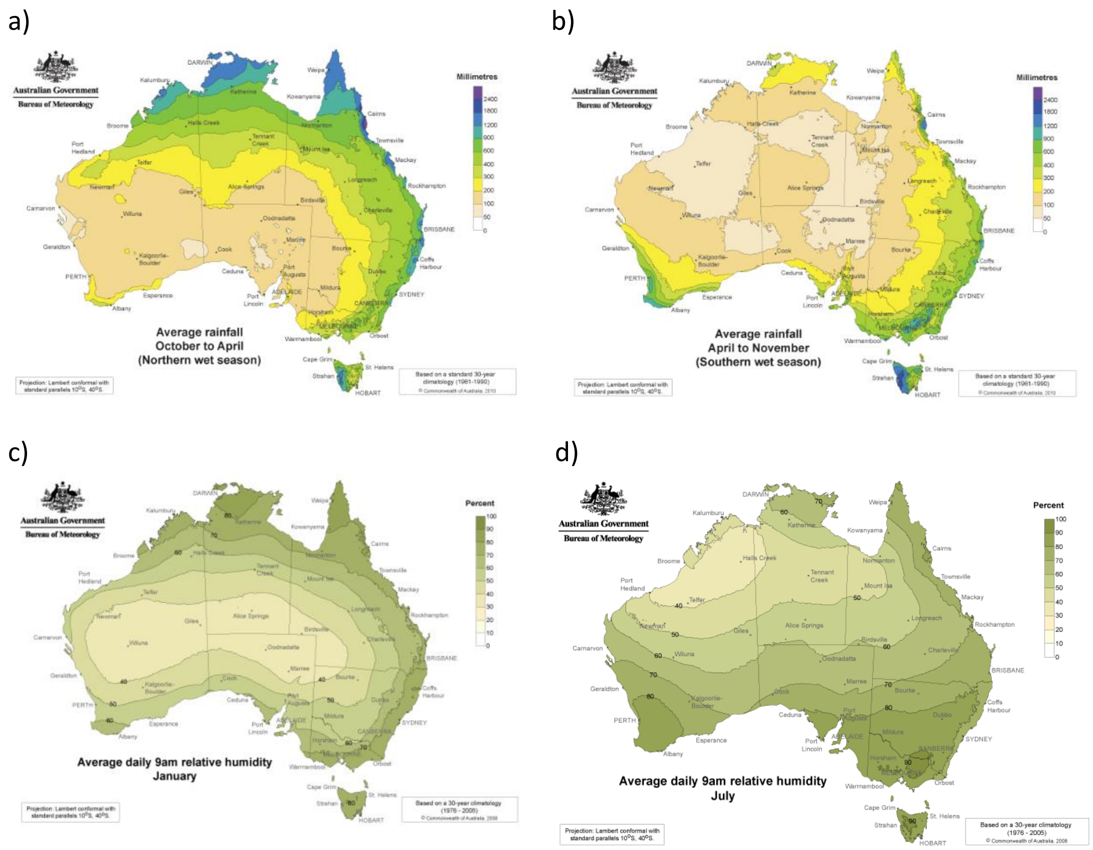


Figure 23. highlights that the Snowy Mountains study area receives the bulk of its precipitation during the more humid winter months (b, d), while the comparison east coast and arid rivers receive more rainfall through the comparatively less humid summer (a, c). (Source: Australian Bureau of Meteorology 2015)

The climate in the Snowy Mountains is influenced by the north-south orientation of the range which creates a barrier for weather moving in from the west. Abrupt elevation gains of over 1500 m in the space of around 20 kilometres cause significant orographic precipitation to occur. Mean annual precipitation over the study area is 1648 mm/y with larger annual totals falling at higher elevations (Fig. 24). The Snowy River at Guthrie site has an elevation of 1655 m and receives the most precipitation with 2177 mm/y in contrast to Maragle Creek at Maragle which has an elevation of 384 m and receives 1092 mm/y (Australian Bureau of Meteorology 2015). The months with consistently higher precipitation are those in the latter half of the year.

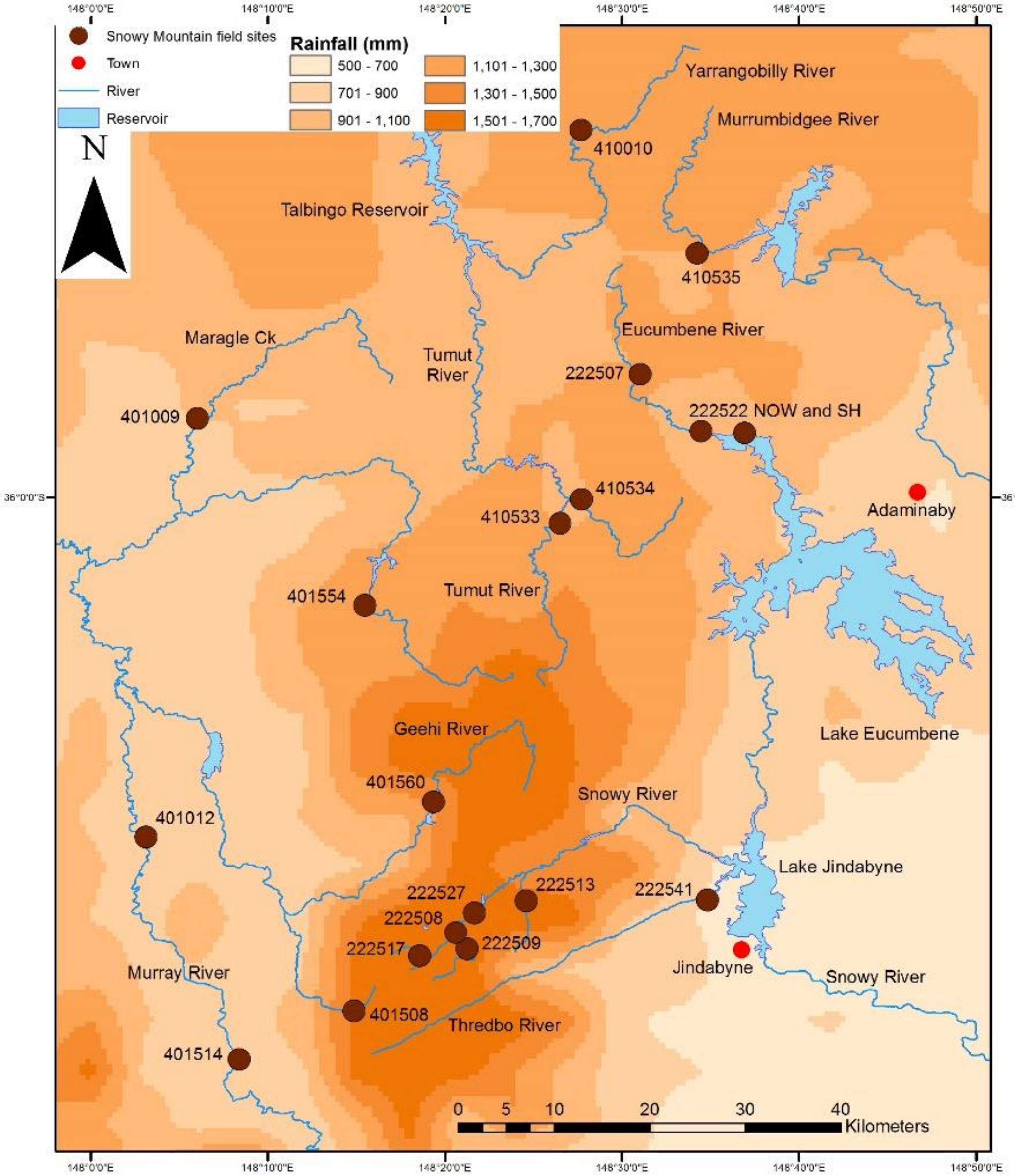


Figure 24. Mean annual rainfall over the study area. Data source: Bureau of Meteorology (Australian Bureau of Meteorology 2007)

In the Snowy Mountains, freshly fallen snow contains approximately 20-25% water; therefore 10 cm of snow has a water content of 2-2.5 cm. Over time, as the snowpack settles, it becomes denser resulting in an increase in water volume. The snowpack in the region contains 25-50% water, therefore a 1 m snowpack will contain 25-50 cm of water (Snowy Hydro Limited 2014). The Snowy Scheme receives 50% of its inflow during the spring months due to the combination of snowmelt and rain on snow events (Snowy Hydro Limited 2014). Peak discharges for the rivers in the study area occur between August and November (NSW Office of Water 2012) as shown in Figure 25. These trends may change in the future because the Snowy Mountains are seeing a reducing trend in snowfall as temperatures in the area increase. By 2020, maximum snow depth levels are predicted to decline by 5 to 50% at elevations above 1600 m and by 15 to 80% below 1600 m, and peak annual maximum snow depth is predicted to occur earlier in the winter (Hennessy et al. 2008).

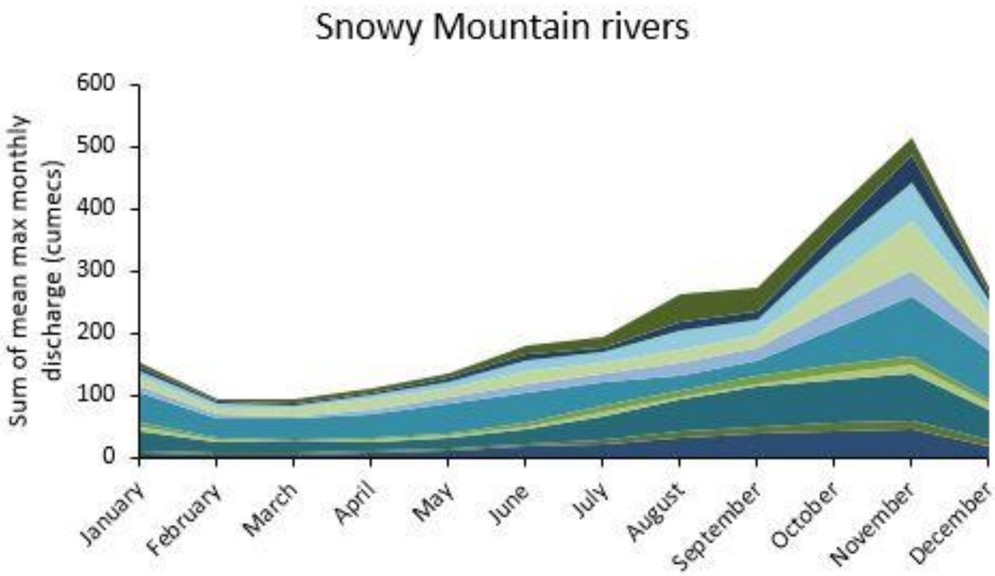


Figure 25. Stacked area graph highlighting the seasonal discharge pattern of Snowy Mountains rivers. Data source (NSW Office of Water 2012).

Vegetation in the Snowy Mountains includes eucalyptus trees and shrubs in the subalpine zone, then graduating from shrubs to various grasses and herbs in the alpine zone. Vegetation species have changed over the millennia. During the Neogene and Paleogene, the climate in the Snowy Mountains was warm and humid as evidenced by broad leaf vegetation fossils found in the Kiandra region (Gill and Sharp 1956) with beech (*Nothofagus*) and conifers (*Dacrycarpites australiensis*, *D. florinii* and *Microcachrydites antarcticus*) once populating the area. Currently treeline occurs at approximately 1830 m and vegetation includes eucalypt forest. *Eucalyptus pauciflora* subspecies *niphophilia* are found at the higher elevations (McVean 1969) (Fig. 26.d), *E. delegatensis* and *E. dalrympleana* grow between 1250-1550 m while *E. fastigata, E. viminalis, E. macrorhyncha and E.* rossii grow below 1250 m (Fig. 26.e, Costin & Polach 1971). Shrubs such as *Grevillea australis*, *Olearia algida* and *Ozothamnus alpinus* may be found in the region (Green et al. 2014). Above 1500 m snow grasses become more dominant, the three-major species are *Poa costiniana, Poa heimata* and *Poa fawcettiae*, these grasses grow in clumps and tussocks and become more stunted with altitude (Figs. 26.a-b). The Snowy Mountains feature internationally important wetland areas including those at Blue Lake which are on the RAMSAR list (Australian Government Department of the Environment 2013). Growing in the wetter alpine bog areas are sedges such as *Carex imcomitata* (Warren and Taranto 2011; Green et al. 2014). Because Australian alpine vegetation includes a large amount of nitrogen fixing plants, Australian alpine soils have significantly higher levels of nitrogen than overseas alpine regions (Kirkpatrick et al. 2014).

a)

b)

c)

d)

e)

Figure 26. a) Stunted alpine grasses and herbs are found in the high alpine at elevations of around 2000 m. b) low perennial vegetation and tussock grasses dominate elevations of approximately 1900 m such as by Cootapatamba Creek. c) Dense low vegetation around 1800 m at Club Lake Creek. d) Eucalyptus trees populate the country around the Snowy River at 1650 m. e) Eucalyptus forest and farmland surround the lower portions of the western Snowy Mountains such as at Tom Groggin on the Murray River, elevation 500 m.

3.4 Glaciation in the Snowy Mountains

Australia does not currently have glaciers and historical ice sheets were globally speaking, very small. On mainland Australia, the previous climate was once cold enough that the prevailing northwest to south-westerly winds combined with orographic precipitation to create glaciers in south facing cirques in the high country (Barrows et al. 2001). The Early Kosciuszko glaciation known as the Snowy River Advance (approximately 60 ka) was followed by the Late Kosciuszko glaciation; this latter period occurred in three stages with peaks 32 ka (Headly Tarn), 19 ka (Blue Lake) and 17 ka (Mt Twynam) (Barrows et al. 2001). The glaciations became progressively smaller with time so that during the last glacial maximum (LGM) only the higher peaks had ice (Barrows et al. 2002). However even during their peak, glaciers only covered an area of approximately 15 km^2 above the Snowy River. The largest glacier was approximately 1.7 km long and flowed from the Blue Lake cirque on Mt Twynam toward the Snowy River. After the LGM (22 ka), melting and deglaciation was rapid and none of the cirques had ice at the start of the Holocene. No ice has reappeared since that period (Barrows et al. 2002). Today evidence of previous glaciers can be seen in locations such as Blue Lake (Fig. 27) and periglacial (freeze/thaw) activity occurs mostly above the tree limit.

Figure 27. Glacial lakes remain in the Snowy Mountains at locations such as Blue Lake by Mt Twynam

3.5 Historical land use of the Snowy Mountains

The Snowy Mountains form the bulk of Australia's high country and as with high elevated areas in other countries, they have drawn protagonists and dreamers for centuries. Two Aboriginal groups lived in the Snowy Mountains, the Walgal people in the north by Kiandra, and the Ngarigo in the south (NSW Office of Environment & Heritage 2011). For over 20,000 years, aboriginal people from what is now southern NSW gathered in the alpine during summer months to strengthen social bonds and feast on Bogong moths (*Agrotis infusa*) that estivate in the area. Aboriginal people were followed by European adventurers looking to put the high country onto the map, by pastoralists seeking summertime high ground for their stock, by gold miners searching for wealth and notoriety and by tourists hoping for scenery and fresh air.

Sheep and cattle were introduced to the Snowy Mountains in the 1830s (Scherrer and Pickering 2005). In the following decades stock was moved into the alpine for the duration of the summer months (NSW Office of Environment & Heritage 2011). Prior to this time, the high alpine country had not been majorly affected by human activity (Scherrer and Pickering 2005). Poor management

and farming practices such as high stock numbers led to increased erosion and major changes in vegetation cover. These problems were further exacerbated using fire to “improve” pasture lands and remove unpalatable snow grasses such as *Poa*. Damage caused by grazing was long lasting because alpine plants experience a harsh climate with a short growing season (Scherrer and Pickering 2005). Grazing and pasture management ceased around Mt Kosciuszko in 1944, followed elsewhere in the alpine region by 1958.

Gold was first discovered in the Snowy Mountains in the early to mid-1850’s (Gill and Sharp 1956; Kaufman 2002) and then in 1859 sheep graziers found viable deposits in tertiary sediments by Kiandra (Fig. 28). This led to much excitement and by 1860 an estimated ten thousand miners had arrived in the region (Kaufman 2002). Although much of the mining focus was in the area around Kiandra, many smaller sites were spread throughout the region. Environmental Impacts of mining weren’t only limited to erosion caused by excavating, dredging and sluicing; towns were created, roads and tracks were blazed and cropping and sawmilling supported the miners (Kaufman 2002). The peak of the gold mining boom occurred in the early 1860’s and was short-lived as surface alluvial deposits were quickly exhausted. Hydraulic sluicing and bucket dredging prolonged mining for several decades, however production levels were low. Mining for other metals such as copper and silver continued in areas such as Yarrangobilly while further short term gold mines occurred at Maragle in 1874. By 1920 mining operations in the area had mostly ceased (Kaufman 2002).

Figure 28. The Kiandra goldfields were in the region around the Eucumbene River

Although time has softened the visual impacts of mining sites, the effect of gold mining in Australia’s high country persists. In Victoria, children living in towns by historical gold mining areas have been found to have elevated levels of arsenic (Martin et al. 2013). Arsenic occurs in sulphide minerals such as arsenopyrite which may be found in tailings dumps from gold mines. Bogong moths migrating north after spending their summer estivating in the Snowy Mountains have been sampled with elevated arsenic levels in their systems (Green 2008). While individual moths only have small amounts of arsenic, levels in the soil around summer estivation areas were found to be concentrated to phytotoxic levels.

Skiing was introduced to Australia by gold miners in 1861 (Kaufman 2002) and the Kiandra Ski Club claims to be the oldest of its kind in the world (Lennon 2003). Skiing has expanded into a large tourism industry that endures today and in NSW there are four major ski areas with associated infrastructure such as villages and an underground train.

Australia's current national psyche includes a bond to the high country built through famous literature and film titles such as "The Man from Snowy River", a story that glorifies pastoralism in the mountain regions, and through engineering projects such as the Snowy Hydro Scheme. These elements of the national psyche demonstrate a situation where cultural values are in opposition to conservation needs, for example, wild horses are relics of pastoralism and still cause environmental degradation and management issues in the region. Pastoralism was also partly responsible for the cessation of Aboriginal influence in the Snowy Mountains as the Bogong moth harvest no longer occurs and the connection to sacred sites has been dimmed.

3.6 Background on the Snowy Hydro Scheme

Construction of the Snowy Hydroelectric scheme occurred between 1949 and 1974 (Domicelj, 1980; Reinfelds et al., 2014). At the time the Snowy Hydro Scheme was one of the world's largest and most complex hydro-electric and irrigation projects ever undertaken (Hardman, 1968).

The aim of the scheme was to divert flows from the Snowy River and its tributary the Eucumbene, on the eastern side of the Great Dividing Range, through trans mountain tunnels to the Murray and Murrumbidgee rivers on the west for the purpose of town-water supply and irrigation (Snowy Hydro Limited, 2014). The Snowy Hydro Scheme covers an area of over 5000 km^2 (Hardman, 1968) and has a generating capacity of 4100 megawatts. Costing US$900 million, the project includes nine power stations, 16 dams, a pumping station and 225 km of tunnels and aqueducts. The scheme generates electricity by dropping water over a total elevation loss of approximately 800 m and it supplies irrigation water to the Murray and Murrumbidgee river plains through reservoirs (Domicelj, 1980; Erskine et al., 1999; Snowy Hydro Limited, 2014). The Snowy River was once Australia's greatest snowmelt river, flowing from its headwaters under Mt Kosciuszko in NSW to the coast in Victoria. Prior to the enlarged environmental flow program that began in 2002, 130 GL per year or 99% of the Snowy Rivers discharge was diverted through the scheme (Morton et al., 2010).

3.6.1 Conceptualization of the plan

The Snowy Hydro Scheme was proposed in response to seven major droughts which occurred in the period 1864-1945, with a particularly severe one from 1895-1903 during which wheat yields suffered drastically and sheep and cattle mortality were 50% and 30% (Hardman, 1968). The Snowy Mountains were seen as an "endowment from Nature" whose snow fed waters could protect the rich farmlands of the Monaro region from the hardships of drought (Hardman, 1968) while at the same time furthering Australia's "nationhood" (Domicelj, 1980). An open canal that would divert water from the Snowy River into the Murrumbidgee was first suggested in 1884 (Hardman 1968). The project began to gain interest; however, the proposed cost of construction and maintenance was off putting so alternative options were sought. Studies of the hydrology of the Murrumbidgee and Murray River's began in 1896 to determine canal and water storage opportunities in those localities and over the following decades, as wet years followed drought, perceived levels of importance of all such projects waxed and waned (Hardman, 1968).

The potential of the Snowy River as a source for hydropower was first discussed in 1904 when a town on its banks, Dalgety, was the leading contender in the search for the site of Australia's capital city. The hydropower plans sat idle after Canberra was instead nominated to become the federal capital. New plans re-emerged in 1920, with dreams of a series of dams and tunnels in the area around Jindabyne, a scheme that would potentially produce 24,000 kW of electricity. The plans were

shelved once more, until 1937 when options to meet the electrical needs of a growing population were considered, however farmers were opposed to the idea of using valuable irrigation water solely for the purpose of electricity generation and the plans stalled again (Hardman, 1968). During the same period, the Snowy River was being considered as a source of water for Sydney with another series of tunnels and pipelines proposed. Eventually this plan was scrapped in favour of the Warragamba Dam which would be located closer to Sydney in the Hawkesbury-Nepean catchment, but it was through these studies that a plan linking power generation and irrigation by diverting the Snowy River into the Murrumbidgee River was proposed (Hardman, 1968).

There were conflicting opinions in how to best utilize waters from the Snowy River. Victoria was most interested in power generation and suggested the waters be diverted into the Murray River, while NSW prioritized irrigation and preferred the waters to be diverted into the Murrumbidgee River. Eventually in 1946, a compromise plan was forged, with waters from the upper Eucumbene, the Tooma and the upper Murrumbidgee Rivers (tributaries of the Snowy, the Murray and the Murrumbidgee itself) diverted into the Tumut River, a tributary of the Murrumbidgee to enable irrigation as per the wishes of NSW. A second part of the plan decreed that waters from the upper Snowy and its tributaries would be diverted into a series of storages before flowing into the Murray, enabling the generation of electricity as proposed by Victoria. The project was officially opened for construction in October 1949 (Hardman, 1968).

3.6.2 Construction and effects of the Snowy Hydro Scheme on regional Australia

The Snowy Hydro Scheme is the largest engineering project in Australian history and contributed greatly to the nations multicultural identity (Lennon 2003). The project impacted the region through the creation of roads, infrastructure and towns such as Cabramurra and Khancoban which housed many of the workers. To make way for reservoirs, communities such as Jindabyne and Adaminaby were relocated and the towns flooded. The Snowy Hydro Scheme played a role in the conversion of the Kosciusko State Park into the Kosciusko National Park in 1966, through its goal to protect water catchment areas within its project boundary (Domicelj 1980; Pearson 2005). Ten years later it was recognized by UNESCO as an “International Biosphere Reserve”. The name of the park was misspelt until 1997 when it was changed to Kosciuszko.

Over the entire phase of construction, the Snowy Hydro Scheme employed 60,000 people (Lennon 2003) with a peak of 7,300 workers during 1959 (Domicelj 1980). Because many of the workers were European immigrants, the scheme played an enormous role in the building of Australia’s multicultural society. Located approximately halfway between Sydney and Melbourne, the project promised plentiful water for irrigation and electricity in a country known for its limited rainfall and it was thought that it would allow for a decentralization of population development (Domicelj 1980). Through the Snowy Hydro Scheme, approximately 2,600 km^2 of arid land became irrigated for agriculture. Since the projects construction, the region has become a major provider of foods such as grapes, citrus and rice and by the 1980’s contributed over US$600 million to the Australian economy (Domicelj 1980).

3.6.3 Effects of the Snowy Hydro Scheme on the environment

Many of the common environmental impacts discussed in chapter two occurred in the Snowy Mountains as a direct result of the Snowy Hydro Scheme. The Snowy River has three dams and has had its flow diverted into other catchments. Between 1967 and 2002 flow diversions resulted in

discharge volumes of only 1% of the rivers mean annual natural flow below the Jindabyne Dam (Rose and Erskine 2011). The greatly reduced flow led to the changes highlighted by Figure 11 where significant channel reduction and encroachment by vegetation can be plainly seen. Exotic plants such as willows have intruded on the channel due to the reduction in frequency and magnitude of floods (Erskine et al. 1999).

Below the Jindabyne dam, mean annual suspended sediment yield decreased from pre-regulation levels of 62,114 tons/y in 1955-1957 to post-regulation levels of 311 tons/y between 1967-1994 (Erskine et al. 1999). The significant decrease in sediment flux has caused degradation of the channel all the way to the coast.

3.6.4 Momentum for river rehabilitation grows

Since the completion of the Snowy Hydro Scheme, the Snowy River was subjected to massive decreases in discharge. In 1961, the licensing authority deemed it acceptable to release a maximum daily discharge of 0.57 m^3/s below the Jindabyne Dam, a volume 1.6 times smaller than the lowest ever recorded daily discharge at that location (Erskine et al. 1999), and 1/16th of the volume of the natural mean maximum flow by Jindabyne for the month of December, traditionally the month with the largest discharge (NSW Office of Water 2012).

River degradation including loss of habitat due to the many years of low flow became a public issue as more and more people began demanding the health of the Snowy River system be improved. Initially reluctant to reduce electricity production and therefore profits, the Snowy Mountains Hydro-Electric Authority was finally forced into compliance by legislation passed by the NSW State Government in the 1990s (Erskine et al. 1999). This led to the establishment of the Snowy Water Inquiry in 1998 whose mission was to determine the environmental flow needs of the river (Rose and Erskine 2011). Key strategies addressed included the need to recover ecological habitat, restore flushing flows and hydrologic connectivity and improve the overall aesthetic of the river.

3.6.5 Environmental flows

The results of the Snowy Water Inquiry indicated that an increase in discharge below the Jindabyne dam was needed. This was to be implemented over a 10-year period, beginning in 2002, so that by 2012, 28% of the Snowy River's mean annual natural flow levels would be reached. Unfortunately a prolonged drought occurred in the early 2000's resulting in flow targets not being met (Rose and Erskine 2011). The plan was further developed by the Snowy Scientific Community who called for the implementation of the building block method for determining and managing environmental flows. This bottom-up strategy considers each component of the river systems water needs and adjusts them proportionally to add up to the total amount of water allocated for the environmental flow program. The building block method has since been improved on through the creation of the "natural flow scaling" system (Reinfelds et al., 2014). The natural flow scaling method is the current approach and has the dual purpose of mimicking natural hydrologic variability while scaling environmental water volumes available to the managed river. Today, the Snowy River's environmental flow discharge pattern is modelled on the variability and seasonality of the unregulated Thredbo River which was chosen as a suitable analogue to the Snowy due to similarities in catchment elevation and discharge.

Chapter - 4 Methods

4.1 Data acquisition

Data was accessed through the NSW Office of Water and Snowy Hydro Limited Hydstra hydrological databases (Table 4). From these resources, 18 sites were chosen by using the following criteria: unregulated streams with a minimum of 10 years of stream discharge and corresponding stream water level data for sites that covered a range of catchment areas across an altitudinal gradient that controls snowpack accumulation and snowmelt runoff volumes. Catchment areas of the selected gauges cover several orders of magnitude from 4.8 km^2 for Club Lake Creek at Clarke to 1256 km^2 for the Murray River at Biggara (Appendix 1). Data from 18 unregulated non-snowmelt rivers was also accessed to enable comparison with the Snowy Mountain gauges. Nine rivers located close to the east coast of NSW with a similar range of catchment areas to those in the Snowy Mountain study zone were chosen, as well as nine sites on semi-arid NSW rivers. The semi-arid sites had a broader range of catchment areas ranging from 15 km^2 to over 60,600 km^2.

Where historical cross-section data was lacking, field surveys were undertaken during March and April 2015, using either a total station or electronic level to gather cross-sectional data (Table 4). The purpose of the surveys was to determine channel geometry within the reaches around the gauging stations to enable an assessment of relationships between stream discharge, channel width, depth and cross-sectional area. Reach length was calculated as 10 times the mean channel width and included pool/riffle sequences (Williams 1984; Montgomery and Buffington 1997; Wohl and Merritt 2005). Multiple cross-sections were surveyed at riffle crests and were conducted in alluvial reaches as close to the current or historically active gauging station as could be determined so that the channel geometry data could be matched with the corresponding discharge and velocity data for each site.

Table 4. The source of the field and gauge data used for each study site

Site	Cross-section data source	Gauge data source
Murray River at Biggara	NSW Office of Water	NSW Office of Water
Maragle Ck at Maragle	NSW Office of Water	NSW Office of Water
Yarrangobilly River at Yarrangobilly	NSW Office of Water	NSW Office of Water
Club Lake Ck at Clarke	Field survey	NSW Office of Water
Cootapatamba Ck at Ramshead	Field survey	NSW Office of Water
Spencers Ck at Paralyzer	Field survey	NSW Office of Water
Snowy River at Guthrie	Field survey	NSW Office of Water
Perisher Ck at Blue Cow	Field survey	NSW Office of Water
Murray River at Tom Groggin	Field survey	NSW Office of Water
Eucumbene River at Kiandra	Unavailable	NSW Office of Water
Eucumbene River at Providence	Unavailable	NSW Office of Water and Snowy Hydro
Murrumbidgee River above Tantangara Dam	Snowy Hydro	Snowy Hydro
Crackenback River at Paddy's Corner	Snowy Hydro	Snowy Hydro
Snowy River above Guthega Dam	Snowy Hydro	Snowy Hydro
Tooma River above Tooma Reservoir	Snowy Hydro	Snowy Hydro
Tumut River above Happy Jacks Pondage	Snowy Hydro	Snowy Hydro
Happy Jacks River above Happy Jacks Pondage	Snowy Hydro	Snowy Hydro
Geehi River above Geehi Reservoir	Snowy Hydro	Snowy Hydro

4.2 Data analysis

4.2.1 Spatial analysis

The Geoscience Australia 1-arc second smoothed SRTM derived digital elevation model (DEM) with a cell size of 30m and the Geofabric stream and catchment layer produced by the Australian Bureau of Meteorology were used for topographic analyses including reach average channel slope determinations (Geoscience Australia 2011; Australian Bureau of Meteorology 2012). Examination and enquiry of GIS data was undertaken using ArcGIS 10.2 (Esri 2013). Individual rivers were extracted from the Geofabric (Australian Bureau of Meteorology 2012) beginning at the highest point of the stream network, down to each rivers confluence with the trunk stream, where the river entered a lake/reservoir or downstream of the gauge site. So that the channels could be categorized by gradient, long-profile and reach-scale slope were calculated using the DEM in ArcGIS 10.2. Contributing catchment area was determined using the DEM to enable morphological examination of mean channel width against catchment area and hydrological analysis such as runoff coefficients.

4.2.2 Valley confinement, channel morphology and hydraulic geometry

One of the major controls on river morphology is valley confinement (Fryirs et al. 2016). The extent of valley confinement determines the scope for channel adjustment and does so over timeframes of centuries to thousands of years (Fryirs et al. 2016). Valley confinement may be categorized as confined, partly-confined or laterally-unconfined and rivers in partly-confined valleys are controlled to a greater or lesser extent by bedrock (Fig. 29.a-d. Fryirs et al. 2016). The distinguishing factor between each category is the percentage of bedrock along channel margins. In a confined-valley setting channel margins are comprised of a minimum of 90% bedrock, bedrock-controlled partly-confined settings include 50-90% bedrock, planform-controlled partly-confined settings have 10-50% bedrock and laterally-unconfined settings have less than 10% bedrock within the channel margins (Fryirs et al. 2016). An understanding of the level of valley confinement at each site location enabled appreciation of factors contributing to channel morphology in the Snowy Mountains region. The study sites were categorised as confined, partly confined or laterally-unconfined through inspection using Google Earth to differentiate hillslopes from areas containing alluvial deposits. For this analysis, hillslopes were assumed to be bedrock, and alluvial deposits were not.

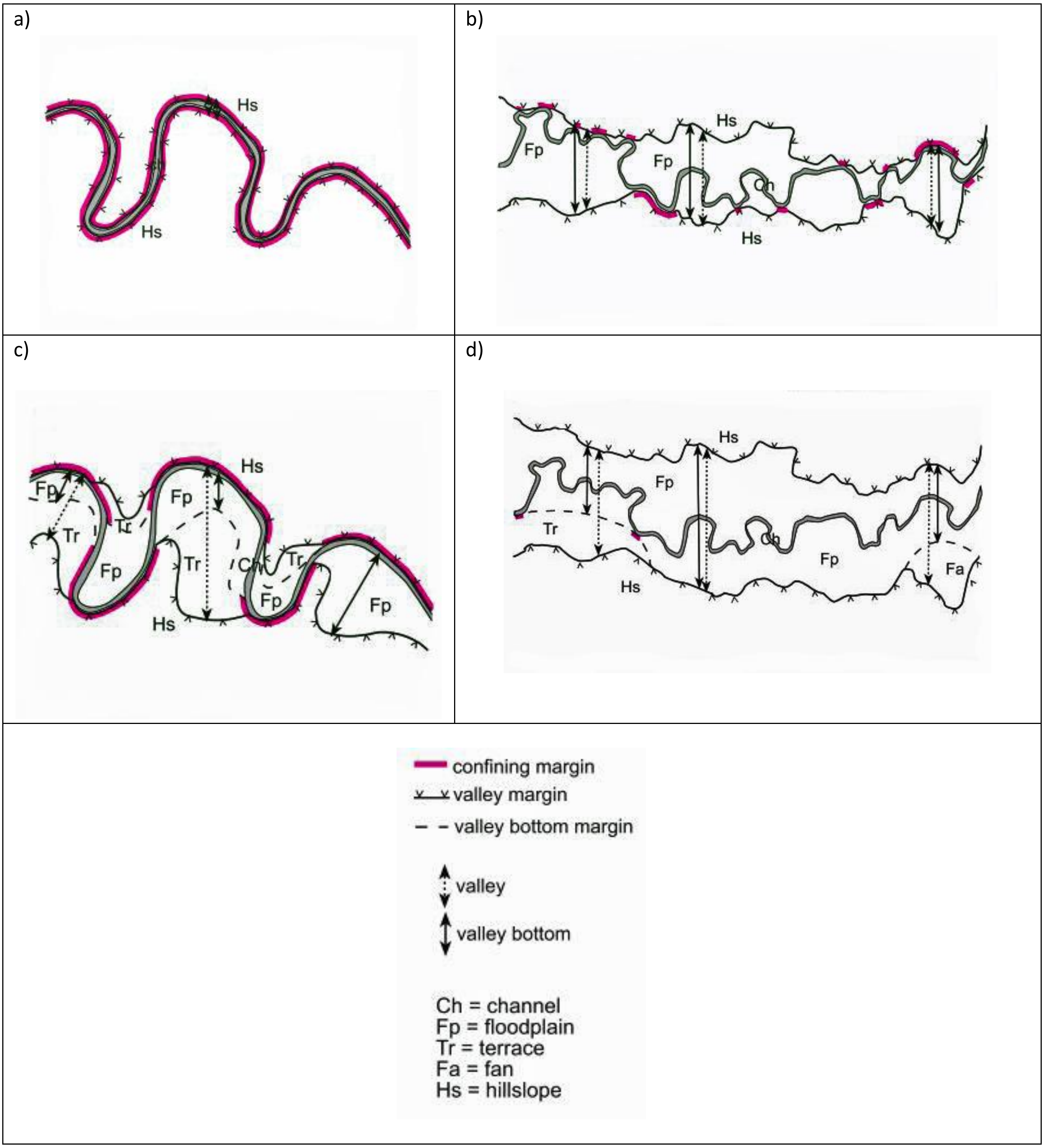


Figure 29. Rivers in a a) confined-valley setting, b) planform-controlled partly-confined valley setting c) bedrock-controlled partly-confined valley setting, d) laterally-unconfined, alluvial dominated setting. Source: (Fryirs et al. 2016)

Relationships between channel characteristics and catchment area were explored. As catchment area increases, the percentage of land with low angled slopes increases (Leopold and Maddock 1953) and therefore channel slope tends to decrease in a downstream direction. It is also common for cross-sectional area to increase as catchment area and discharge increase (Leopold and Wolman 1960). To verify that the study rivers conform to these broad relationships, long profile channel

gradient and channel cross-sectional area were calculated in ArcGIS using the 1-arc second DEM. The channel cross-sectional area was calculated using simulations in the freeware program Channel v0.07. The simulations used the default Manning's n value of 0.05 and the individual reach slope calculated via spatial study. The channel was filled to the height of the 2-year flood and cross-sectional area was computed.

Channel classification provides a link between form and process where alluvial channel morphology is influenced by hydrological processes (Kasprak et al. 2016). In addition to long profile channel gradient, reach-based channel gradient was calculated to determine if the study rivers and reaches had gradients equal to or greater than 0.002m/m and could therefore be classified as mountain streams (Wohl 2004). For further categorization, the channels within the study area were considered using the mountain stream classifications proposed by Montgomery and Buffington (1997) and Wohl and Merrit (1997). Table 5 illustrates these categories.

Table 5. A synthesis of the features of mountain stream classifications by (Montgomery and Buffington 1997; Wohl and Merritt 2005)

Feature	**Cascade**	**Step-pool**	**Plane-bed**	**Pool-riffle**
Bed material	Boulder	Cobble-boulder	Gravel-cobble	gravel
Valley confinement	Confined	Confined	Variable	Unconfined
General bed form	Disorganized	Longitudinally stepped	Relatively uniform	Undulating
Channel gradient (m/m)	≥0.065	0.03-0.065	0.015-0.03	≤0.015

Because rivers in natural settings demonstrate local variability, there will be occasions when a channel does not fit cleanly inside the proposed classifications. For this reason, Montgomery and Buffington (1997) suggested the possibility of "intermediate" categories, in particular cascade-pool and riffle-step (Montgomery and Buffington 1997). These categories were expanded on by Thompson et al. (2006) who suggested that cascade-pool channels occur between gradients of 0.04-0.12 m/m. They share similarities to pool-riffle reaches with alternating morphological features but have a coarser gain size with boulders rather than gravel creating the cascades. Riffle-step reaches occur between gradients of 0.02-0.03 m/m and share similarities to the step-pool and plane-bed categories where steps are present but are irregularly spaced (Thompson et al. 2006). Where required, the Snowy Mountain rivers are classified in the intermediate categories.

Hydraulic geometry may be calculated for alluvial streams using at-a-station or downstream analysis approaches (Leopold and Maddock 1953). At-a-station hydraulic geometry exponents are calculated by measuring the water surface width, mean depth and velocity on-site at various stages of discharge within a single cross-section. Downstream hydraulic geometry exponents are determined using multiple cross-sections and gauging stations within a single catchment. At each site, discharges flowing at bankfull height are most often used to establish channel width, depth and velocity. Bankfull height occurs in many streams with a return interval of approximately two years (Wolman and Miller 1960; Jowett 1998; Singh 2003; Segura and Pitlick 2010).

Bankfull flows are those which fill the channel to the point where water begins to spill onto the floodplain. In alluvial channels, these flows engage with sediment in the bed and banks of the channel and are considered to contribute largely to channel and floodplain morphology (Wolman and Miller, 1960; Segura and Pitlick, 2010; Agouridis et al., 2011). For this study, bankfull height was ascertained from the cross-section data and was determined as the height in the channel where there were significant changes in the width/depth ratio, specifically where width increased beyond that point much more rapidly than mean depth (Harvey 1969; Pickup and Warner 1976; Reinfelds 1997). This is demonstrated by Figure 30.

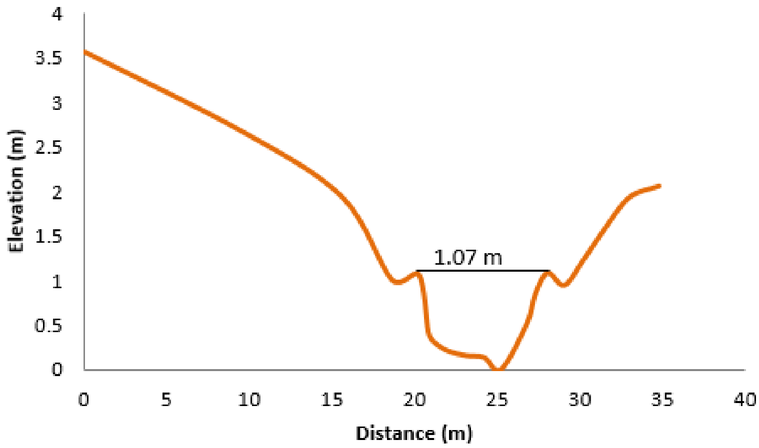


Figure 30. The location of bankfull stage at 1.07 m, on Perisher Creek at Blue Cow as determined by the location where the width/depth ratio changed drastically through little gain in stage.

Velocity data was only available for ten of the eighteen Snowy Mountain sites and so hydraulic geometry calculations were limited to these locations. Each hydraulic geometry variable (width, depth and velocity) was plotted against discharge in log-log fashion. The power trendline graphed represented the mean rate of change for each variable and the exponents highlighted the percentage that each variable contributed to the overall channel geometry (Leopold and Maddock 1953). The calculation of the exponents was done using the power functions proposed by Leopold and Maddock (1953):

$$w = aQ^b$$
$$d = cQ^f$$
$$v = kQ^m$$

Where w = channel width, d = mean channel depth, v = velocity, Q = mean period discharge and a, c and k are coefficients. b, f and m are exponents and represent the slope of the line when each parameter is plotted against discharge.

4.2.3 Hydrological analysis

An appreciation for the factors contributing to the hydrology of the study and comparison sites was gained on a regional and site specific scale. Average rainfall and humidity data downloaded from the Bureau of Meteorology (BOM) (Australian Bureau of Meteorology 2015) were used to understand climatological drivers behind seasonal discharge patterns. These seasonal patterns were determined by calculating the mean monthly discharge for the period of record at each site. Next, a time-series analysis was undertaken on the Snowy Mountain sites with a minimum of 20 years of discharge data to become aware of long-term trends.

Several unit-less metrics were calculated to understand and compare the flow variability between Snowy Mountain rivers, east coast and semi-arid rivers, as well as between other studies. The metrics calculated were the flash flood magnitude index (FFMI) (Baker 1977; Erskine and Livingstone 1999), coefficient of variation (CV) (Morton et al. 2010) and baseflow index (Gordon et al. 2004). 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 and is a way to determine the flash flood potential of a river (Baker 1977). The CV was calculated for each river that had NSW Office of Water data (Table 4), by dividing the standard deviation of the annual total discharge by the mean. The CV is a measure that allows comparison of inter-annual flow variability between rivers and regions even if there is a large difference in mean values (Morton et al. 2010). A high CV can be expected in rivers that have an unpredictable discharge pattern. A second CV was calculated using mean annual precipitation data for the NSW Office of Water sites. The data was separated by elevation into sites above and below 1500 m to learn if differences in runoff CV's were caused by differences in elevation driven annual rainfall variability. The baseflow index was calculated using the freeware program "River Analysis Package" (RAP) (Marsh et al. 2003). The baseflow index is used to understand the mean low flow of a perennial stream (Gordon et al. 2004).

Flood frequency analysis calculates the probable return period for the flow of a given size. These flows can be expressed as a "1-in-*n*-year" flood and are useful to determine the flow regime of a river. Hydrologists, ecologists and engineers often use flood frequency analysis to understand the regularity with which river features and structures are likely to be inundated (Gordon et al. 2004). Annual maximum series flood frequency analysis using the Log Pearson III (LP3) distribution (Pilgrim 1987; NSW Office of Water 2012) was undertaken on the instantaneous maximum discharge and stream level data using the freeware program "Flike v4.50" (Kuczera 2001) to calculate the magnitude of floods with annual return intervals (ARI) of 1.01-100 years. Flood frequency analysis was also undertaken using the Generalized Pareto probability density function (Rustomji et al. 2009) to establish if the ARI discharge values calculated varied significantly from those predicted by the LP3 model. Flike was also used to complete partial series flood frequency analysis for several sites to determine if the results differed significantly from the annual maximum series. The discharge threshold used for the partial series analysis was the 2-year ARI flood calculated in the annual series. A flood was deemed a discrete event if it was separated from another flood peak by a minimum of three days and so all floods above the discharge threshold and with more than three days separating each event were considered (Pilgrim 1987).

The flood frequency data were used to calculate flood frequency ratio curves (Pickup, 1984; Farquharson et al., 1992) to enable a comparison between differences in relative magnitude for floods of various return periods for each river and region. The flood frequency ratio curves (Qf/Qx – sensu Pickup, 1984) were determined using flows with a return period of two years on the annual maximum flood series.

Floods can be expected to increase or scale in size as catchment area increases. Flow scaling analysis on the mean discharge for rivers with catchments 10-100 km^2 and >1000 km^2 determined the difference in magnitude between a calculated flood of each return interval for each category of catchment scale and provided perspective of how the calculated ARI floods in Snowy Mountain and east coast rivers differed in size. Discharge per unit area relationships were then explored for the Snowy Mountain and east coast regions by dividing the calculated ARI flood by each catchment area.

The aim of the analysis was to understand if the assertion that smaller catchments are relatively more hydrologically productive than larger catchments (Mackin 1963) held true for the study rivers.

Flood frequency analysis was undertaken on stage data to visualise the vertical spread of floods of various ARI's across landforms within each channel. The surveyed cross-sections were plotted with the corresponding level of floods derived from the annual maximum level analyses. This examination enabled comparison of the vertical spread in predicted water levels for the 2 to 20-year ARI flows between each study river and between those of the other regions.

Runoff coefficients provide a useful measure of how a catchment responds to precipitation events by enabling an appreciation of what percentage of the precipitation falling over the catchment enters the river as runoff (Blume et al. 2007). Runoff coefficients are unit-less and so a comparison can be made between rivers and regions. Annual runoff coefficients were calculated in a two-step process, first dividing the mean annual discharge (ML) by catchment area (km^2) to determine the mean annual runoff (mm); then dividing mean annual runoff by the mean annual rainfall (mm) to calculate the runoff coefficient. Event-based runoff coefficients were also calculated using daily discharge data (ML) available from the NSW Office of Water website (NSW Office of Water 2016). Discrete 2, 10 and 20-year flood events were analysed at study area sites with catchment areas ranging from 100-1000 km^2 (Maragle Ck at Maragle) and >1000 km^2 (Murray River at Biggara). For comparison, the analysis was also undertaken on two east coast non-snowmelt rivers having the similar order of magnitude catchment area scales; Timbarra River at Billyrimbah (100-1000km^2) and Shoalhaven River at Warri (>1000km^2). The data were sufficiently long for the Murray River at Biggara and Shoalhaven River at Warri to allow analysis of the 50-year flood events, but this was not possible for the other two sites. The raw daily discharge data (ML/d) were searched for events where a flood peak matched as closely as possible to the LP3 2, 10, 20 or 50-year events calculated previously. Each event was then paired to the corresponding daily rainfall data. The gridded rainfall data for those flood events was accessed via the BOM website (Australian Bureau of Meteorology 2009). Extraction of the BOM data relevant to each catchment was done using zonal statistics routines in ArcGIS Spatial Analyst. Discharge and rainfall data were analysed starting at the day with zero measured rainfall immediately prior to the flood event until the day that the rainfall again reached zero. In four occasions, rainfall measurements did not reach zero between flood events, here the analysis was done until the day that the measured rainfall was at its minimum. Calculation of the event based runoff coefficients was done by dividing the mean period runoff (mm) by the mean period rainfall (mm) (Blume et al. 2007) and a comparison between event-based runoff coefficients, annual runoff coefficients, catchment area and region was made.

Chapter 5 – Results

5.1 Valley confinement and Channel morphology

5.1.1 Valley confinement

The results of the valley confinement analysis found that of the eighteen Snowy Mountain river sites, three were classified as confined, thirteen as partly-confined and two as laterally-unconfined (Table 6). An example of the results is presented in Figure 31. The channel at Cootapatamba Creek at Ramshead can be seen to flow through alluvial sediments without encountering the hillslopes. Through this assessment, the valley setting was determined to be laterally-unconfined. The annotated Google Earth image for each site can be found in Appendix 6.

Table 6. The field sites organised by level of valley confinement

River/reach	Valley confinement
Happy Jacks River	Confined
Geehi River	Confined
Maragle Ck	Confined
Tooma River	Partly-confined
Club Lake Ck	Partly-confined
Tumut River	Partly-confined
Murrumbidgee River	Partly -confined
Perisher Ck	Partly -confined
Snowy River at Guthrie	Partly -confined
Spencers Ck	Partly -confined
Eucumbene River at Kiandra	Partly -confined
Snowy River above Guthega Dam	Partly -confined
Crackenback River	Partly -confined
Yarrangobilly River	Partly -confined
Murray River at Tom Groggin	Partly -confined
Murray River at Biggara	Partly -confined
Cootapatamba Ck	Laterally-unconfined
Eucumbene River at Providence	Laterally-unconfined

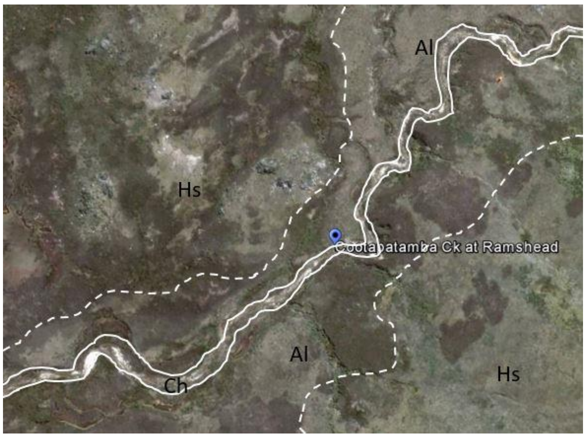


Figure 31. The location of the channel, alluvial surfaces and hillslopes at the field site Cootapatamba Creek at Ramshead. The valley confinement can be classified as laterally-unconfined because the channel is set wholly within alluvial deposits (image by Google and DigitalGlobe 2016).

5.1.2 River classification and channel dimensions in the Snowy Mountains

The results of the channel slope analysis for all eighteen Snowy Mountain rivers are shown in Figure 32 and Tables 7-8. All rivers in the study area have mean gradients more than 0.002 m/m and so may be categorized as mountain streams as per Wohl's (2004) classification. The range in long profile channel slope values is 0.004 – 0.084 m/m and the mean is 0.028 m/m. The reaches range in gradient from 0.007 – 0.126 m/m with a mean of 0.038 m/m. The study rivers behave in a common fashion where, as catchment area increases, mean channel slope decreases (Figure 32). All the Snowy Mountain river sites exhibit the morphological channel forms described by Montgomery and Buffington (1997) and Wohl and Merritt (2005). These categories are cascade, step-pool, plane-bed and pool-riffle also along with the intermediate classes cascade-pool and riffle-step (Fig. 33) that were expanded on by Thompson et al (2006).

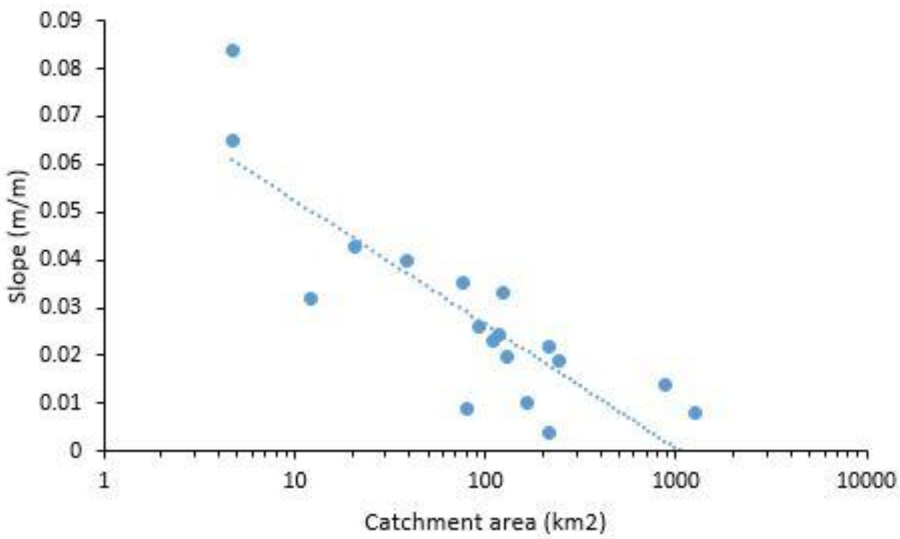


Figure 32. Mean long profile channel gradient for the study rivers, calculated from the DEM as the difference in height from the highest headwater location to the gauge divided by the length of the river. All rivers have a mean gradient more than 0.002m/m and so may be classified as mountain rivers (Wohl 2004). The logarithmic trendline fitted had an R^2 value of 0.71

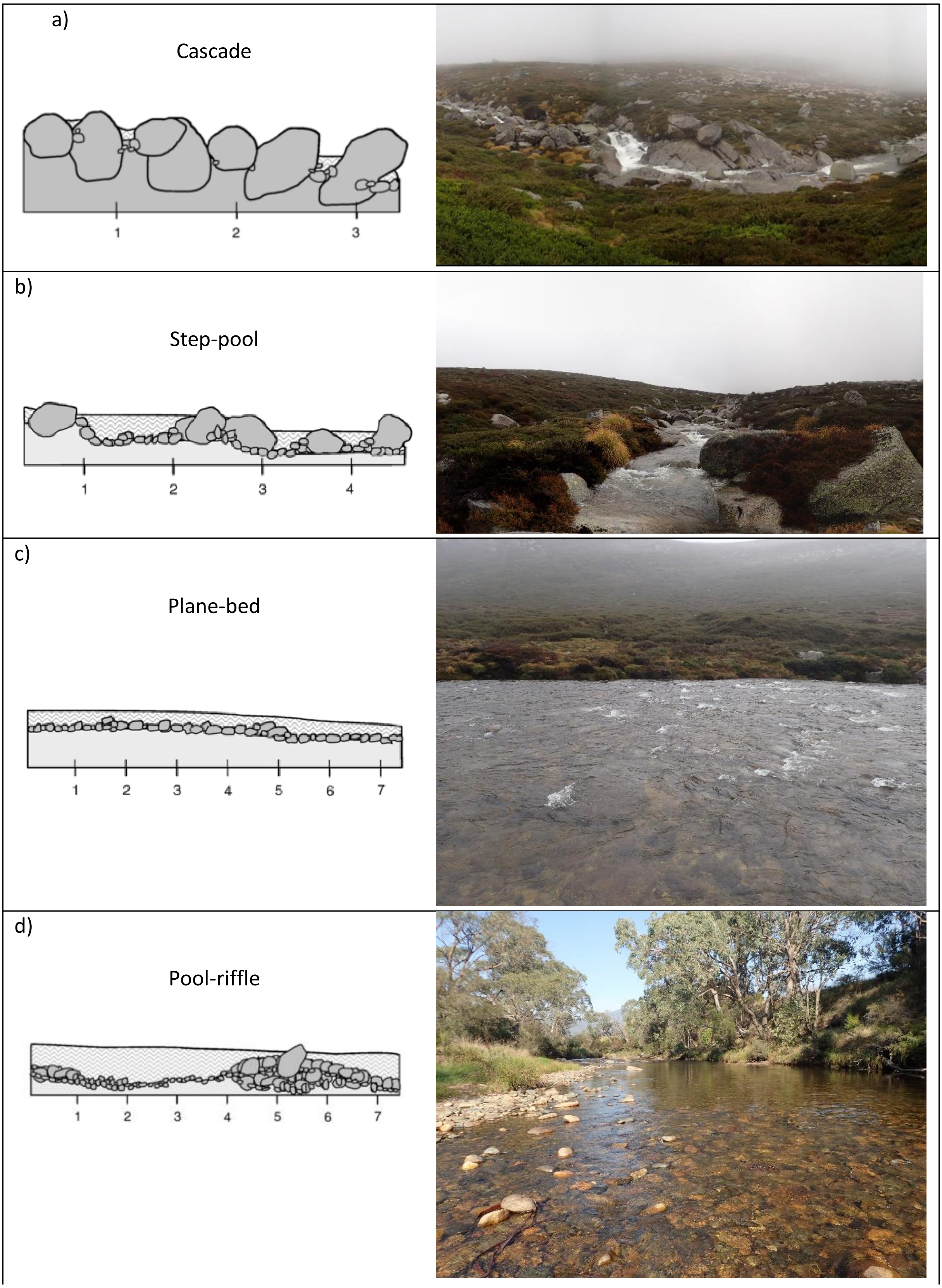
Table 7. The study rivers from the headwaters down to the gauge site classified by stream gradient per the classes proposed by Montgomery and Buffington (1997) and Wohl and Merritt (2005).

River - long profile	Cascade	Step-pool	Plane-bed	Pool-riffle
Club Lake Ck at Clarke	0.084			
Cootapatamba Ck at Ramshead	0.065			
Spencers Ck at Paralyzer		0.043		
Snowy River at Guthrie		0.040		
Snowy above Guthega Dam		0.035		
Geehi above Geehi Reservoir		0.033		
Perisher Ck at Blue Cow		0.032		
Yarrangobilly River at Yarrangobilly			0.026	
Tooma above Tooma Reservoir			0.024	
Happy Jacks River above Happy Jacks Reservoir			0.023	
Maragle Ck at Maragle			0.022	
Tumut above Happy Jacks Reservoir			0.020	
Crackenback at Paddys Corner			0.019	
Murray River at Tom Groggin				0.014
Eucumbene River at Providence				0.010
Eucumbene River at Kiandra				0.009
Murray River at Biggara				0.008
Murrumbidgee above Tantangara Dam				0.004

Table 8. The study river reaches categorized by their channel gradient per the classes proposed by Montgomery and Buffington (1997) and Wohl and Merritt (2005).

River - reach	Cascade	Step-pool	Plane-bed	Pool-riffle
Happy Jacks River above Happy Jacks Reservoir	0.126			
Tooma River above Tooma Reservoir	0.121			
Club Lake Ck at Clarke*	0.111			
Geehi River above Geehi Reservoir		0.062		
Tumut River above Happy Jacks Reservoir		0.061		
Murrumbidgee River above Tantangara Dam		0.044		
Perisher Ck at Blue Cow*			0.029	
Spencers Ck at Paralyzer			0.026	
Cootapatamba Ck at Ramshead			0.025	
Eucumbene River at Kiandra			0.018	
Eucumbene River at Providence			0.015	
Snowy River above Guthega Dam				0.014
Crackenback River at Paddys Corner				0.014
Snowy River at Guthrie*				0.014
Yarrangobilly River at Yarrangobilly				0.012
Maragle Ck at Maragle				0.010
Murray River at Biggara				0.007
Murray River at Tom Groggin				0.007

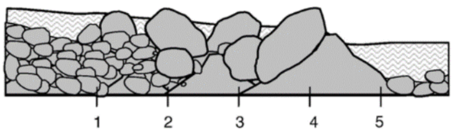
** Club Lake Ck at Clarke and Perisher Ck at Blue Cow are better suited to the intermediate classifications of cascade-pool and riffle-step respectively and Snowy River at Guthrie demonstrates the morphology of a plane-bed channel*


a)
Cascade
1
2
3
b)
Step-pool
1
2
3
4
c)
Plane-bed
1
2
3
4
5
6
7
d)
Pool-riffle
1
2
3
4
5
6
7

e)

f)

Cascade-pool



g)

Riffle-step

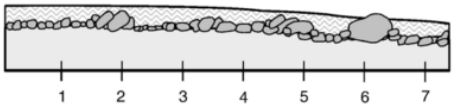
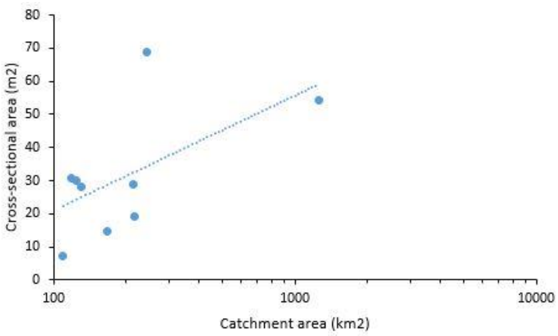


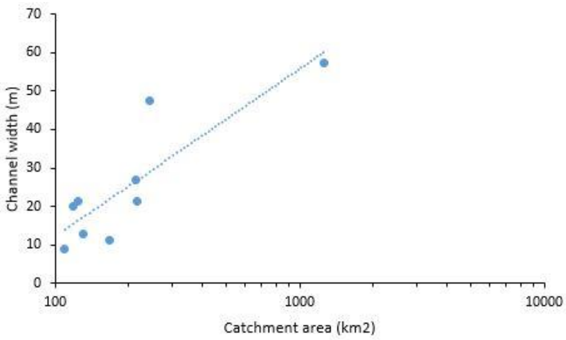
Figure 33. Channel morphology schematics as per Thompson et al. (2006) with examples from the Snowy Mountain field sites. Numbers on the schematics indicate the common length of features by channel width. a) cascade channel: upstream of the field site on Club Lake, b) step-pool channel: below the field site on Club Lake Ck c) plane-bed channel: Snowy River at Guthrie d) pool-riffle channel: Murray River at Tom Groggin. e) Club Lake Creek and the site at Clarke may be classified as a cascade channel due to a gradient in of 0.065 m/m (Wohl and Merritt 2005), however, f) it is more suited to the cascade-pool classification described by Thompson et al. (2006) because at the field survey location the river descends in a series of steps created by large boulders. g) The long-profile channel slope of 0.032 m/m classifies Perisher Creek as step-pool, but the irregular morphology and reach-scale slope of 0.029 m/m suggest that the field site may fall into the intermediate category of riffle-step described by Thompson et al. (2006). The riffle-step category has a range of gradient of 0.02-0.03 m/m.

Using channel cross-section data from nine Snowy Mountain sites that also had stage height data allowed an assessment of channel width to catchment area relationships. The results demonstrate a weak relationship that as catchment area increases, so too does the channel cross-sectional area (Fig. 34-a, R^2 = 0.35). The weak relationship may be due to the limited amount of data, particularly for catchments above 1000 km^2, and because the Crackenback River at Paddy's Corner has a disproportionately large cross-sectional area for the size of its catchment (Appendix 3-e). The channel at Paddy's Corner is wide because it is downstream of a steeper section that features rapids running through a gorge while the site itself is in a calm stretch with a wide valley (Appendix 3-e). The low gradient and wide valley by the gauge ensure that the channel at Paddy's Corner is a sediment accumulation zone and results in a wider channel. With the Crackenback River removed, the R^2 value in Figure 34-a increases from 0.35 to 0.59. The same data were also able to demonstrate that channel width increased as catchment area increased (Fig. 34-b), but mean channel depth decreased (Fig. 34-c) demonstrating that smaller streams are narrower and deeper while the bigger rivers are wide and shallow. Further research could be done to decide if net incising processes are slower in larger streams because of slower sediment transfer rates that result in shallower, wider channels.

a)



b)



c)

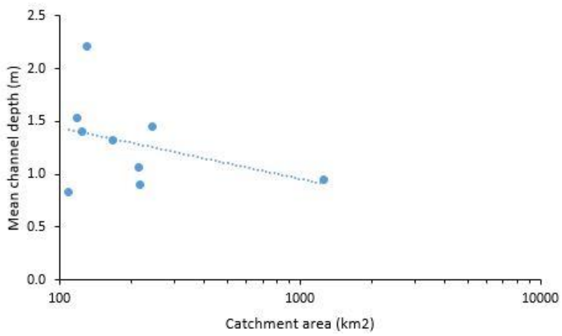


Figure 34. Surveyed cross-sections were filled via simulation in the program "Channel" to the height of the calculated 2-year flood using a roughness coefficient of 0.5 and DEM derived channel slope. a) The resulting cross-sectional area was plotted against each sites catchment area and was found to have a positive relationship (R^2 = 0.35). b) The mean channel width also increased with increasing catchment area (R^2=0.74) but c) mean channel depth was found to decrease (R^2=0.14)

There will be no data presentation on the hydraulic geometry of Snowy Mountain rivers because the results for the calculations were not valid. The velocity data provided by the NSW Office of Water and Snowy Hydro Limited were not measured in the field, rather they were derived from Q =AV and this resulted in the value of the exponents not summing to one. Unfortunately, this practice was not restricted to the historic data as the current gauges have the same issue. Examples of the results are shown in Appendix 8.

5.2 Climatological characteristics

5.2.1 Seasonal trend analysis

Rivers in the Snowy Mountains demonstrate a strong seasonal discharge signal with peak monthly discharge occurring between August and November (Fig. 35-a). The seasonal signal is most dramatic for sites on the Murray River, Eucumbene River, Spencers Creek and Cootapatamba Creek. In contrast, the east coast non-snowmelt rivers achieve their maximum monthly discharge between January and April (except for the Shoalhaven River, Fig. 35-b). These rivers are mostly located north of Sydney (Fig. 1) where the bulk of precipitation falls during summer, whereas the Shoalhaven River is located south of Sydney in an area of uniform precipitation. The Snowy Mountain rivers are several hundred kilometres further south where the bulk of the precipitation falls during winter months as rain and snow. Figure 35-c demonstrates that the semi-arid rivers located in northern NSW have a strong seasonal discharge pattern. This is because, like the east coast rivers, the headwaters of the semi-arid rivers analysed receive precipitation mostly in the first half of the year.

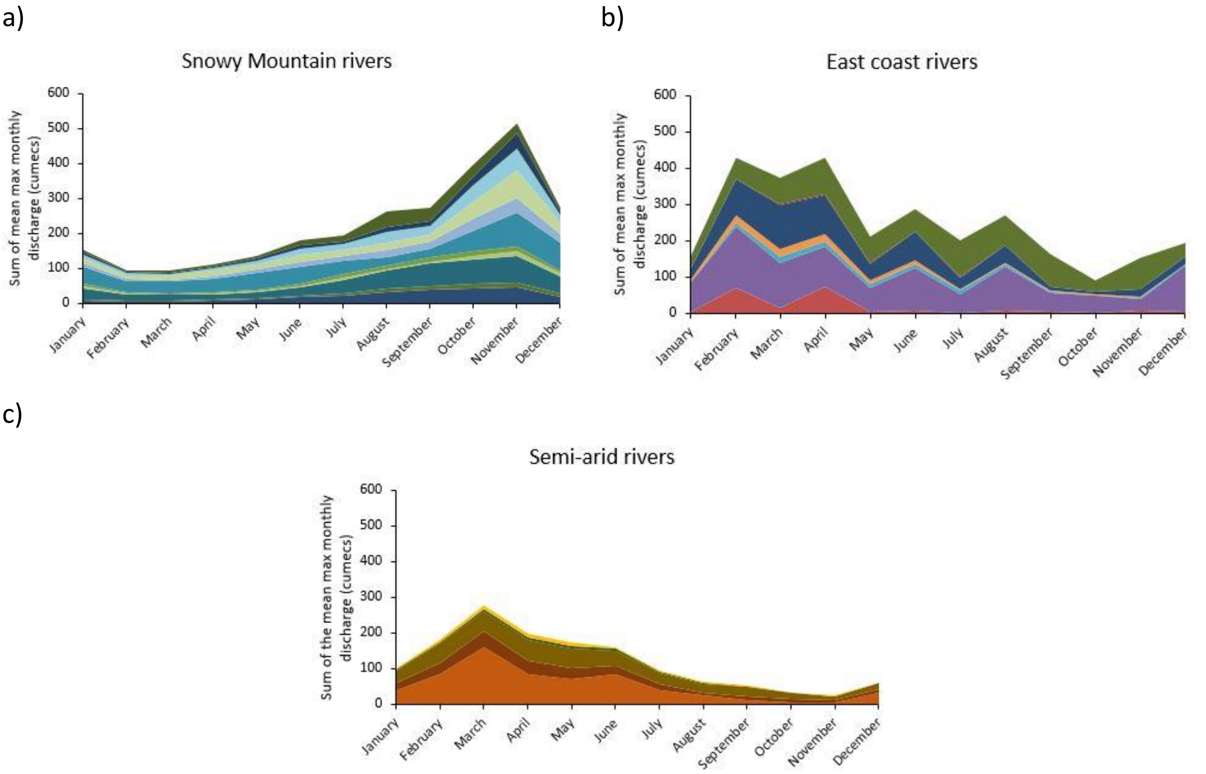


Figure 35. Seasonal trends between (a) snowmelt (b) east coast non-snowmelt and (c) semi-arid non-snowmelt rivers which demonstrate that the Snowy Mountain rivers in this study have their highest monthly discharge in the last half of the year and the comparison non-snowmelt rivers achieve high discharge volumes in the first half of the year.

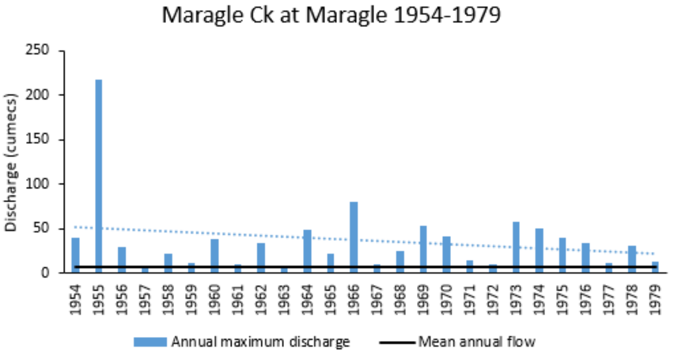
5.3 Flow variability

5.3.1 Time series

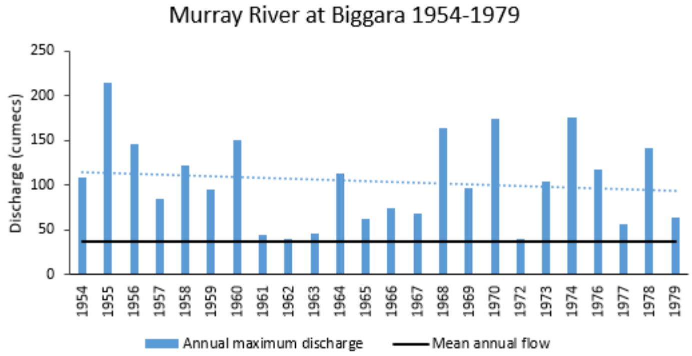
The time series analyses on the NSW Office of Water discharge data demonstrates some inter-annual variability but no progressive change through time (R^2 of 0.06 and less; Fig. 36). The remaining five NSW Office of Water sites did not have lengthy data records that demonstrate discharge trends in annual maximum flow.

The time series analyses also demonstrate that the historic Snowy River at Jindabyne was once the region's largest river with a mean annual flow three times the size of the next largest river, the Murray at Biggara. These sites share similar catchment areas, for the Snowy River at Jindabyne it is 1848 km^2 and for the Murray River at Biggara it is 1256 km^2. These two sites also share similar mean catchment elevations, 1382 m at Jindabyne and 1100 m at Biggara.

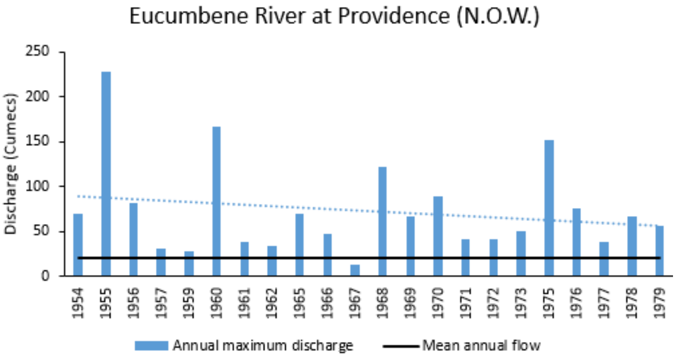
a)



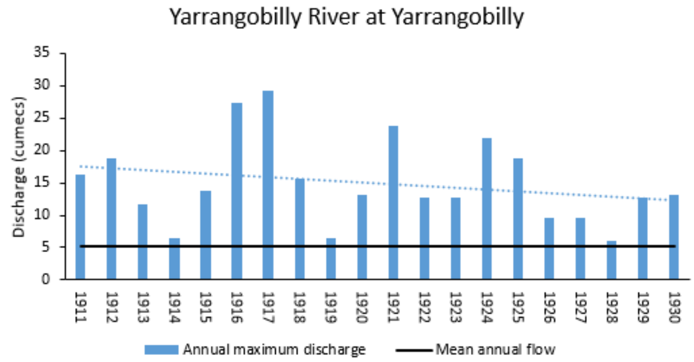
b)

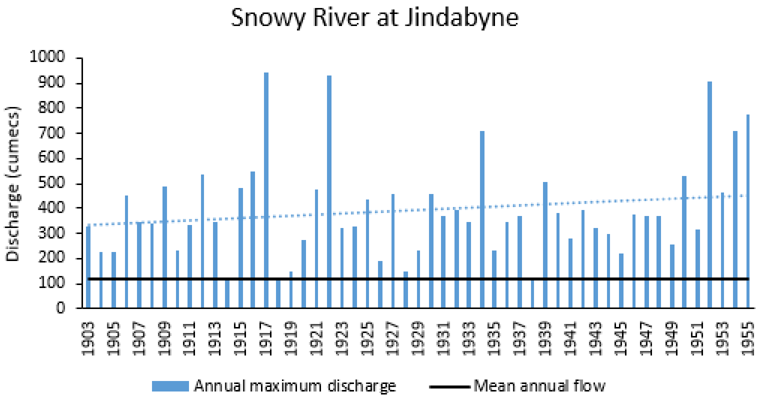


c)



d)





e)

Figure 36. The rate of annual maximum discharge remained essentially stable with only a very minor decreasing trend over time for the sites a) Maragle Ck (R^2 = 0.06), b) Murray River (R^2 = 0.01) c) Eucumbene River (R^2 = 0.04) and d) Yarrangobilly River (R^2 = 0.06). e) The Snowy River demonstrated a very minor increasing trend in discharge (R^2 = 0.04). Time series analysis was undertaken on years with complete ML/d data records and converted into cumecs.

5.3.2 Flash flood magnitude index

An approach to quantifying hydrological variability is the use of the flash flood magnitude index (FFMI) which provides a method to compare flood variability between regions (Fig. 37, Baker 1977; Erskine & Livingstone 1999). The mean FFMI calculated for Snowy Mountain rivers was 0.27 and the range in the data was 0.18 – 0.53. Six of the 13 Snowy Mountain rivers analysed had FFMI values in excess of the global mean (0.28) however none of the Snowy Mountain rivers had FFMIs greater than 0.60, which is often the threshold used for rivers with high hydrologic variability (Erskine and Livingstone 1999).

Nine east coast rivers were analysed, six of which had FFMIs greater than 0.60. The east coast rivers had a mean FFMI value of 0.74 with Warrah Ck proving to be an outlier in the dataset (1.29). However even with the outlier removed, the FFMI for the east coast rivers was still calculated to be 0.67 and the range in the data was 0.50 – 1.29 (Fig. 37). For semi-arid rivers, the mean FFMI value was 0.62 and the range was 0.52 – 0.72 with three of the five examined having FFMIs greater than 0.60.

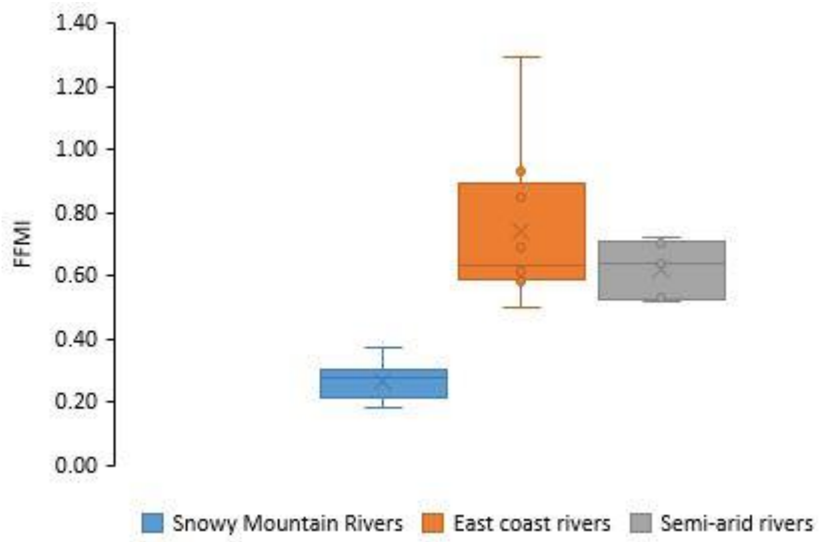


Figure 37. The flash flood magnitude index for Snowy Mountain rivers and comparison non-snowmelt rivers (including Warrah Ck).

5.3.3 Coefficient of variation

The runoff coefficient of variation was calculated for rivers in each region (Fig. 38.a) and the results show that Snowy Mountain rivers have the least inter-annual flow variability of the three datasets, while the semi-arid rivers have the most. The range in the data was 0.20 – 0.69 with a mean of 0.38 for Snowy Mountain rivers, 0.51 – 1.19 with a mean of 1.19 for east coast rivers and 1.10 – 1.79 with a mean of 1.41 for arid rivers. In Snowy Mountain rivers, there was trend of decreasing CV with increasing mean catchment elevation as shown by Figure 38.b.

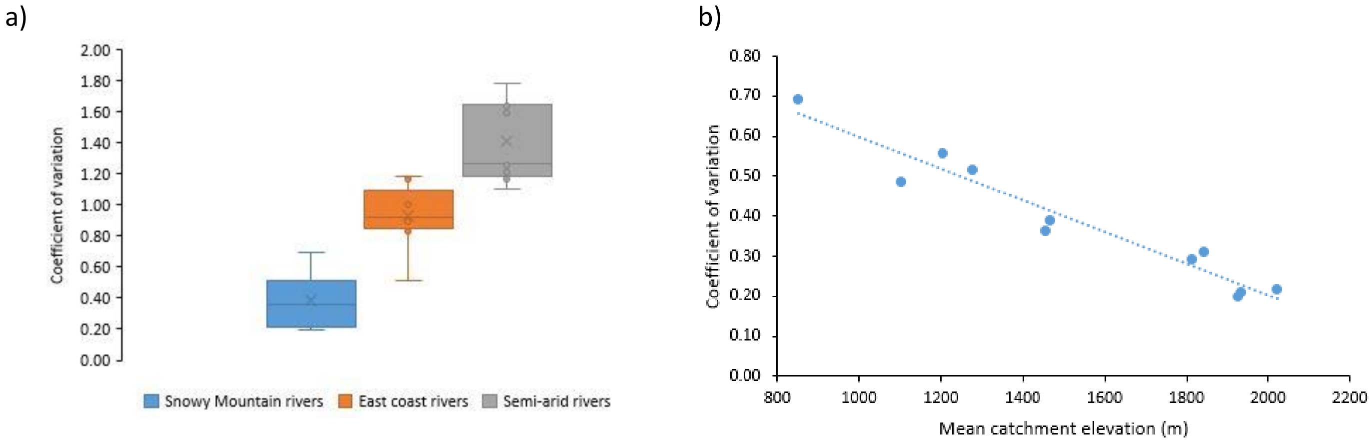


Figure 38. a) The coefficients of variation plotted for Snowy Mountain, east coast and semi-arid rivers. Boxes represent the 25th, 50th and 75th percentile while the whiskers show the 10th and 90th percentile. b) The coefficients of variation for each Snowy Mountain river plotted against their mean catchment elevation show a decreasing trend as elevation increases, $R^2 = 0.94$.

Rainfall CV values are low for Snowy Mountain catchments above and below 1500 m in elevation meaning that the highest elevation catchments have a similar degree of rainfall variability as lower elevation catchments (Table 9). Therefore, differences in annual runoff coefficients are not driven by differences in annual rainfall variability. Previous work has shown high elevation catchments have reliable runoff because of factors such as a greater proportion of precipitation falling as snow, and lower rates of evapotranspiration driven by elevation related changes to vegetation (Reinfelds et al. 2014).

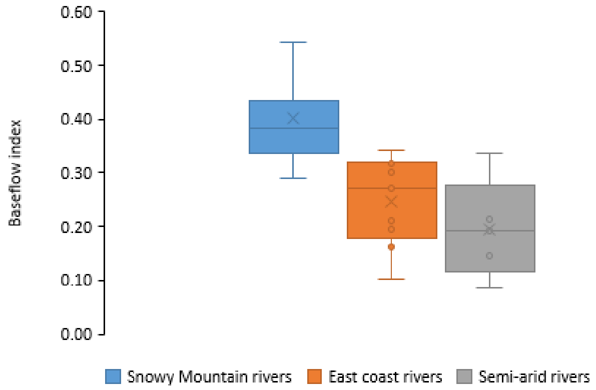
Table 9. The CV for the mean annual precipitation over catchments above and below 1500 m in elevation is low demonstrating that there is little difference in elevation driven annual rainfall variability

Precipitation	**> 1500 m**	**< 1500 m**
Mean (mm)	1803	1313
Standard Deviation	278	106
Coefficient of variation	0.15	0.08

5.3.4 Baseflow index

Snowy Mountain rivers were found to have higher baseflows than east coast and semi-arid rivers (Figs. 39.a-b). The mean baseflow index (BFI) for Snowy Mountain rivers was 0.41 with a data range of 0.29-0.55. East coast rivers had a mean BFI of 0.25 with a range of 0.10-0.34 and semi-arid rivers had a mean BFI of 0.19, with a range of 0.09-0.34. The mean daily baseflow was higher in Snowy Mountain rivers through each order of catchment scale and there was a decreasing trend of the BFI with altitude (Appendix 10, R^2=0.53).

a)



b)

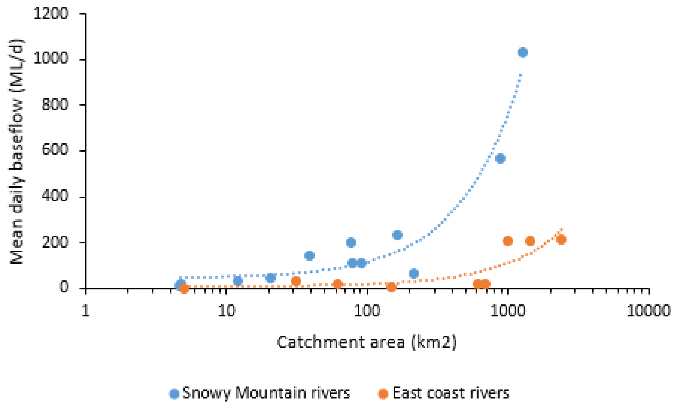


Figure 39. a) The baseflow index for rivers in each region demonstrated that Snowy Mountain rivers have the highest baseflows followed by east coast rivers, then semi-arid rivers. b) Snowy Mountain rivers have higher mean daily baseflow than east coast rivers through all orders of catchment scale

5.4 Flood frequency analysis

5.4.1 Log Pearson III vs Generalized Pareto and Annual series vs Partial series

The comparison of data analysis methods for the flood frequency analysis show that there is good agreement between the Log Pearson III (LP3) and Generalized Pareto (GP) probability models (Fig. 40.a-b). Given the LP3 model is a widely-used distribution within industry in Australia (Institute of Engineers), it will be the model used to calculate hydrological statistical data in this thesis.

A comparison of annual versus partial series flood frequency analyses was undertaken for Murray River at Biggara (Figure 40.c). For LP3 distributions, the results of this comparison show that there is relatively little difference between partial series and annual series flood magnitude estimates for Murray River at Biggara. For simplicity, flood frequency analyses for this thesis were based on annual maximum discharge series.

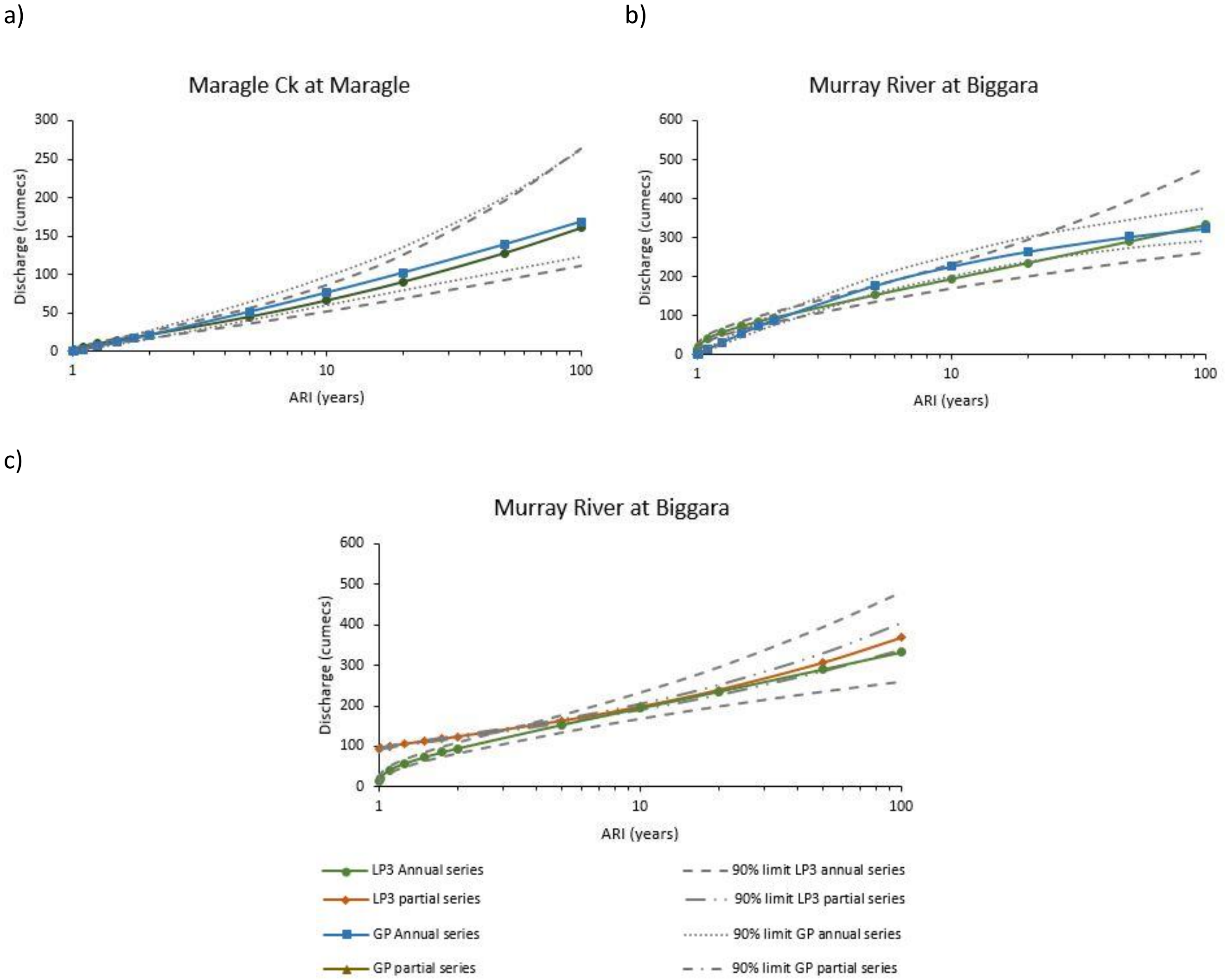


Figure 40. Comparison of the Log Pearson III and Generalized Pareto flood frequency models for the sites (a) Maragle Ck at Maragle and (b) Murray River at Biggara show that there is some agreeance between the methods, particularly for predicting floods with return periods of 20-100 years. Comparison of the annual series and partial series results for (c) Murray River at Biggara highlights that the results and trends are very similar

5.4.2 Flood frequency ratio curves

Figure 41 presents the ratio Qf/Q2 for snowmelt and non-snowmelt rivers and highlights the low gradient of the regionally-averaged curve for Snowy Mountain rivers, in contrast to those of the rivers located along the east coast and semi-arid regions of NSW. This means in NSW, there is a smaller difference between floods of various magnitudes in the alpine region than in other locations. The data for the Snowy Mountain rivers ranges from 0.22 to 4.64 for the 1.01-year flood to the 100-year flood, between 0.021 and 22.94 for east coast rivers, and for semi-arid rivers is 0.04-49.47 (Fig. 41). The mean Qf/Q2 values are 1.76, 5.58 and 9.31 for the Snowy Mountain, east coast and semi-arid rivers respectively.

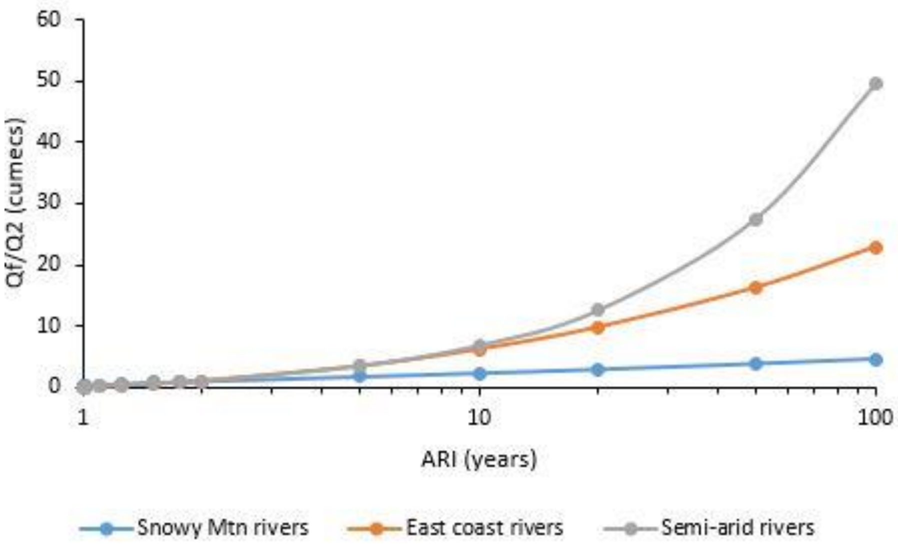


Figure 41. Regional average flood frequency ratio curves for 1.001 – 100-year events in Snowy Mountain rivers and comparison non-snowmelt rivers. Flood frequency ratios calculated against 2-year annual maximum flood discharges and then averaged across the two regions.

5.4.3 Flow scaling

Figure 42-a shows that floods in both regions scale in volume by catchment area, meaning that as catchment area increases the size of each calculated ARI flood also increases. The magnitude of scaling relationships in Snowy Mountain rivers are much smaller than the other regions and so is the size of the difference between the various orders of magnitude of catchment area. When plotted for the Snowy Mountain rivers, the R^2 values for the logarithmic trendlines highlight the strong correlation between the data, with values of 0.98, and 0.99 for catchments with areas of 10-100km^2 and >1000km^2 respectively. For the east coast rivers, those same R^2 values are 0.99 and 0.89.

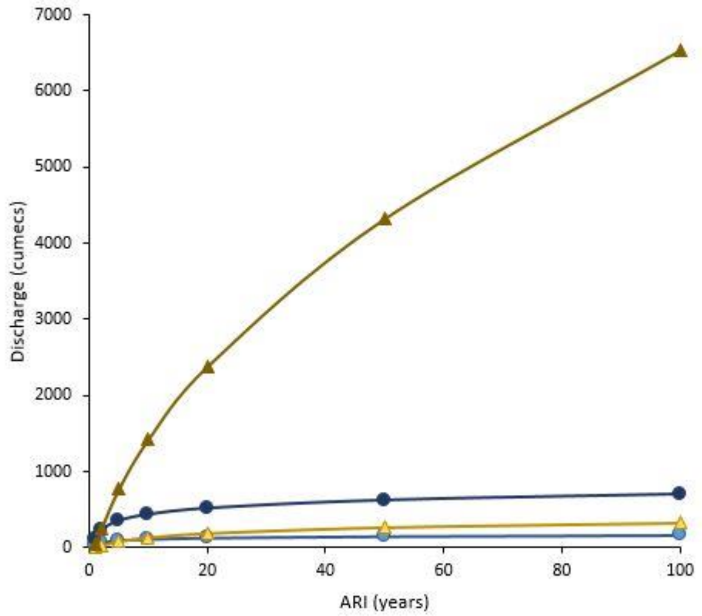
The predicted 100-year flood in Snowy Mountain rivers is 2.8 times larger than a 2-year flood in catchments 10-100 km^2 in area. For catchments larger than 1000 km^2 the difference is 3.1 times. The magnitude of the difference is much larger in east coast rivers than it is in Snowy Mountain rivers, where for catchments 10-100 km^2, the 100-year flood is 11.7 times larger than the 2-year flood and for catchments greater than 1000 km^2 it is 27.2 times.

In the Snowy Mountains, a 2-year flood in a catchment larger than 1000 km^2 is only four times larger than a 2-year flood in a catchment 10-100 km^2, where along the east coast it is 8.5 times larger for the same catchment scale. Predicted 100-year floods in the Snowy Mountains catchments larger than 1000 km^2 are still only 4.4 times larger than those in the catchments 10-100 km^2, where in east coast rivers, these floods are 19.8 times larger. The results show that Snowy Mountain rivers have relatively large 2-year floods in comparison to the east coast rivers. The outcome is that Snowy Mountains rivers have extremely flat flood frequency ratio curves compared to elsewhere in Australia.

Figure 42-b shows that as catchment area increases, unit discharge decreases. This occurs in the Snowy Mountains and in the east coast non-snowmelt rivers but the Snowy Mountain rivers do not scale to the same magnitude as do the non-snowmelt rivers. The gradient of each curve in Figure 42-b decreases with increasing catchment area highlighting that as catchment area increases, the

difference in unit area discharge between floods of various return interval decreases. For example, in Snowy Mountain catchment areas of 10-100 km^2, the difference between 100-year floods and 1.1-year floods is 3.46 cumecs/km^2. For catchments greater than 1000km^2 the difference is 0.36 cumecs/km^2. The trend is the same for east coast rivers with cumecs/km^2 values of 7.18 and 3.24 respectively.

a)



b)

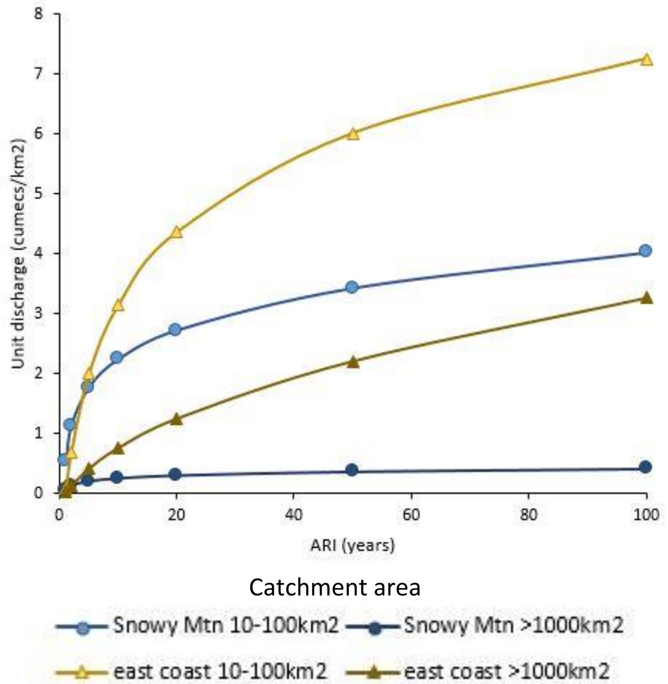


Figure 42. a) Mean discharge values for floods with a 1.1 – 100-year return interval, scaled by catchment area for Snowy Mountain rivers and east coast rivers. The values plotted are the mean annual series ARI discharge volumes in cumecs for each catchment scale. b) Unit area discharge values for floods with a return interval of 1.1 – 100 years, scaled by catchment area for Snowy Mountain rivers and for east coast rivers. Unit area discharge was calculated by dividing the calculated ARI flood magnitude for each river by its catchment area and plotting the mean for each region and catchment scale.

5.4.5 Inundation frequency at gauge cross-sections

Figure 43 presents the surveyed cross-sections at the various gauges in both the Snowy Mountain Rivers and other regions. This figure highlights that in the Snowy Mountains, there is less vertical spread in predicted water levels for the 2 to 20-year ARI flows (a mean of 1.19 m) in comparison to the non-snowmelt rivers (a mean of 3.23 m for the east coast rivers and 2.02 m for the semi-arid rivers); see examples on the Murrumbidgee, Murray, Merriwa, Apsley, Paroo and Culgoa Rivers. 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 means of 7.23 m and 2.01 m on the non-snowmelt systems of the east coast and semi-arid rivers respectively. Further cross-sections with field photos and Google Earth images for each site may be found in Appendices 2-5 with inundation frequencies plotted in Appendices 12.

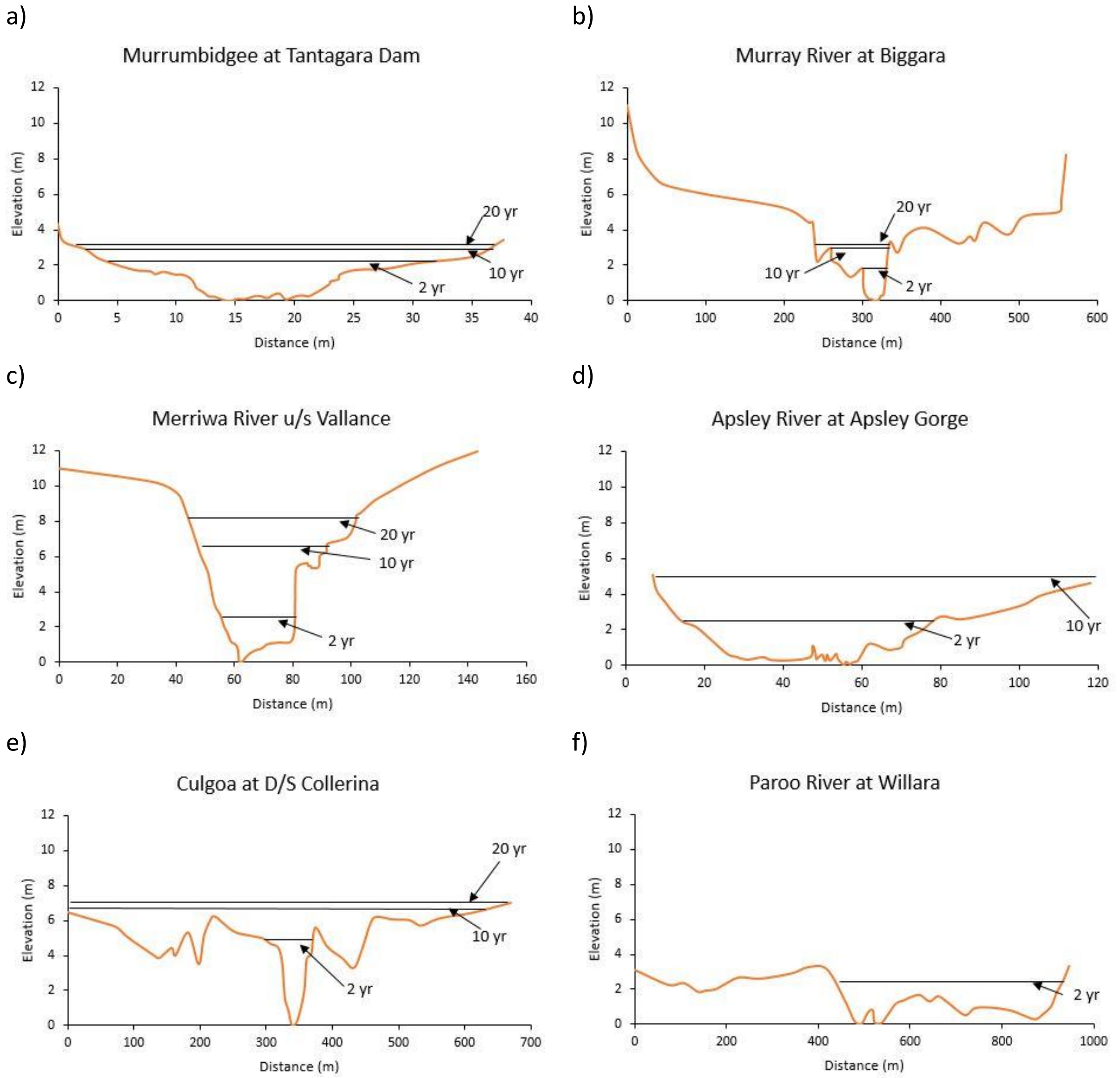


Figure 43. Cross-section of the channel at a) Murrumbidgee River above Tantangara Dam; b) Murray River at Biggara; c) Merriwa River upstream of Vallance d) Apsley River at Apsley Gorge; e) Culgoa River at Collerina and f) Paroo River at Willara with heights of the 2, 10 and 20 year ARI floods plotted (unless the flood was at a higher level than the cross-section).

5.5 Annual and event-based runoff coefficients

The mean annual runoff coefficient for Snowy Mountain rivers was calculated as 0.86 and the data range was 0.15 – 1.75 (Appendix 1). Five of the sites had runoff coefficients greater than one and in this subset of the data, the range was 1.16 – 1.75. These five sites were the highest catchments and each had mean catchment elevations higher than 1842m (Fig. 44).

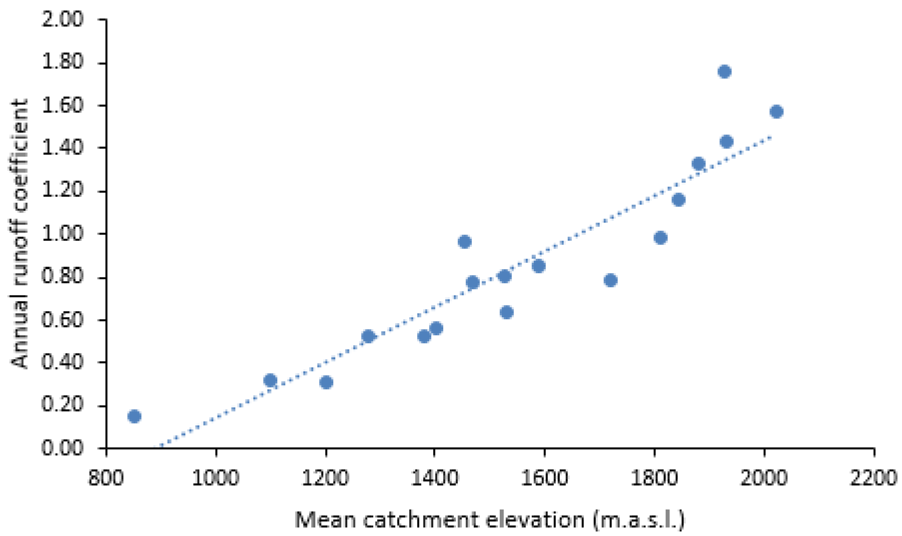


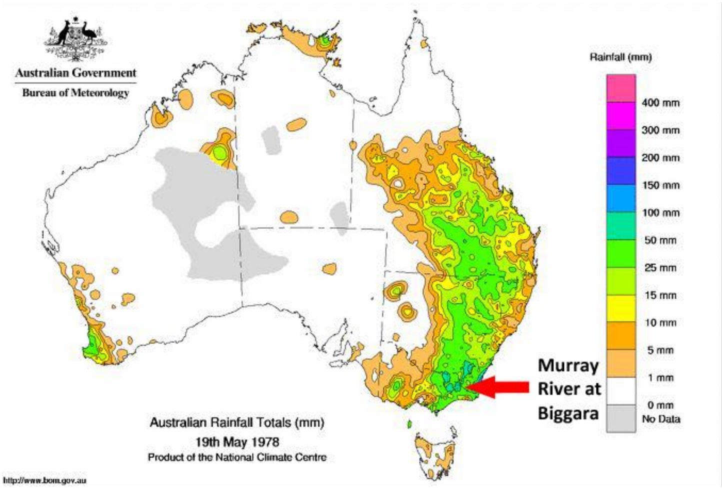
Figure 44. The annual runoff coefficients for Snowy Mountain rivers increase with increasing mean catchment elevation (R^2 = 0.86).

An assessment of event-based runoff coefficients was undertaken to further investigate the cause of the differences in gradient of the flood-frequency ratio curves between regions. Event runoff coefficients were calculated for the 2, 10, 20 and 50-year flood events for two sites in the Snowy Mountains and two in the east coast rivers. The two Snowy Mountain river sites analysed (Murray River at Biggara and Maragle Creek at Maragle) were chosen because only these gauges had daily discharge data. It is important to note that these two sites had the lowest mean catchment elevations of the Snowy Mountain rivers dataset and so could be expected to have lower event-based runoff coefficients than high elevation catchments such as Club Lake Creek at Clarke which had the highest mean annual runoff coefficient of 1.75. In comparison, the mean annual runoff coefficient for Murray River at Biggara was 0.32, and for Maragle Creek at Maragle it was 0.15. The trend for event-based runoff coefficients was expected to be the same as that of the mean annual runoff coefficients.

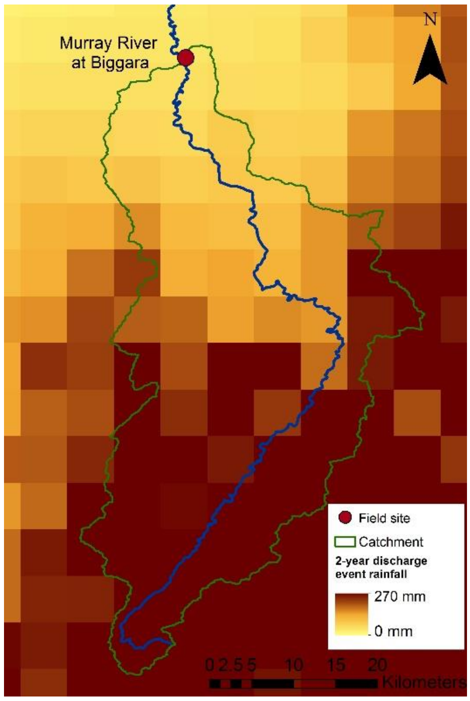
The day of the maximum rainfall over the Murray River at Biggara and Shoalhaven River at Warri catchments for the 2 and 50-year flood events are shown in Figures 45-48. The accompanying hydrographs show the mean rainfall depth over each catchment for the entire period. To provide explanation, the highest daily calculated rainfall for Murray River at Biggara's 2-year flood event occurred on 19/5/1978. On that day, the maximum rainfall depth falling over an individual grid cell was 97 mm, and the mean rainfall depth across the catchment was 53 mm. The mean daily rainfall depth over the catchment is plotted on the hydrograph/precipitation graph shown in Figure 45-c and a summary of the rainfall amounts is provided in Appendices 13.

On the peak rainfall day at Biggara (Fig. 45- b), the highest rainfall totals fell over the upstream portion of the catchment and falls of up to 100 mm were recorded in the area (Fig. 45-a). The hydrograph for the entire flood event is shown in Figure 45-c and the peak in rainfall occurred 16 days before the 2-year discharge event. Total daily precipitation decreased from 20/5/1978 until 28/5/1978, then increased to a second peak on the 3/6/1978. The 2-year flood occurred on the 4/6/1978. The mean rainfall depth over the catchment for the entire 28-day period was 205 mm.

a)



b)



c)

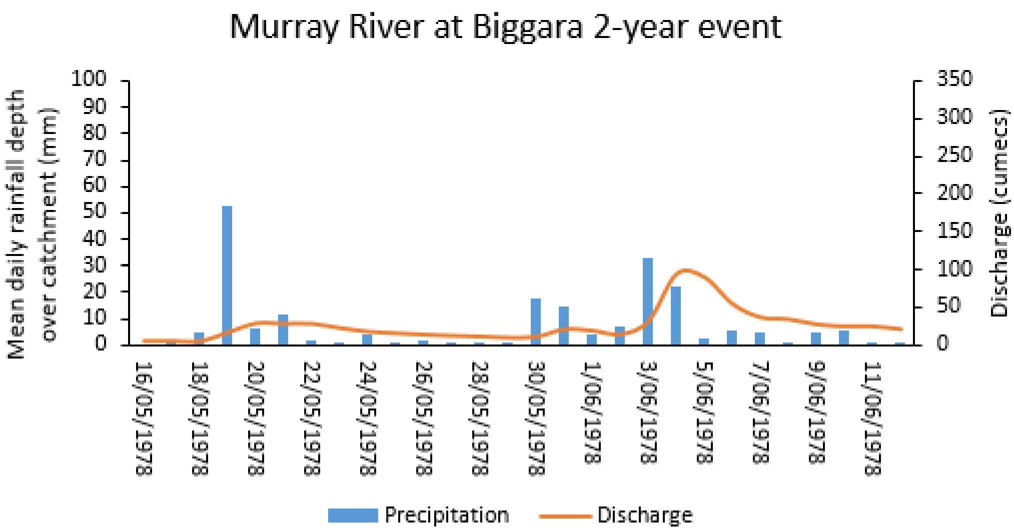


Figure 45. a) The BOM rainfall map for the day of maximum rainfall during the 2-year flood event at Murray River at Biggara, showing falls of up to 100 mm over the area of the catchment (Australian Bureau of Meteorology 2016). b) The BOM gridded data shows that on the 19th of May, the highest rainfall amounts fell over the southern half of the Murray River at Biggara catchment (Australian Bureau of Meteorology 2016). c) The mean daily rainfall depth (mm) over the catchment with the corresponding hydrograph for the 2-year flood event

On the day of peak rainfall at Warri, daily totals of approximately 300 mm were recorded in the region (Fig. 46-a), however, only a portion of the eastern catchment received significant rainfall (Fig. 46-b). The hydrograph (Fig. 46-c) shows that for two days in a row, mean daily rainfall depths over the catchment were 43 mm, providing a significant contribution to the 2-year flood event.

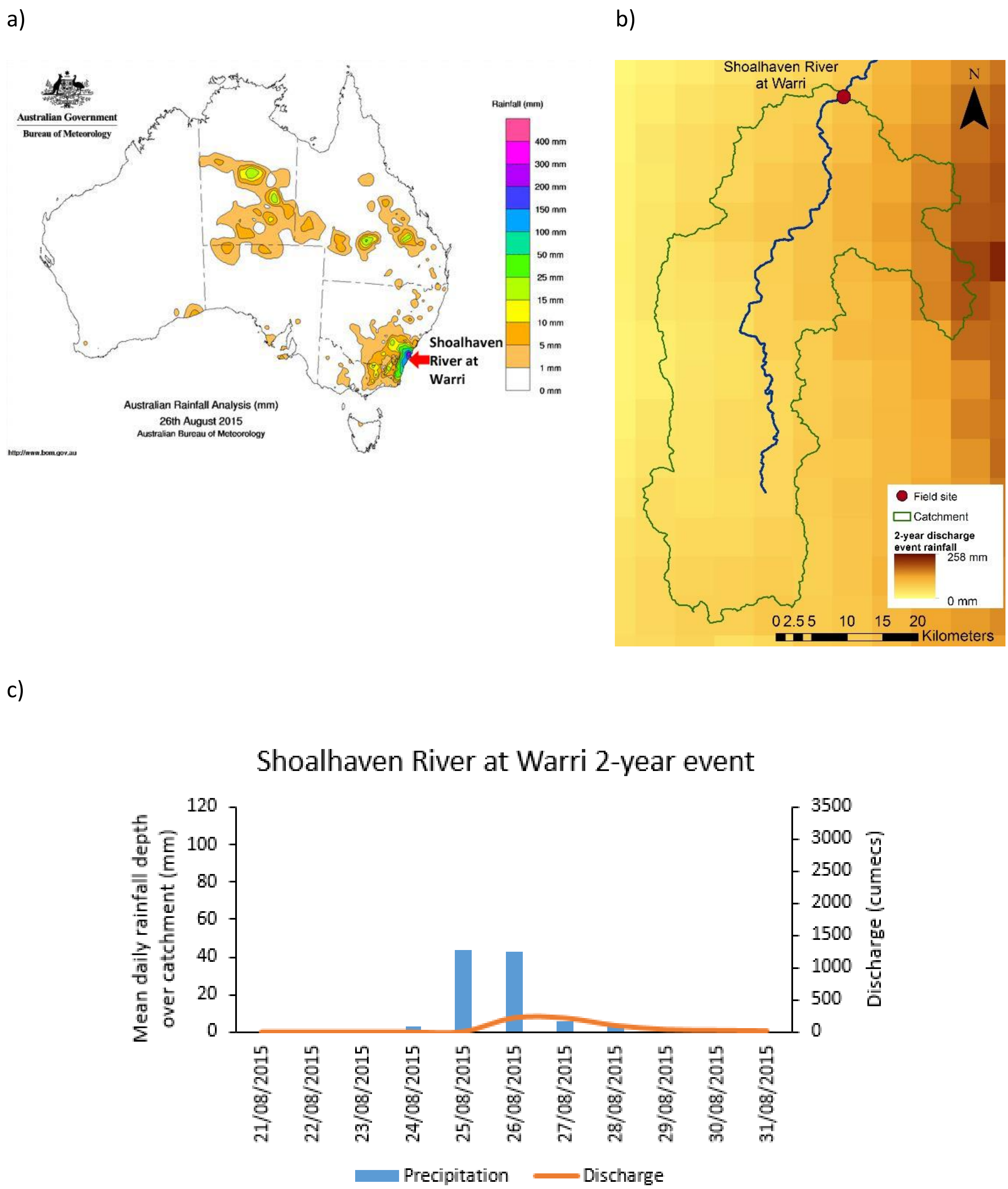
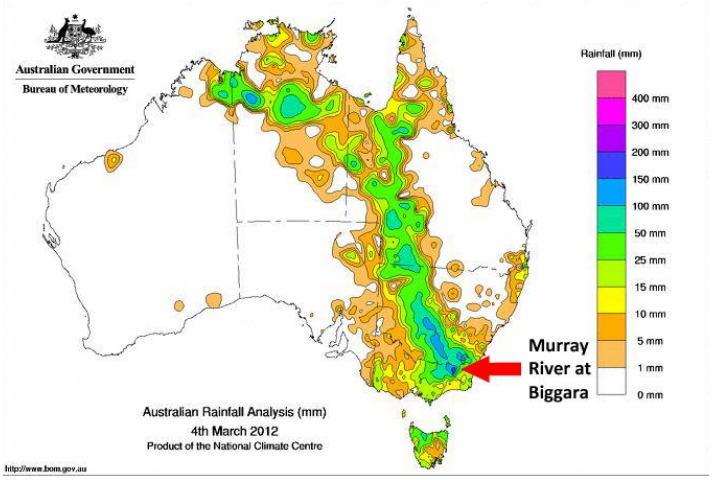


Figure 46. a) The BOM rainfall map for the day of maximum rainfall during the 2-year flood event for the Shoalhaven River at Warri gauge, showing falls of up to 300 mm in the region where the catchment is located (Australian Bureau of Meteorology 2016). b) The BOM gridded data shows that on the 25th of August, the highest rainfall amounts were in the north-eastern portion of the Shoalhaven at Warri catchment (Australian Bureau of Meteorology 2016). c) The mean daily rainfall depth (mm) over the catchment with the corresponding hydrograph for the 2-year flood event

The 50-year flood at Biggara had nine days of precipitation leading up to peak discharge with four days of high rainfall interspersed with persistent moisture (Fig. 47-c) The four peaks each had mean daily rainfall amounts over the catchment more than 45 mm with a maximum of 93 mm. On the day of peak rainfall, precipitation was highest in the mid to lowland portion of the catchment (Fig. 47-b) and totals of close to 200 mm were recorded (Fig. 47-a). The mean daily rainfall over the catchment throughout the 16-day period was 338 mm.

a)



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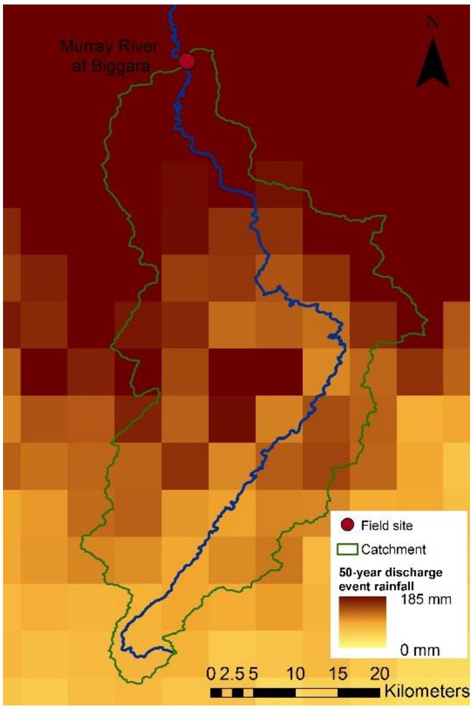

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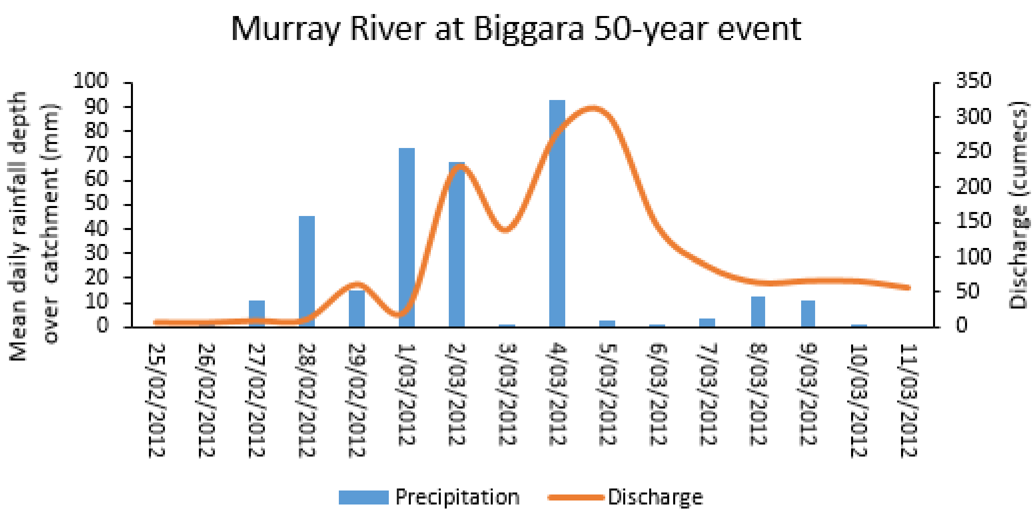
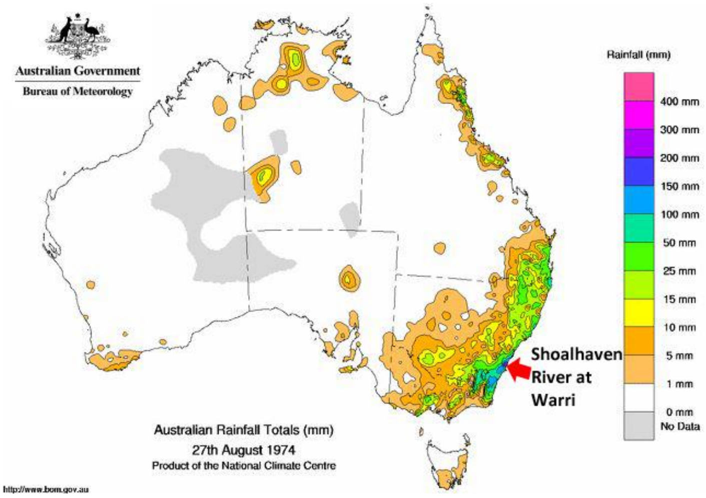


Figure 47. a) The BOM rainfall map for the day of the maximum rainfall during the 50-year flood event for Murray River at Biggara when falls of up to 200 mm were recorded in the region where the catchment is located (Australian Bureau of Meteorology 2016). b) The BOM gridded data shows that on the 4th of March, the heaviest falls occurred in the northern half of the catchment (Australian Bureau of Meteorology 2016). c) The mean daily rainfall depth (mm) over the catchment with the corresponding hydrograph for the 50-year flood event

The peak rainfall day for the 50-year flood event at Warri included falls of up to 200 mm (Fig. 48-a). The largest rainfall amounts were over the headwaters of the catchment, but most of the catchment saw high rainfall amounts (Fig. 48-b). The event hydrograph shows that there were three days with approximately 100 mm of mean daily precipitation totals over the catchment (Fig. 48-c).

a)



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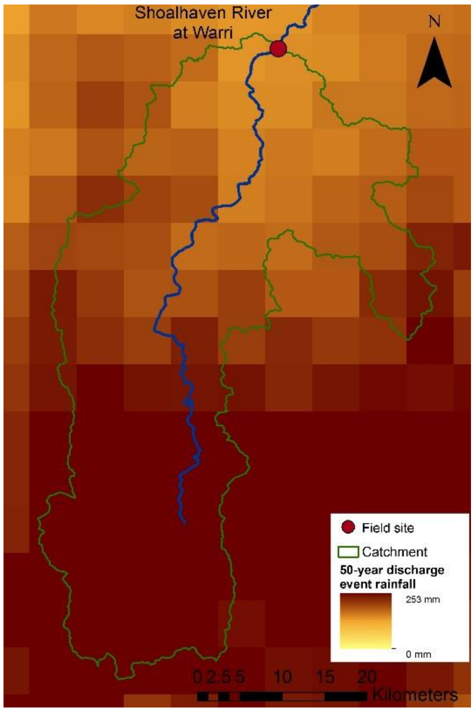

c)

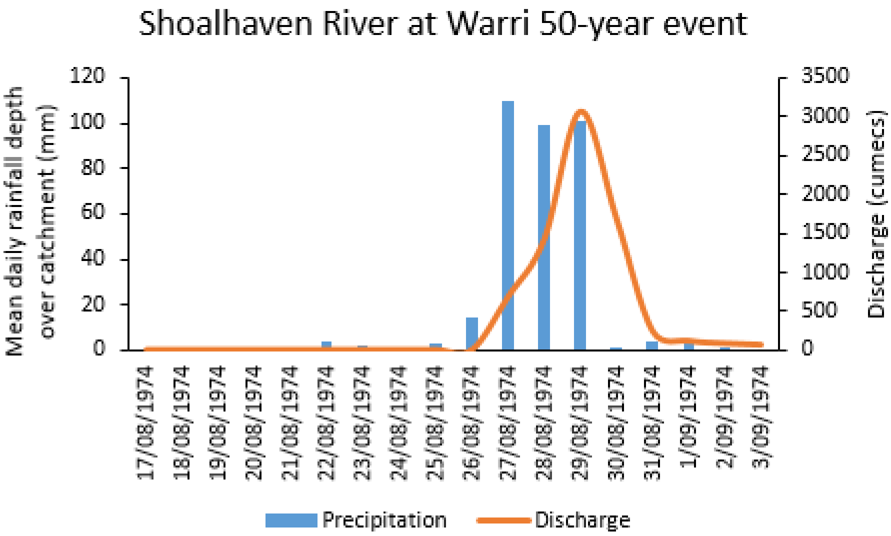

Figure 48. a) The BOM rainfall map for the day of maximum rainfall during the 50-year flood event for the Shoalhaven River at Warri, showing falls of up to 200 mm in the region where the catchment is located (Australian Bureau of Meteorology 2016). b) The BOM gridded data shows that on the 27th of August, the heaviest falls occurred in the southern half of the catchment (Australian Bureau of Meteorology 2016). c) The mean daily rainfall depth (mm) over the catchment with the corresponding hydrograph for the 50-year flood event

The results for the 10 and 20-year events for Murray River at Biggara and Shoalhaven River at Warri as well as all the results for Maragle Creek and Timbarra River at Billyrimbah can be found in the appendices 13.

Figure 49 plots the mean event-based runoff coefficients against the calculated ARI flood events. In the graph, the gradient of the linear trend line for Snowy Mountain rivers is almost flat, while the gradient of the trend line for east coast rivers is positive and comparatively steep. The range in mean values for Snowy Mountain rivers is 0.17-0.24 with the highest event-based runoff coefficient occurring at the 10-year event. The range in mean values for east coast rivers is 0.19-0.79 with the peak occurring at the 50-year event. The mean event-based runoff coefficient for Snowy Mountain rivers is 0.20, while for east coast rivers it is 0.54. In Snowy Mountain rivers, the mean 50-year event runoff coefficient was 1.2 times larger than the mean 2-year event, for the east coast rivers, the mean 50-year runoff coefficient was 4.2 times larger than the mean 2-year runoff coefficient.

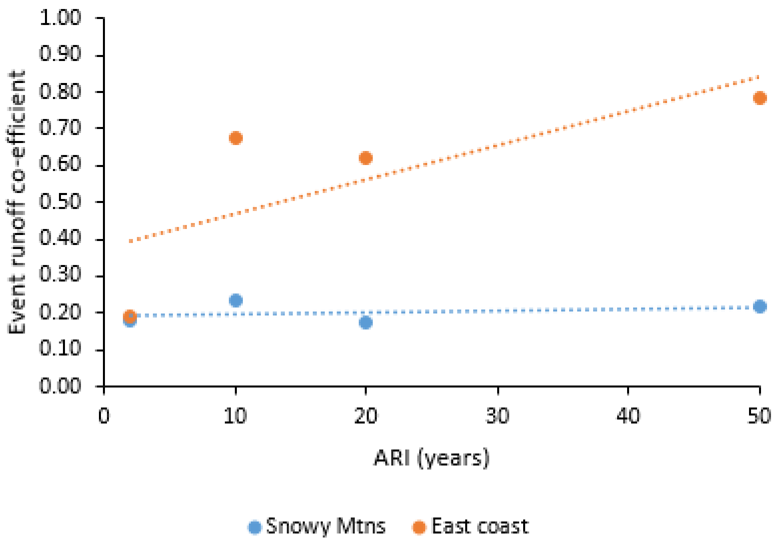

Figure 49. The mean event-based runoff coefficients for the calculated 2, 10, 20 and 50-year floods for Snowy Mountain and east coast rivers. R^2 = 0.10 for Snowy Mountain rivers and R^2 = 0.56 for east coast rivers. The mean 50-year event-based runoff coefficients are based off one gauge in each location

Chapter 6 – Discussion

It has been proposed that temperate Australian rivers exhibit high hydrologic variability when compared to overseas rivers in similar climate zones (Peel et al. 2001; Fig. 22). Hydrologic variability can be characterized by a large difference between the discharge of rare floods (e.g. 100-year event) and frequent floods (e.g. 2-year event). It is also the inconsistency in annual runoff (Peel et al. 2001) and the level of predictability within daily or seasonal flow patterns (Poff et al. 1997). Hydrologic variability may be caused by climate, and it has been noted that either small or very large catchment size tends to increase this variability (Baker 1977; Nanson et al. 2002). For example, small catchments exhibit high variability due to the flashiness of runoff events, while very large catchments have spatial variations in hydrologic variability due to slow runoff rates or incidences where runoff evaporates or infiltrates before it reaches downstream. Hydrologic variability is geomorphologically important because in regions with high variability, more of the stream load (sediment and water) is transported by less frequent flows (Wolman and Miller 1960) leading to large changes in stream morphology during those events (Baker 1977; Erskine and Saynor 1996; Rustomji et al. 2009).

Previous studies have suggested the drivers of the hydrologic variability found in Australia were temporally inconsistent precipitation and runoff in combination with evergreen rather than deciduous forests (Peel et al. 2004). However, these studies were either broad-scale (McMahon et al. 1992; Peel et al. 2004) or most often done on non-snowmelt rivers (Erskine and Livingstone 1999). One of the aims of this thesis is to provide an understanding of whether Australian mountain rivers display the same level of variability as the non-snowmelt rivers and the results demonstrate that Snowy Mountain rivers do not conform to the notions of high variability seen in non-snowmelt settings.

The discussion will explore the factors that combine to create the hydrology of Snowy Mountain rivers. Whilst not a major aim of the thesis, the data collected allows for an assessment of mountain channel morphology and its interaction with the transport of sediment and water discharge. This is followed by an assessment of the climatological input to the study rivers and the long-term discharge trends, flow variability measures and flood frequency analyses. These factors that result in the low hydrological variability of Snowy Mountain rivers are examined and then compared to other Australian non-snowmelt rivers in temperate and semi-arid settings.

6.1 River classification and channel dimensions in the Snowy Mountains

The major controls on river morphology are valley confinement, channel gradient, discharge and sediment load (Fryirs et al. 2016). The topography of the valley floor influences the route that stream power will take at various stages of flow and so helps determine where sediment is eroded and stored (Magilligan 1992). In alluvial river settings, this impacts the capacity for morphological channel adjustments in reaction to changes in discharge. Capacity for channel adjustment is least in rivers set within confined valley settings, and most for rivers set in laterally-unconfined valley settings (Fryirs et al. 2016). Most of the Snowy Mountain river valley settings studied were classified as partly-confined (Table. 6) and conformed with the characteristic flat-bottomed valley bounded by gentle hillslopes (Fryirs et al. 2016). The remaining sites were either in laterally-unconfined settings that featured similar, but wider valleys, or in confined valleys with steeper hillslopes and a v-shaped

valley profile (Fryirs et al. 2016). There was no first-order control between valley confinement and in-channel morphology using the classifications of Fryirs et al. (2016) and Montgomery and Buffington (1997), with reaches representing each channel morphology classification existing in both granite and sedimentary sequences and partly-confined and confined valley settings.

The study rivers in the partly-confined settings exhibited discontinuous pockets of alluvium linked by stretches where bedrock impacted channel form through sharp-angled bends or straight sections (Appendix 6). These valleys were asymmetrical and the proximity of hillslopes to the channel determined where geomorphic features such as floodplains had formed. Similar findings have been discussed in work by Jain et al. (2008) and Fryirs et al. (2016). The laterally-unconfined valley settings were less common in the study area, with only two out of eighteen sites categorized this way. In this valley setting, river morphology is most impacted by factors such as the discharge and sediment regime and vegetation pattern, and these factors influence the planform of the channel (Leopold and Maddock 1953; Rhodes 1987; Harman et al. 2008; Fryirs et al. 2016). In the Snowy Mountain river examples, the greater scope for adjustment of channel form resulted in the two rivers demonstrating variation in planform. Cootapatamba Creek exhibited a single thread, meandering channel pattern (Fig. 31), and the Eucumbene River at Providence featured sections of multiple thread, meandering channel pattern (Appendix 6-k). Rivers in laterally-unconfined valley settings may also take on an anabranching planform (Fryirs et al. 2016). The variation in form of rivers in laterally-unconfined settings contrasts to those in confined valley settings because the channels of the former currently have more space for adjustment than those of the latter which have adjusted their gradient commensurate with sediment load and discharge over geological time frames and now follow the path of the valley.

The relationship of channel dimensions to catchment area was presented in Figure 34. As catchment area increased, bankfull channel capacity was found to increase through increased cross-sectional area and channel width, but with decreases in mean depth. Various channel configurations are thought to occur as a reaction to the dominant sediment transport regime. Wide, shallow alluvial channels carry proportionately more sediment as bedload (Leopold and Maddock 1953; Pickup 1976; Rhodes 1987; Harman et al. 2008), while deep and narrow channels are more suspended-load dominant (Rhodes 1987; Harman et al. 2008). Mountain rivers such as those in the Snowy Mountains are commonly clear-running, sediment supply-limited and bedload dominant. The sediment calibre of the steepest study reaches is too coarse to be mobilised by all but the very largest of floods (Chin and Wohl 2005) and the valley constriction is such that these streams are narrower than their counterparts in non-mountain locations.

Channel classification provides a method for understanding the hydrologic processes occurring within a river (Kasprak et al. 2016). It allows comparison to rivers in other regions and can explain why a channel looks a certain way. Of the eighteen sites investigated, 33% represented the steep (>0.03 m/m) reach-based channel morphology categories of cascade, cascade-pool and step-pool (Table 8). The remaining 67% were classified in the lower gradient (<0.03) categories of riffle-step, plane-bed and pool-riffle. A full explanation of each category was given in section 2.1. Three of the sites were proximal to prior glaciation, but only one of those featured a channel gradient more than 0.03 m/m (Club Lake Ck at Clarke). The other two sites were on the Snowy River and featured lower gradient channels. A channel is more likely to be steeper if it is in a small catchment (Fig. 32), because as catchment area decreases, the percentage of land with high angled slopes increases

(Leopold and Maddock 1953). Club Lake Creek at Clarke is one example of this fact (Fig. 33-e). It has a steep long profile and reach-based gradient, its catchment area is 4.76 km^2 and the headwaters are sourced directly from Australia's 9^{th} and 10^{th} tallest peaks. Steep channels often have steep adjacent hillslopes and these provide more sediment to a river than low angled slopes, therefore sediment supply per unit area increases in an upstream direction (Leopold and Maddock 1953). Although sediment supply per unit area is high, steep reaches are commonly supply limited because the catchment area is still relatively small and the river has enough hydraulic capacity to move the available load (Montgomery and Buffington 1997). The result within a supply limited reach is often channel erosion and scour. Steeper channels such as Club Lake Creek at Clarke (cascade-pool channel) and Geehi River above Geehi Reservoir (step-pool channel) are more resistant to changes in sediment and discharge than lower gradient channels such as Murray River at Tom Groggin (pool-riffle channel) (Montgomery and Buffington 1997). In lower gradient channels, sediment supply outpaces sediment transport and so deposition occurs. Within these transport limited reaches, the storage capacity is higher and so not only are they less resistant to changes, any morphological changes that do occur are more pronounced and longer lasting (Montgomery and Buffington 1997).

In the Snowy Mountain rivers, the DEM-derived long-profile channel slope decreased with increasing catchment area (Fig. 50, R^2 = 0.71) as predicted by Leopold and Maddock (1953), however, reach-scale channel slope showed a similar but much weaker trend (R^2 = 0.08), highlighting localized reach-scale variability (Fig. 50). The long profile channel slope calculation averages out the overall channel gradient, smoothing out the variations of each individual reach. Mountain streams commonly demonstrate spatial variability in channel form between reaches and this possibly explains the spread in the data of sites with medium sized catchment areas.

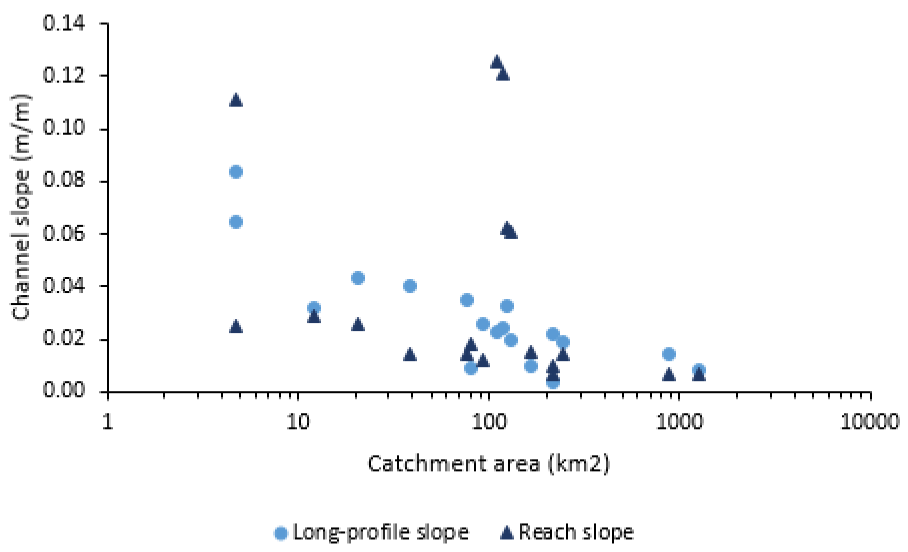

Figure 50. The long-profile and reach-scale channel slope calculated for Snowy Mountain rivers using the 1-arc second DEM. Long-profile channel slope decreased with increasing catchment area, reach-scale channel slope followed the same trend aside from Club Lake and sites with catchment areas 79-215 km^2 where several sites had steep gradients.

6.2 Climatological characteristics

Similar to its hydrology, Australia's rainfall is known for its spatial and temporal variability (Chowdhury and Beecham 2010; Chowdhury et al. 2015). Notwithstanding this, the Australian climate has also been changing during the past century as temperatures have increased and decreasing rainfall trends have occurred. Mean nationwide temperature increases have risen from 0.09°C/decade for the period 1910-2006 to increases of 0.19°C/decade for the period 1970-2006 (Chowdhury and Beecham 2010). Through the same period, rainfall patterns have shown decreased precipitation over the eastern portion of Australia (Australian Bureau of Meteorology 2009; Lavender and Abbs 2013) due to an increase in El Niño events that result in drier conditions on the east coast, the decline in rain producing weather systems known as cut-off lows (Lavender and Abbs 2013) and a southward shift in weather systems moving across Australia (Frederiksen and Frederiksen 2007). South-eastern Australia experienced the worst drought on record from 1997-2009 (CSIRO 2010), a phase that was followed by the wettest two-year period ever documented (Chowdhury et al. 2015). Throughout this period of change, the time series analysis on the Snowy Mountains annual maximum river discharge records suggest that the size of annual maximum floods has remained stable at various sites from 1911-2010 (Fig. 36).

The spatial and temporal variability of Australian rainfall and discharge patterns are demonstrated by the results of the seasonal trend analysis. Snowy Mountain rivers consistently receive the bulk of their precipitation over the winter months (Fig. 23-b) during the period of highest relative humidity (Fig. 23-d), and maximum discharge rates occur between August and November (Fig. 35-a). This trend contrasts with the east coast and semi-arid rivers (Figs. 23 and 35). A fundamental difference between the regions of comparison is that a percentage of the precipitation over the Australian high country falls as snow. The effect of snow on the region's hydrology is as follows:

1) Rain mixes with melt and increases the effective precipitation at various times through the autumn, winter and spring (Hamlet et al. 2007);
2) Rain-on-snow events driven by fluctuations in the rain/snowline impact the amount of runoff generated and the rate of snowmelt (Sui and Koehler 2001; Lundquist et al. 2008);
3) Changing modes of potential-runoff conveyance as soil moisture levels fluctuate (Bengtsson and Westerstrom 1992; McNamara et al. 2005; Hamlet et al. 2007).

Single rain events can have a drastic impact on a snowpack. For example, during the period 22/23 July 2016, 148 mm of rain fell over Perisher Valley (elevation 1738 m) in the Snowy Mountains. Figure 51 shows a 51 cm decrease in snowpack at nearby Spencers Creek (elevation 1830 m, Snowy Hydro Limited 2016). With a snow water equivalent of 25-50% depending on the density of the snowpack, the amount of snow converted to runoff during that single event was substantial. In addition, with the increased elevation of the rain/snowline, a greater percentage of the Snowy Mountain catchments received rain, rather than snow, on an already saturated landscape, further contributing to runoff. On July 22, the daily maximum temperature in Perisher Valley was 8.1°C (Australian Bureau of Meteorology 2017). Using a lapse rate of 0.55°/100m (Bormann et al. 2013), freezing level at that time was at an elevation of approximately 3138 m. At that temperature, 100% of the study catchments were receiving rain, a total area of 3788 km^2. Had freezing level occurred at

1500 m, the area receiving rain would have reduced to 2013 km^2. The effective precipitation of that event, being a combination of rain plus melt, resulted in a rapid boost of water into the local rivers. This is a distinguishing characteristic of mountain rivers, as non-snowmelt rivers are not subjected to the same vagaries in temperature-driven precipitation types, nor do they experience rain-on-snow events.

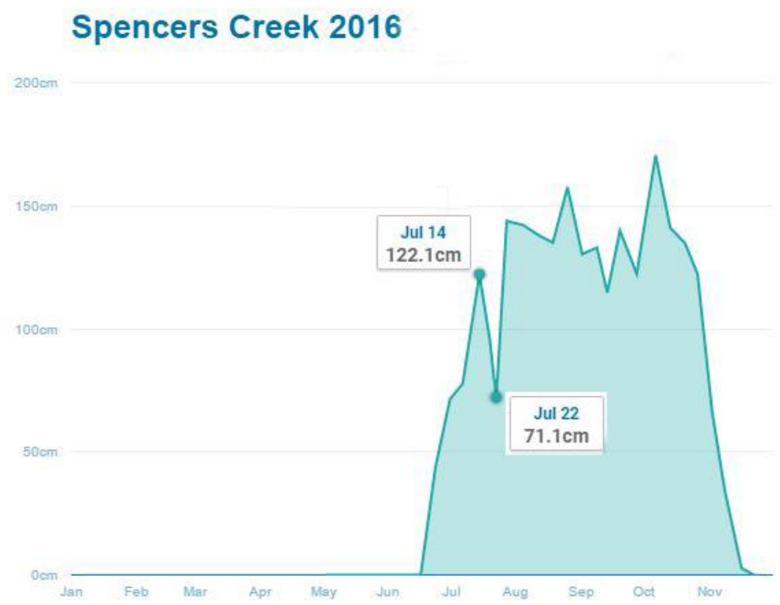

Figure 51. After 148 mm of rain fell over Perisher Valley in the Snowy Mountains, a 51 cm decrease in snowpack was measured at the nearby Spencers Creek snow plot (Snowy Hydro Limited 2016)

Events like the one which occurred in Perisher Valley also occur in other mountainous regions. In January 1997, the Truckee River Basin, USA, experienced severe flooding causing approximately USD$540 million of damages (USGS 1997). Over five days, 700 mm of rain fell to elevations of 3000 m on to an exceptionally deep snowpack. At elevations below 2100 m, the snowpack was reduced from 180% of normal down to 40%. At the peak of the flood, some of the highest river stage and discharge levels ever measured were recorded within the basin, and flows approached that of a calculated 100-year event.

As global climates warm, mid-winter rain-on-snow events are likely to increase (Leung et al. 2004) and leading to more runoff during those times. However, in maritime locations like Oregon, USA and also in Australia (Hennessy et al. 2008; Chubb et al. 2011; Sánchez-Bayo and Green 2013), as winter snowpacks decrease and the number of days with snow on the ground are reduced, the frequency of rain-on-snow events would lessen (Leung et al. 2004). This would result in a fundamental change to the hydrology of mountain rivers with major ecological, social and economic implications. For example, the predictable Snowy Mountains climate has contributed to the success of the Snowy Hydro Scheme that was built on the notion that the Snowy Mountains were a gift to the agricultural lands of the Monaro region (Hardman 1968), and that today forms a major portion of Australia's electricity network. The Scheme relies on snow melt to fill its network of reservoirs and over recent years, has actively implemented cloud seeding strategies to ensure water security in response of decreasing natural snowpack (Heggli et al. 2004).

In comparison to winter storms over the mountains that are often protracted events covering a large area (Lundquist et al. 2008), arid and semi-arid regions storms are commonly heavily localized and short in duration. Convective thunderstorms in areas like Central Texas produce rare, intense rainfall rates of up to 300 mm/hour (Baker 1977), that far exceed the mountain storms described above. Temperate regions can also experience extreme weather events. Examples are the 1994 and 1998 storm events along the Illawarra escarpment that produced narrow bands of rainfall rates more than 120 mm/hour (Reinfields and Nanson 2001). The Illawarra region, 80 kilometres south of Sydney, features a narrow coastal plain that rises quickly to an escarpment with an average elevation of approximately 460 m. Local weather is influenced by proximity to the coast and the orographic influences of the topography. The extreme rainfall events described produced half of the annual precipitation in a matter of hours.

6.3 Hydrologic variability

A region's hydrologic variability can be examined using measures such as the flash flood magnitude index (FFMI), coefficient of variation (CV) and baseflow index (BFI). All three measures were calculated for the Snowy Mountains, and the east coast, and semi-arid rivers enabling a comparison between each region.

6.3.1 Flash flood magnitude index

The results from the FFMI analysis show that Snowy Mountain rivers have a mean FFMI of 0.27, while the comparison east coast rivers have a mean FFMI of 0.74 and the semi-arid rivers have a mean FFMI of 0.62 (Fig. 37). The FFMI is unit-less and thus enables flow variability comparisons between rivers in different regions (Baker, 1977; McMahon et al., 1992; Erskine and Livingston, 1999). FFMI values greater than 0.60 are deemed to show high flood variability (Erskine and Livingstone 1999) and the mean FFMI for global rivers was found to be 0.28 (McMahon et al., 1992). The implications of the results found in this current study is that Snowy Mountain rivers do not experience large flood variability, but east coast and semi-arid rivers do.

Australian rivers and particularly those with large catchments exhibit low mean annual runoff values (McMahon et al. 1992) and because regions with low runoff are considered to have high variability, it was surmised that Australian rivers on average have higher variability in both annual flows and peak flood discharges. A summary of prior work showed FFMI results of 0.65, 0.62 and 0.40 at various sites around eastern Australia (Erskine and Livingstone 1999) and these results are up to 2.3 times higher than the global mean and conform with the notion of high flood variability. However, Erskine et al. (1999) calculated the FFMI on the Snowy River at Jindabyne using only pre-dam flow data and their study returned an FFMI of 0.20. From this they concluded that due to the low flow variability of the pre-regulation Snowy River, the channel forming flows were relatively frequent in occurrence and moderate in volume (Erskine et al., 1999). The results of this thesis further demonstrate that the rivers in the Snowy Mountains region have a consistent hydrologic regime with less variability then elsewhere in Australia.

Climate is a major contributor to a river or region's FFMI and the same arid conditions that lead to steep flood frequency ratio curves can also drive higher FFMI values (Baker 1977). For example, Baker (1977) found that periods of intense rainfall over an otherwise dry region contribute to FFMI values of 0.90 in central Texas, USA. However, climate and aridity are not always the determining factor. Narrow or steep terrain that concentrates runoff producing high discharge with short lag time

also contributes to high FFMI values, as does a situation where a rivers baseflow is low, but storm flow is high (Baker 1977).

The implications of high FFMI values in small catchments were said to include a large potential for catastrophic flood events that cause gross changes to channel morphology (Baker 1977). This was thought to be especially true if the flood event were to differ greatly from the regular flood regime of the river. Snowy Mountain and east coast rivers do not appear to follow this trend because they don't demonstrate a strong relationship between catchment area and FFMI (Fig. 52-a). However, plotting each river's flood frequency factor (Malamud and Turcotte 2006; Rustomji et al. 2009) against the corresponding baseflow highlights that when compared to the east coast rivers, the commonly occurring flows of Snowy Mountain rivers are more like the flood flow (Fig. 52-b). This trend was similar when the predicted 50-year flood event was divided by the predicted 5-year flood event (Appendix. 10). The findings suggest that the hydrology of the mountain rivers analysed is more stable than those studied by Baker (1977) and that Snowy Mountain river hydrology is more stable than that of east coast rivers.

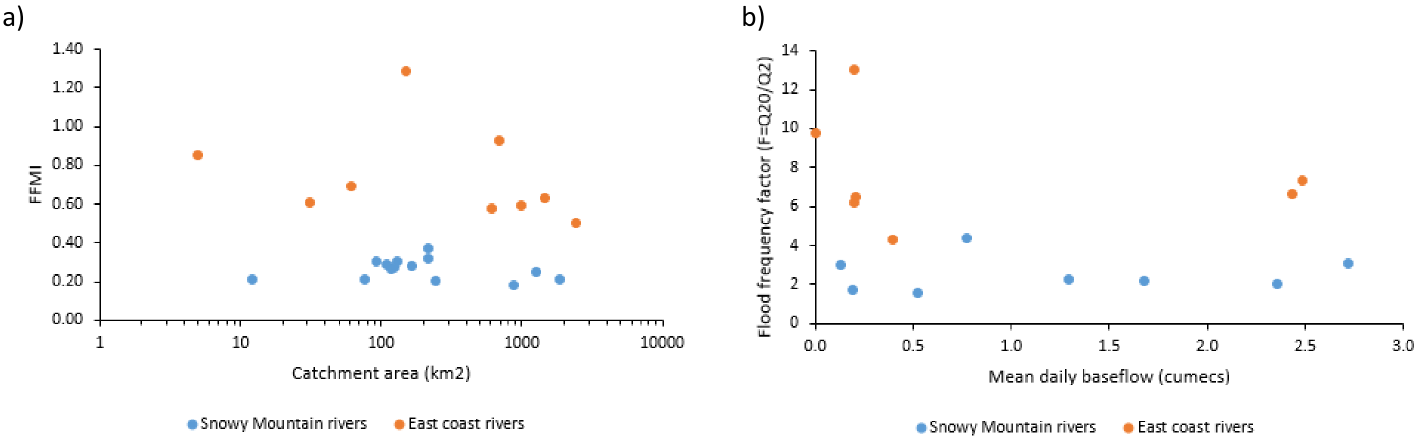

Figure 52. a). FFMI values and their corresponding catchment area for Snowy Mountain and east coast rivers demonstrate that there is not a strong relationship between these variables (Snowy Mountain rivers R^2 = 0.03, east coast rivers R^2 =0.10). b) The difference between flood flow and baseflow for Snowy Mountain and east coast rivers demonstrates that Snowy Mountain rivers have lower F values that are closer in size to the mean daily baseflow across all sites. Calculated using the flood frequency factor F=Q20/Q2 (Malamud and Turcotte 2006; Rustomji et al. 2009).

6.3.2 Coefficient of variation

The runoff coefficient of variation (CV) has been used as a measure of flow variability (Chiew and McMahon 1993; Mazvimavi et al. 2007; Morton et al. 2010) with arid climates found to produce high runoff CV values of 1.20 – 2.25 (Mazvimavi et al. 2007) compared to wet regions such as Tasmania where low runoff CV's of 0.15 – 0.25 have been recorded (Chiew and McMahon 1993). The results of this study show the range of values in Snowy Mountain rivers to be 0.20 – 0.69 (Fig. 38). These values are low compared to the east coast, 0.51 – 1.19, and semi-arid rivers, 1.10 – 1.79. Once again, the Snowy Mountain rivers exhibit low levels of variation in their flow regime and these low runoff CV values suggest that the difference between high, low and mean flows is not extreme. The mean runoff CV for the Snowy Mountain rivers was 0.38 which is lower than the nationwide mean of 0.58 (Chiew and McMahon 1993).

The results also demonstrate that as elevation increases in the study area, the CV for runoff decreases (Fig. 38), demonstrating that elevation is an important driver of Snowy Mountain hydrology. In addition, the CV for mean annual precipitation (for the same period of record as each flow gauge) was low for both high elevation sites above 1500 m and sites below 1500 m (Table. 9), suggesting that the variability in runoff CV is not linked to variability in elevation-driven precipitation. Rather, the variability can be attributed to other elevation effects. Previous work by Reinfelds et al. (2014) found that elevation significantly impacts runoff, flow magnitude and CV values (Reinfelds et al. 2014). The timing and duration of the annual period of evapotranspiration is affected by snow cover, and this is directly linked to the proportion of precipitation that is turned into runoff. The high elevation catchments in the Snowy Mountains receive the most precipitation and windblown snow loading. These catchments also have the lowest rates of evapotranspiration, demonstrate the least hydrologic variability and therefore have the lowest CV values.

6.3.3 Baseflow analysis

A river's discharge may be divided into quickflow and baseflow. Quickflow is sourced from rainfall and pore spaces within the soil and is likely to occur soon after a storm, while baseflow is obtained from longer-term storage such as groundwater aquifers and is what maintains streamflow during dry periods (Rouhani and Malekian 2013; Stewart 2015). Baseflow is a critical component of most river's annual flows because riverine species are adapted to the local baseflow regime and many human populations around the world are reliant on baseflow for navigation, recreation and water supply (Gan et al. 2015). Snowy Mountain rivers have higher BFI values than east coast and semi-arid rivers (BFI's of 0.41, 0.25 and 0.19 for Snowy Mountain, east coast and semi-arid rivers respectively; Fig. 39) demonstrating that baseflow contributes a greater percentage of total discharge in Australia's snowmelt rivers. Comparing BFI's between regions and even between neighbouring catchments is difficult due to differences in precipitation, elevation, temperature and aquifer properties (Gan et al. 2015), yet a mean BFI of 0.57 was found in alpine rivers in North-western China (Gan et al. 2015) and a mountain fed semi-arid region in Iran also returned a BFI of 0.49 (Rouhani and Malekian 2013). These results are not too different to the BFI of 0.41 calculated for the Snowy Mountain rivers and the common ground between the three sets of results is the presence of mountains. Even if comparison is difficult, in general, the higher the BFI value, the more consistent the flow (Gordon et al. 2004) and the results of this analysis support the flow scaling findings discussed below that Snowy Mountain rivers flow with more regularity than the east coast and semi-arid rivers. This regularity somewhat dampens the effect of floods in the region and results in the low flow variability of Snowy Mountain rivers.

Out of the twelve calculated BFI values for Snowy Mountain rivers, the three largest were more than 0.50, with a max of 0.55. Trancoso et al. (2016) found BFI values greater than 0.60 in the Victorian Alps and northern Tasmania, regions that experience wet climates and snowmelt like that of the Snowy Mountains. The same study also calculated low BFI values (>0.15) for ephemeral catchments draining west of the Great Dividing Range, which is similar to the results of this thesis.

6.4 Flood frequency analysis

6.4.1 Flood frequency ratio curves

Steep-gradient flood frequency ratio curves indicate a large difference in volume between larger and smaller floods, while the opposite is true for low-gradient flood frequency ratio curves. Low-gradient flood frequency ratio curves are caused by small inter-annual variability, most likely a function of a regular and predictable seasonal climate with a consistent discharge pattern (Pickup 1984; Rustomji et al. 2009), while steeper curves are often due to somewhat regular large flood events (Erskine and Livingstone 1999) that differ greatly from the mean annual flow (Baker 1977). The flood frequency ratio curves for Snowy Mountain are low-gradient, particularly in comparison to the east coast and semi-arid rivers as shown in Figure 41.

Flood frequency ratio curves allow comparison between individual rivers, different catchments and different regions/climate zones. 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 the Snowy Mountain rivers covered by this thesis, rivers in a study by Pickup (1984) featured low-gradient flood frequency ratio curves. These examples, however, were in tropical Papua New Guinea where Pickup (1984) surmised that local conditions ensured ample moisture was available for prolonged periods throughout the year and so losses through infiltration and evaporation were low before runoff began. In these situations, the soggy ground maintains a regular input of water to the river which makes the overall flood frequency ratio trend much less dramatic than for arid region rivers (Fig. 41). Snowy Mountain rivers have a comparable, low-gradient flood frequency curve that may suggest some similarities in the ground conditions between the two areas. While the Snowy Mountains receive significantly less mean annual precipitation than Papua New Guinea, 1,648mm vs 8,000-11,000mm, and wet season humidity levels are 85% in the Australian highlands compared to 100% in Papua New Guinea (Pickup, 1984; Bureau of Meteorology, 2015), the mean annual runoff coefficients are similarly high in both regions, 86% in the Snowy Mountains and 70-85% in Papua New Guinea (Pickup & Chewings, 1983). These large annual runoff coefficients demonstrate that in both locations the great majority of precipitation across the year is converted to runoff and enters the river network. In the rivers studied by Pickup (1984), the 100-year flood was approximately twice the size of the 2-year flood (Fig. 53). In comparison, in the Snowy Mountain rivers, the predicted 100-year flood is almost five times as large as the predicted 2-year flood, on the east coast rivers, that flood is 23 times larger and in semi-arid rivers it is 50 times larger (Fig. 41). The results of the comparison show that Snowy Mountain river flood frequency ratio curves are much more like those in Papua New Guinea than they are to the east coast and semi-arid rivers.

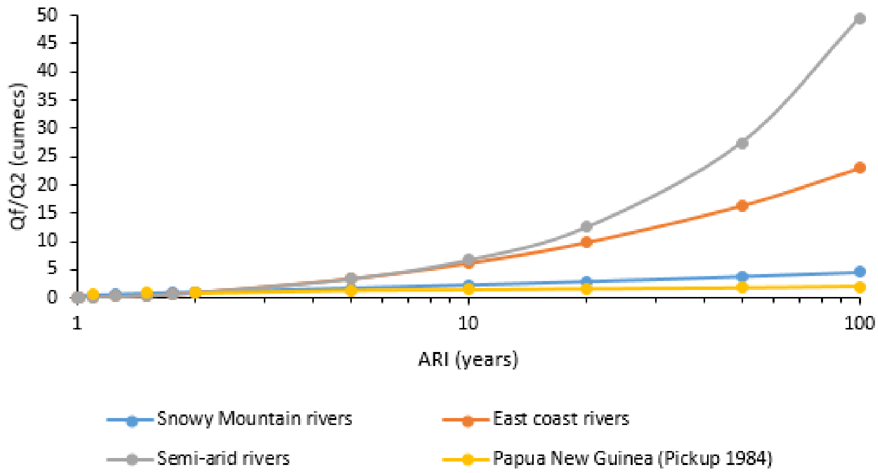

Figure 53. Flood frequency ratio curves for Papua New Guinea rivers from prior research by Pickup (1984) alongside rivers from the Snowy Mountains and the comparison non-snowmelt rivers used in this thesis. Data source: (Pickup, 1984).

As with mountainous regions elsewhere, a factor that contributes to the precipitation and runoff profile of the Snowy Mountain rivers is elevation. With increased elevation, a greater proportion of precipitation falls as snow and rates of melting are reduced (Biggs and Whitaker 2012). Elevation impacts vegetation species distribution and this affects the speed at which snow on the ground melts. In California's Sierra Nevada's, forest covering the montane and subalpine zones were found to slow the pace of snow melt (Biggs and Whitaker 2012). Snow provides an insulating barrier that reduces or prevents soil evaporation (Miralles et al. 2011; Hunsaker et al. 2012; Reinfelds et al. 2014) and so through persistent snow cover, the ground is kept wet for prolonged periods, peaking in annual soil moisture content after spring snowmelt (Nelson et al. 2014). Research has also demonstrated that elevation impacts rates of evapotranspiration which decrease as elevation increases (Reinfelds, et al. 2014) thereby saving more water for release into rivers. In combination, these factors may drive the difference in flood frequency ratio curve gradients for the NSW rivers analysed and for the similarity between the curves from the Snowy Mountain rivers and the Papua New Guinean rivers.

6.4.2 Flow scaling

Flood magnitude scales by catchment area in the Snowy Mountains and on east coast rivers, meaning that as catchment area increases, so too does the volume of each calculated ARI flood. However, Snowy Mountain rivers have much smaller floods in comparison to the east coast rivers for a given catchment area and so the scaling relationships are smaller for Snowy Mountain rivers than they are for the east coast rivers (Fig. 42-a). The vertical spread between the data points at each return interval is visibly less for Snowy Mountains rivers than it is for the east coast rivers, and the gradient of the curve is also less steep for the Snowy Mountain rivers. The result of this can be seen in the data where in Snowy Mountain rivers there is relatively little difference between the magnitude of 100 and 2-year floods across all catchment scales when compared to east coast rivers. The individual 2-year and 100-year floods are also similar in size across all catchment scales and these results demonstrate that there is much less variability between flood volumes with varying basin scale in the Snowy Mountains than in east coast rivers.

The unit area discharge results show that smaller catchments are relatively more productive at producing runoff than large catchments because in both regions, as catchment area increases, the discharge per unit area decreases (Fig. 42-b). These results may be expected because as catchment area increases, it becomes less likely that a storm will cover the entire catchment, leaving ever larger areas within the drainage not contributing to the overall runoff. Segura and Pitlick (2010) noted that rivers with small catchments are subjected to more frequent higher flows and less frequent intermediate flows in comparison to rivers with large drainage areas (Segura and Pitlick 2010). Because of this phenomenon, it was suggested that it is possible for rivers in small catchments to have maximum flood discharges 200 times in excess of their mean annual discharge, where in larger catchments flood discharges may only reach around 10 times the mean annual discharge (Mackin 1963). To understand if Australian rivers reached the extremes of Mackin's (1963) data, maximum discharge was divided by mean discharge for sites with complete data records, including the Snowy Mountains, east coast and semi-arid rivers. The results did not show the suggested result (Fig. 54). The smallest catchment analysed, Cootapatamba Ck at Ramshead, (4.69 km^2) had a maximum discharge 2.6 times larger than the mean annual flow and the largest Snowy Mountains catchment, Murray River at Biggara (1256 km^2) had a maximum discharge 3.0 times larger than the mean annual flow. These results likely occurred because the mean annual flow of Snowy Mountain rivers is high relative to elsewhere in Australia. However, this does not explain why the biggest overall catchment, the semi-arid Warrego River at Fords Bridge, (60,600km^2) only had a maximum discharge 42 times larger than its mean annual flow.

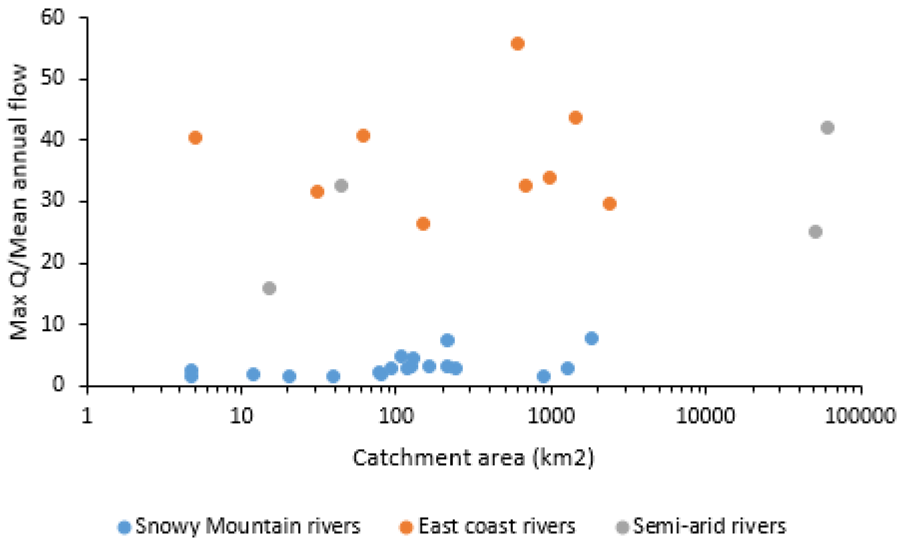

Figure 54. The maximum discharge (ML/d) divided by the mean annual flow plotted against catchment area demonstrated that smaller catchments do not have disproportionately large flood discharges when compared to their mean discharge as per Mackin (1963).

For the smallest storms (1.1 and 2-year), Snowy Mountain rivers contribute more discharge per unit area than the east coast rivers do at each catchment scale (Fig. 42-b). As the floods increase in magnitude, east coast rivers contribute increasingly more discharge per unit area than do the Snowy Mountains rivers. This trend can be seen by the steeper gradient of the east coast river curves compared to those of the Snowy Mountain river curves in Figure 42-b. In east coast rivers, a 100-year storm in a catchment greater than 1000 km^2 contributes 25.2 times the cumecs/km^2 than a 2-year storm does, where in the Snowy Mountains the same relationship at the same catchment scale

is only 5.3 times. That the smaller flows are of greater magnitude in Snowy Mountain rivers suggests that the baseflow is higher than in east coast and semi-arid rivers. This fact plays an important role in the flow variability of a region. In the Snowy Mountains, the rivers go from having some daily flow in their channel, to more when they flood. The east coast rivers go from having less daily flow to a lot more during periods of flood and the semi-arid rivers go from having little-to-no flow up to very large floods.

6.4.3 Inundation frequency at gauge cross-sections

Gauge cross-sections at the study sites vary considerably in their cross-sectional form, from confined coarse-grained cascade systems to the more alluvial pool and riffle systems. Cross-sectional geometry also varies from simple to compound cross-sections. Plotted cross-sections were graphed with the height to which 2, 10 and 20-year ARI flood events would fill each gauge cross-section (Figs.43.a-f). This enabled a visualization and comparison of the vertical spread between the various floods between the regions. The mean height difference between a 20-year and 2-year flood in the Snowy Mountain rivers was 1.2 m whereas on the east coast rivers it was 3.2 m and for semi-arid rivers it was 2.0 m. The results showed that the Snowy Mountain river floods have less vertical difference between larger and smaller floods than the east coast and semi-arid rivers and further solidifies the overall results which show that Snowy Mountain river floods don't show the same variability as non-snowmelt rivers.

Flow variability impacts channel complexity, with greater variability producing more intricate channels (Thoms and Sheldon 2002). Geomorphological features such as bars and floodplains are created through the vertical and horizontal deposition of sediment (Nanson 1986; Vietz et al. 2006) and can be modified through changes in discharge. While the cross-sections shown in Figures 43.a-b and Appendices 2-3 demonstrate the compound nature of each Snowy Mountain river channel, particularly Murray River at Biggara, the semi-arid channels with their higher flow variability (Fig 43. e-f, Appendix 5) are visibly more complex. The role of in-channel and floodplain features include temporary sediment storage that increase habitat diversity (Gordon et al. 2004; Charlton 2008) and provide an important source of carbon to the river food web (Sheldon and Thoms 2006; NSW Office of Water 2014). The low flow variability and less complex nature of Snowy Mountain river channels suggests that these rivers may have less complex ecosystems than rivers in other regions.

6.5 Runoff coefficients

Not all precipitation falling over a catchment makes it to the river with water lost through processes such as infiltration into the ground and the returning of water to the atmosphere through evapotranspiration. Runoff coefficients show the percentage of precipitation that is converted to runoff within a catchment and have been used to gain an appreciation of catchment hydrology (Stewardson et al. 2005; Blume et al. 2007; Hrachowitz et al. 2013; Reinfelds et al. 2014). Runoff coefficients may be calculated on an annual or event time scale. Mean annual runoff coefficients show the overall trend of a catchment, while event-based runoff coefficients provide an understanding of how a catchment behaves in response to storms of a particular magnitude (Blume et al. 2007).

6.5.1 Annual runoff coefficients

The mean annual runoff coefficient for Snowy Mountain rivers was 0.86, in comparison, values of up to 0.80 were calculated in alpine region of Austria (Merz and Blöschl 2009). The same Austrian study noted that catchments receiving more than 1000 mm/y of precipitation had mean annual runoff coefficients greater than 0.25 (Merz and Blöschl 2009), aside from the study site at Maragle Creek, the Snowy Mountain rivers demonstrated the same results. The overall mean value for Snowy Mountain rivers was influenced by five sites within the study area that have mean annual runoff coefficients greater than one, meaning that at these locations, runoff exceeds precipitation. Each of these sites have mean catchment elevations higher than 1840 m and are in the heart of the Snowy Mountains "Main Range", near the highest point in Australia, Mt Kosciuszko. Because of the impact of elevation on vegetation type and distribution and because higher elevations in alpine regions have a greater percentage of precipitation falling as snow, elevation is a major driver of runoff coefficient values (Reinfelds et al. 2014). Evapotranspiration is an important method of energy flux and is made up of transpiration, interception, bare soil evaporation and snow sublimation. Globally, transpiration of water from plants to the atmosphere accounts for 80% of evapotranspiration (Miralles et al. 2011) and so as vegetation diminishes through increased elevation, transpiration rates decrease and runoff coefficients may increase. The anomalous data where runoff coefficients are greater than one is likely due to several reasons: 1) under catch of precipitation, and 2) windblown snow that is not registered by BoM gridded rainfall data leading to under-recording of precipitation over the catchments (Reinfelds et al. 2014). As discussed earlier, areas covered by snow have lower evaporation rates in comparison to regions without snow and so wet ground in an area receiving an extra deep snowpack through wind loading will remain protected from evaporation for a longer period. This will also impact runoff coefficient values.

6.5.2 Event based runoff coefficients

This study analysed the event based runoff coefficients for 2, 10, 20 and 50-year discharge events for two rivers in the Snowy Mountains and two rivers in the east coast dataset (Fig. 49). The trend in both regions showed that for the predicted 10 and 20-year flood events, the larger catchments had higher runoff coefficients and that the event based runoff coefficients for the two Snowy Mountain rivers conform with the annual runoff coefficient at each site. The data range for the Murray River at Biggara was 0.21 – 0.32 for the event based and 0.32 for the mean annual runoff coefficient. For Maragle Ck at Maragle, the range was 0.03 – 0.15 for the event based, and 0.15 for the annual. At these sites, up to 32% and 15% of the annual precipitation falling over the catchment is converted to runoff. The sites with the lowest mean catchment elevations, Maragle Ck at Maragle (850m), Murray River at Biggara (1100m) and Murray River at Tom Groggin (1203m), correspond with the lowest annual runoff coefficients (Appendix 1). These low runoff coefficient values occur because evapotranspiration increases rapidly with decreasing catchment mean elevation within energy limited catchments (Reinfelds et al. 2014). A catchment will be energy limited if more heat/sunlight is needed to drive higher evapotranspiration rates, conversely, a catchment will be supply limited if more water is required.

The east coast rivers event based runoff coefficients were 0.25 – 0.95 on the Shoalhaven River at Warri and 0.13 – 0.42 on the Timbarra River at Billyrimbah. The range of mean event-based runoff coefficients in the lowest elevation catchments of the Snowy Mountains were accordingly much lower than those of the east coast rivers. 0.17 – 0.24 for the Snowy Mountains, compared to 0.19 – 0.79 for the east coast rivers (Appendices 13). The low range in values for Snowy Mountain rivers further demonstrates a low level of hydrologic variability and are comparable to the mean event based runoff coefficient of 0.28 for rivers in the Italian Alps (Norbiato et al. 2009).

The driver behind the lower variability of the event based runoff coefficients in Snowy Mountain rivers does not appear to be lower rainfall intensity and the highest rainfall intensity did not produce the highest runoff coefficient. For example, Appendix 13 shows that Murray River at Biggara had an event based runoff coefficient of 0.32 for the 20-year event with a precipitation rate of 5.0 mm/hour while the 50-year event had a lower event based runoff coefficient of 0.22, with a higher precipitation rate of 7.1 mm/hr. The contributing factor may then be higher low flows which take the edge off the larger flood events in Snowy Mountain rivers and influence the overall low flood variability of rivers in that region. The greatest increase in event based runoff coefficients in east coast rivers occurred by a factor of 2-12 between the 2 and 10-year floods where in the Snowy Mountain rivers this change was much less significant. Higher low flows are a product of local conditions that keep the ground wet for prolonged periods, such as the dependable wet season climate and the influence of snow in the upper elevations.

6.6 Implications of research and how it relates to environmental flow assessments

The aim of environmental flow programs is to provide water in regulated rivers for ecological and geomorphological benefit (Graf 2006; Bobbi et al. 2014). Environmental flow allocations are often significantly less than pre-dam discharge volumes. The Snowy River below Jindabyne Dam for example, receives only 21% of its historical mean annual flow (Reinfelds et al. 2013). To use the allocated water so that environmental flow goals are met, discharge regimes that are scaled proportionately to a suitable analogue river and that mimic natural hydrologic patterns should be used (Reinfelds et al. 2014). As part of a complete evaluation, environmental flow assessments need to consider analyses such as those done for this thesis. Through use of historical gauge data from the pre-dammed river itself, and/or gauge data from local rivers, an understanding of the regional hydrology can be attained. The seasonal discharge profile can help determine the timing and duration of flow releases while flood frequency ratio curves and flow scaling provide information on the range in magnitude of discharge on the former river or in the region, so that appropriate flows are designed. The FFMI, runoff CV and BFI demonstrate the flow variability suitable for a river. Understanding the scale of variability that a natural river system has adapted to, provides an indication of the level of vulnerability to change, that system has (Nolin 2011). Systems adapted to low variability such as the Snowy Mountain rivers, are more easily pushed beyond their level of resilience when confronted with change (Nolin 2011) and future research could determine how climate change will affect the regions stable hydrology. The BFI also provides knowledge of what proportion of discharge is comprised of the low flows that are critical for ecosystem health, water supply security, navigation and recreation. The plotted flood level heights within a surveyed cross-section highlight how a channel adjusts its geometry for the range of flows that it experiences. Environmental flow programs should ensure inundation relationships to inset channel features are preserved so that carbon storage and exchange and habitat diversity is maintained (Thoms and

Sheldon 2002). Runoff coefficients enable an assessment of a catchments efficiency at converting precipitation to discharge and may be calculated at various locations along a river. This sort of assessment can aid in environmental flow programs that target specific features such as wetlands where dam releases can bolster mean annual precipitation in the catchment downstream of a dam so that sufficient water is provided to achieve ecological and geomorphic goals.

Through water budgeting by resource managers, the annual amount of water allocated for an environmental flow program is predetermined and so it is important any releases are scaled appropriately to the overall water allocation. If this is not considered, and “floods” are released only for specific goals such as flushing flows, then proportionately too much water may be released for an individual flood event resulting in an overall environmental flow program that is unnatural and ineffective. An example of this failure was provided by the environmental flow regime in place on the Snowy River below Jindabyne Dam from 2009-13 where 51% of the annual water allocation was released in a single pulse (Reinfelds et al. 2014). Two issues arose from this strategy. Firstly, the artificial flood was 34-40 times larger than the mean post regulation flow and was drastically out of line for the regional hydrology demonstrated by this thesis which found that the 100-year flood is only five times larger than the 2-year flood (Fig. 41). This flushing flow was equivalent to the 1.1-year pre-regulation flood but was grossly out of proportion to the post-regulation regime and so likely resulted in channel scour rather than in-channel feature creation. The second issue was that by releasing such a high percentage of the annual flow allocation over a 15-day period, the remainder of the flow allocation had to be spread out over the remainder of the year, resulting in constant low flows and an overall departure from the lack of flow variability seen in Snowy Mountain rivers (Figs. 37-38 and 41-42). Fortunately for the Snowy River, the natural flow scaling method has since been implemented which models the environmental flow program hydrograph on a local river with similar hydrology to the post-regulation Snowy (Reinfelds et al. 2013).

Chapter 7 – Conclusion

Analysis of eighteen Snowy Mountain rivers found that they were mostly set within partly-confined valley settings and the reaches predominantly had cascade, step-pool, plane-bed and pool-riffle channel morphologies (Montgomery and Buffington 1997). Steeper reaches such as cascade, step-pool and plane-bed are often sediment supply limited and act as conduits, transporting sediment and water to lower angled, transport limited reaches such as and pool-riffle. Because of the increased competence, supply limited reaches are more resistant to changes in channel geometry than transport limited reaches (Montgomery and Buffington 1997). It is assumed that the size and regularity of floods determine the dimensions of the channel (Huang and Nanson, 2000) and in Snowy Mountain rivers this was demonstrated by the increase in channel cross-sectional area in a downstream direction. The larger channels were more able to accommodate larger flows that are a function of a larger catchment area.

Australian rivers have been said to demonstrate high variability in their hydrology. To understand whether Snowy Mountain rivers conform to the status quo, the hydrology of the eighteen Snowy Mountain rivers was compared to a total of fifteen rivers in non-snowmelt temperate and semi-arid settings. The results show that Snowy Mountain rivers do not exhibit the same hydrological variability that rivers in other Australian settings do. Snowy Mountain rivers have a reliable seasonal climate with orographic precipitation, cool winters and snow. Evaporation is reduced by snow cover that initially insulates the ground, then provides a slow release of water to the rivers. Through these processes, a greater percentage of water reaches the river in Snowy Mountain rivers than in the comparison non-snowmelt settings. This is reflected by high mean annual runoff coefficient values and a higher baseflow than east coast and semi-arid rivers, meaning the difference between mean daily flows and flood flows is less. The flash flood magnitude index and runoff coefficient of variation were low, as was the rainfall coefficient of variation, which was low for both high elevation (>1500 m) and low elevation (< 1500 m) catchments, demonstrating that any differences in calculated runoff coefficients were not caused by elevation driven variability in rainfall. Rather, they were likely to be caused by elevation driven properties such as differences in the proportion of precipitation falling as rain vs snow and by decreasing rates of evapotranspiration (Reinfelds et al. 2014). The vertical spread of flood stage within the Snowy Mountain river channels was less than in the other locations, and the order of magnitude that floods scaled by catchment area was significantly less in alpine setting than it was in non-snowmelt settings. The scaling relationships demonstrate that smaller floods in Snowy Mountain rivers are not too dissimilar in magnitude to larger floods and the combination of all these factors combine to produce low gradient flood frequency ratio curves.

Analyses such as those done for this thesis provide useful information for river managers and policy makers because among other things, they demonstrate the vulnerability of a region to climate change and provide information on how to manage, restore or best use the river resources of an area. Systems such as the Snowy Mountain rivers that are adapted to low variability, are less resilient to change than those adjusted to high variability (Nolin 2011), and so care must be taken to ensure that river systems such as those studied, remain an endowment from nature for all that rely on them.

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Appendices

Appendix 1. General statistics

Appendix 1. General statistics for the Snowy Mountain river gauges

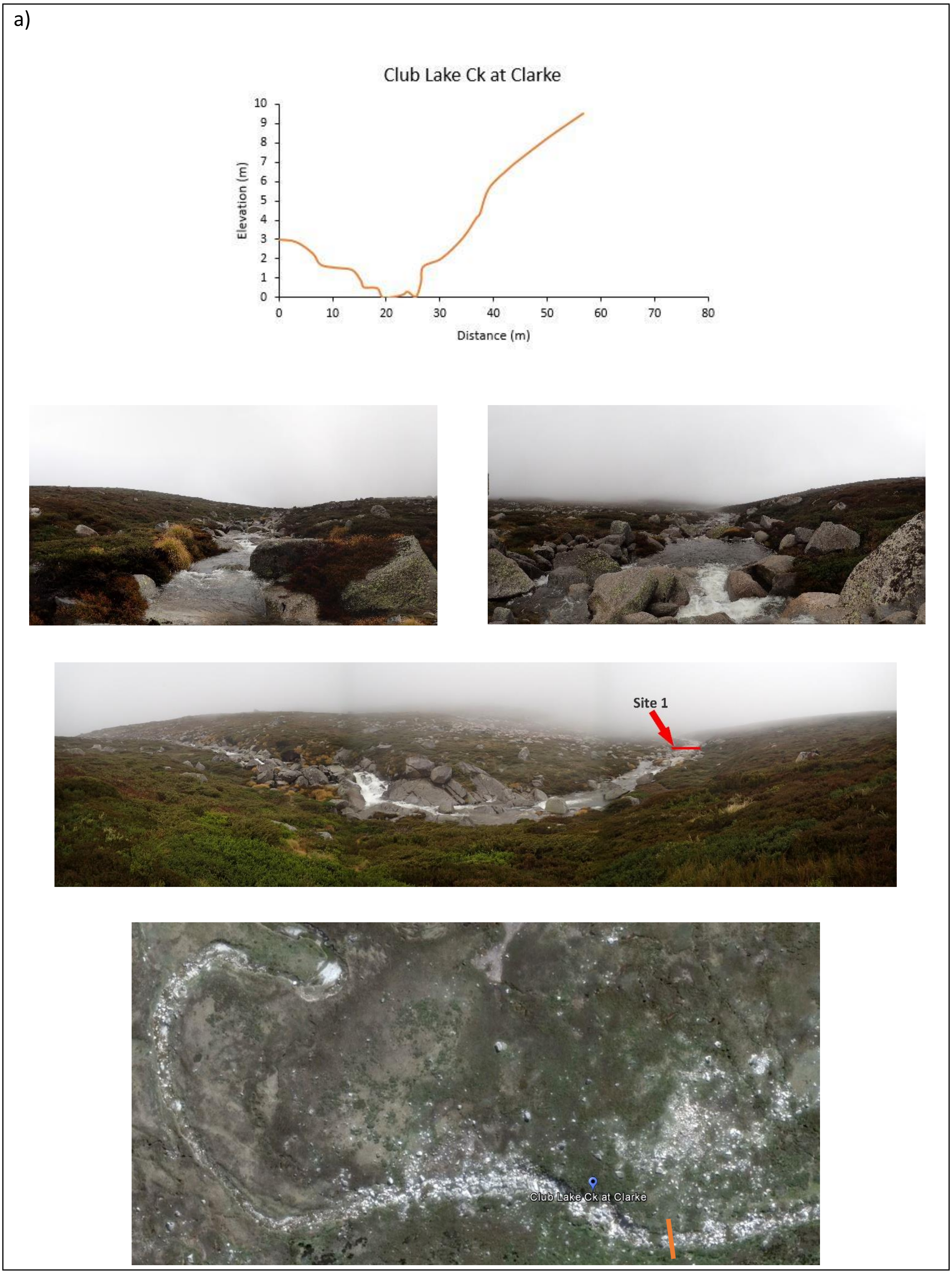
Gauge	River	Years of records	Dam regulated	Catchment area (km2)	Mean catchment elevation (m)	Max gauged stage (m)	Mean annual precipitation (mm) (POR)	Mean annual runoff (mm)	Annual runoff coefficient	Unit discharge (cumecs/km2)
222507	Eucumbene River at Kiandra	11	FALSE	79.18	1454	145.83	1452.23	1398.31	0.96	3.51
222508	Snowy River at Guthrie	13	FALSE	38.78	1933	210.68	2176.83	3121.57	1.43	3.84
222509	Spencers Creek at Paralyzer	18	FALSE	20.66	1842	77.87	2023.19	2344.04	1.16	1.53
222513	Perisher Creek at Blue Cow	15	FALSE	12.07	1811	39.93	2026.79	2002.21	0.99	0.77
222517	Club Lake Creek at Clarke	13	FALSE	4.76	1927	30.58	2053.81	3603.91	1.75	0.54
222522	Eucumbene River at Providence	15	FALSE	164.91	1467	227.67	1337.01	1036.76	0.78	5.42
222527	Snowy River above Guthega Dam	13	FALSE	76.78	1881	320.46	1861.39	2479.16	1.33	6.03
222541	Crackenback River at Paddys Corner	14	FALSE	243.76	1511	245.77	No data	488.66	No data	3.77
401009	Maragle Creek at Maragle	20	FALSE	214.98	850	217.69	1092.04	187.47	0.15	1.28
401012	Murray River at Biggara	20	FALSE	1256.00	1100	334.71	1286.09	461.10	0.32	18.35
401508	Cootapatamba Creek at Ramshead	13	FALSE	4.69	2021	62.30	1951.32	3058.39	1.57	0.45
401514	Murray River at Tom Groggin	15	FALSE	883.95	1203	153.48	1298.98	398.17	0.31	11.15
401554	Tooma River above Tooma Reservoir	10	FALSE	117.77	1526	178.93	1509.95	1219.34	0.81	4.55
401560	Geehi River above Geehi Reservoir	6	FALSE	124.11	1720	372.09	1626.98	1278.88	0.79	5.03
410010	Yarrangobilly River at Yarrangobilly	13	FALSE	91.93	1277	99.11	1429.82	754.73	0.53	2.20
410533	Tumut River above Happy Jacks Reservoir	10	FALSE	129.91	1589	407.86	1455.09	1234.57	0.85	5.08
410534	Happy Jacks River above Happy Jacks Reservoir	10	FALSE	108.99	1530	204.95	1343.60	862.51	0.64	2.98
410535	Murrumbidgee River above Tantangara Dam	10	FALSE	214.57	1404	169.47	1247.94	700.77	0.56	4.76
222501	Snowy River above Jindabyne 1902-1955	53	FALSE	1848.40	1382	940.12	1358	713.8	0.53	41.81

Appendix 1 continued. General statistics for the east coast and semi-arid river gauges

Gauge	River	Years of records	Dam regulated	Catchment area (km2)	Max gauged stage (m)
210066	Merriwa River upstream of Vallance	29.0	FALSE	684	1.46
210086	Munmurra Brook at Tomimbil	19.0	FALSE	606	1.19
419076	Warrah Creek at Old Warrah	26.0	FALSE	150	2.95
206033	Apsley River at Apsley Gorge	29.0	FALSE	2406	1.73
204008	Guy Fawkes River at Ebor	38.0	FALSE	31	2.46
204037	Clouds Creek at Clouds Creek	40.0	FALSE	62	2.68
204033	Timbarra River at Billyrimbah	38.0	FALSE	985	1.65
210069	Muggyrang Creek at Pokolbin site 4	22.0	FALSE	5	0.86
215002	Shoalhaven River at Warri	42.0	FALSE	1450	6.78
424001	Paroo River at Wanaaring	15.4	FALSE	not given	4.00
424002	Paroo River at Willara Crossing	35.5	FALSE	not given	4.32
425016	Box Creek at Cobar	32.2	FALSE	15	1.52
412093	Naradhan Creek at Naradhan	16.8	FALSE	44	1.45
422017	Culgoa River at Weilmoringle	46.6	FALSE	not given	5.91
422006	Culgoa River at downstream Collerina (Kenebree)	66.7	FALSE	51541	6.66
423001	Warrego River at Fords Bridge	39.5	FALSE	60600	2.72
422010	Birrie River at Talawanta	45.6	FALSE	not given	4.22
422029	Narran River at Narran Park	9.4	FALSE	not given	2.89

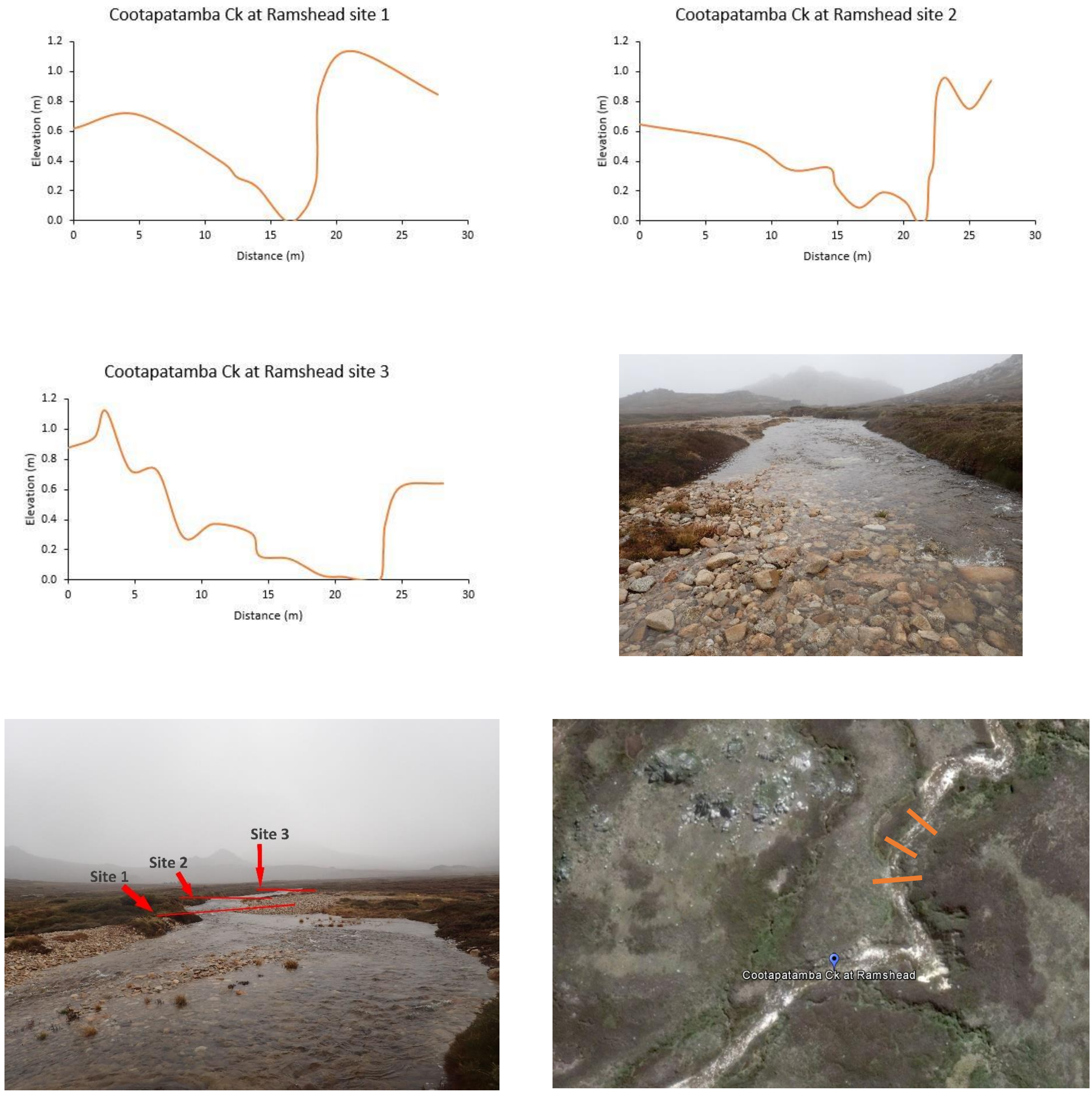
Appendix 2 - Study sites

Field surveyed sites

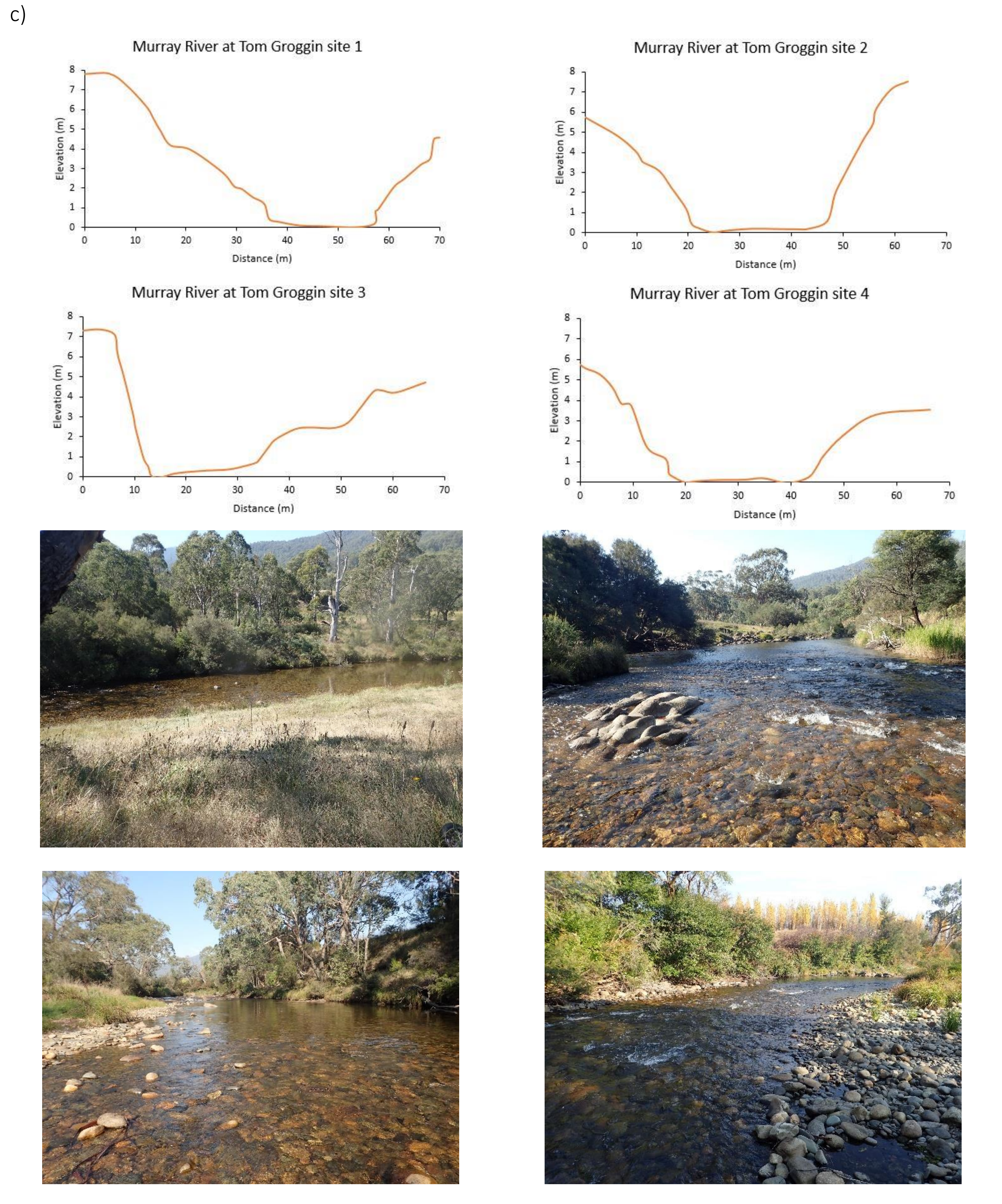


Appendix 2. a) Field surveyed cross-section at the site Club Lake Ck at Clarke, upstream and downstream of the cross-section, the site with the location of the cross-section marked and aerial view with the location of the surveyed cross-section (Google and DigitalGlobe 2016)

b)



Appendix 2 continued. b) Field surveys at the site Cootapatamba at Ramshead, looking downstream from site 3 and upstream from below site 1. An overview with location of the surveyed cross-sections (Google and DigitalGlobe 2016)

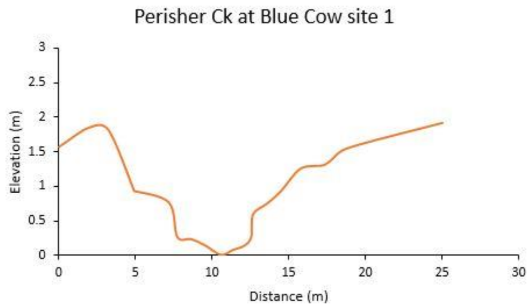


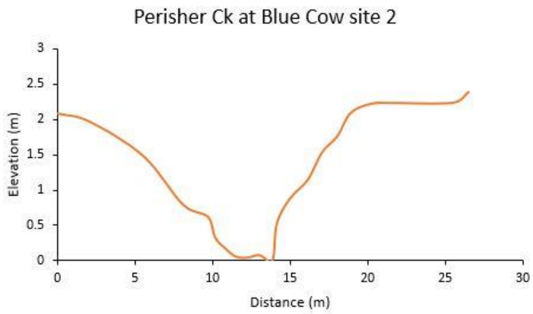
Appendix 2 continued. c) Cross-sections and photos for the study site Murray River at Tom Groggin

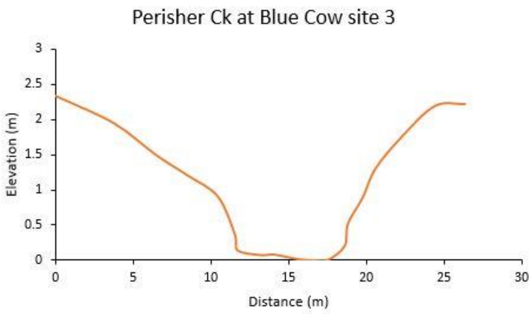
d)

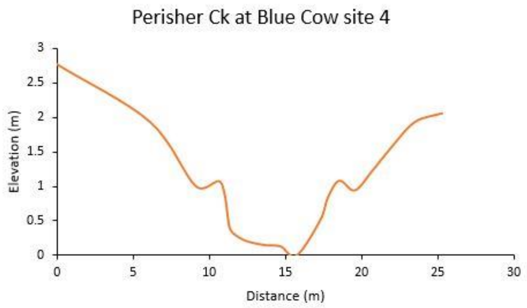
Appendix 2 continued. d) Overview with the location of the cross-sections at Murray River at Tom Groggin (Google and DigitalGlobe 2016)

e)



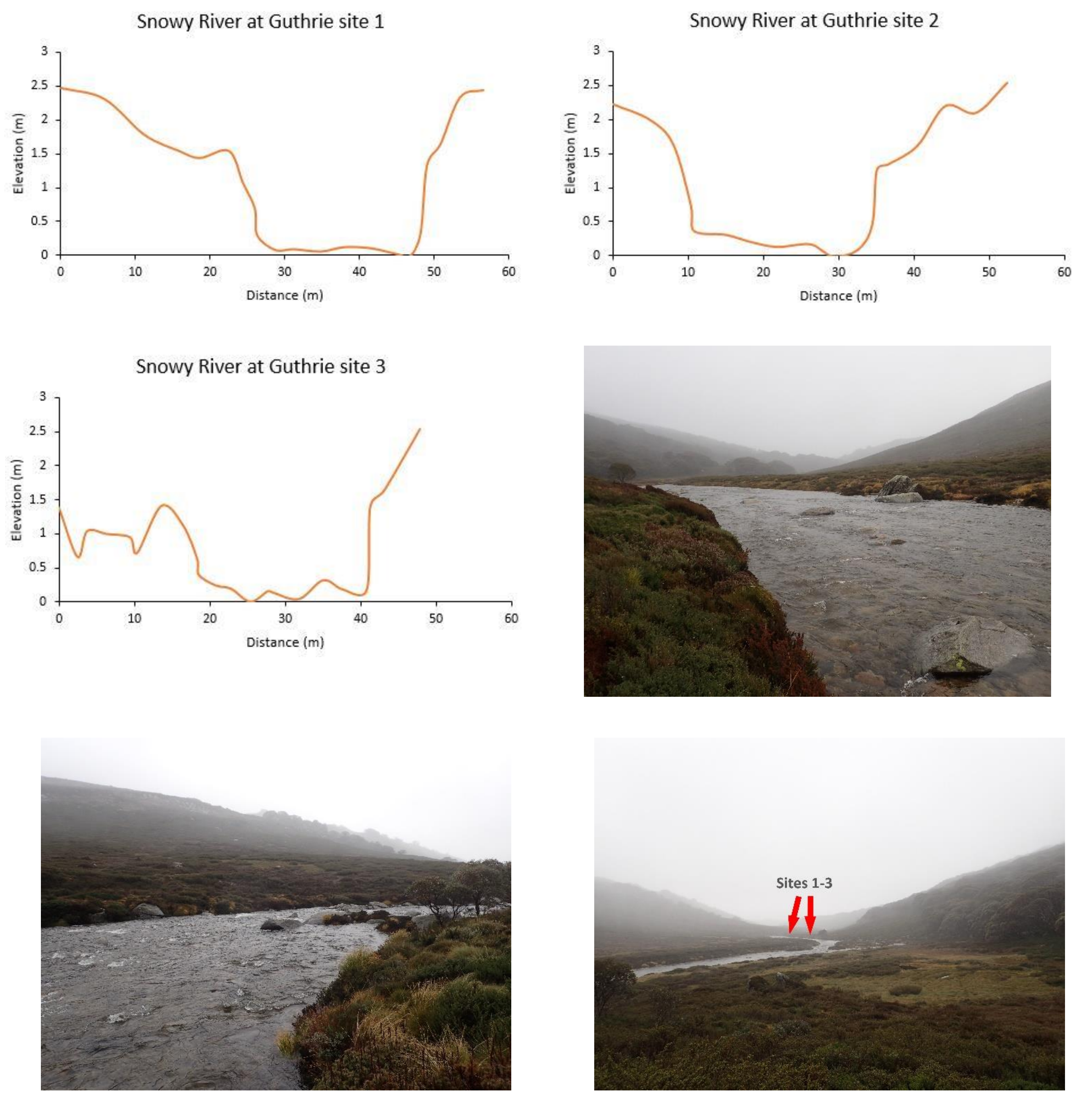






Appendix 2 continued. e) Field surveyed cross-sections at the site Perisher Creek at Blue Cow, looking upstream and downstream from site 2 and overview showing location of cross-sections (Google and DigitalGlobe 2016)

f)

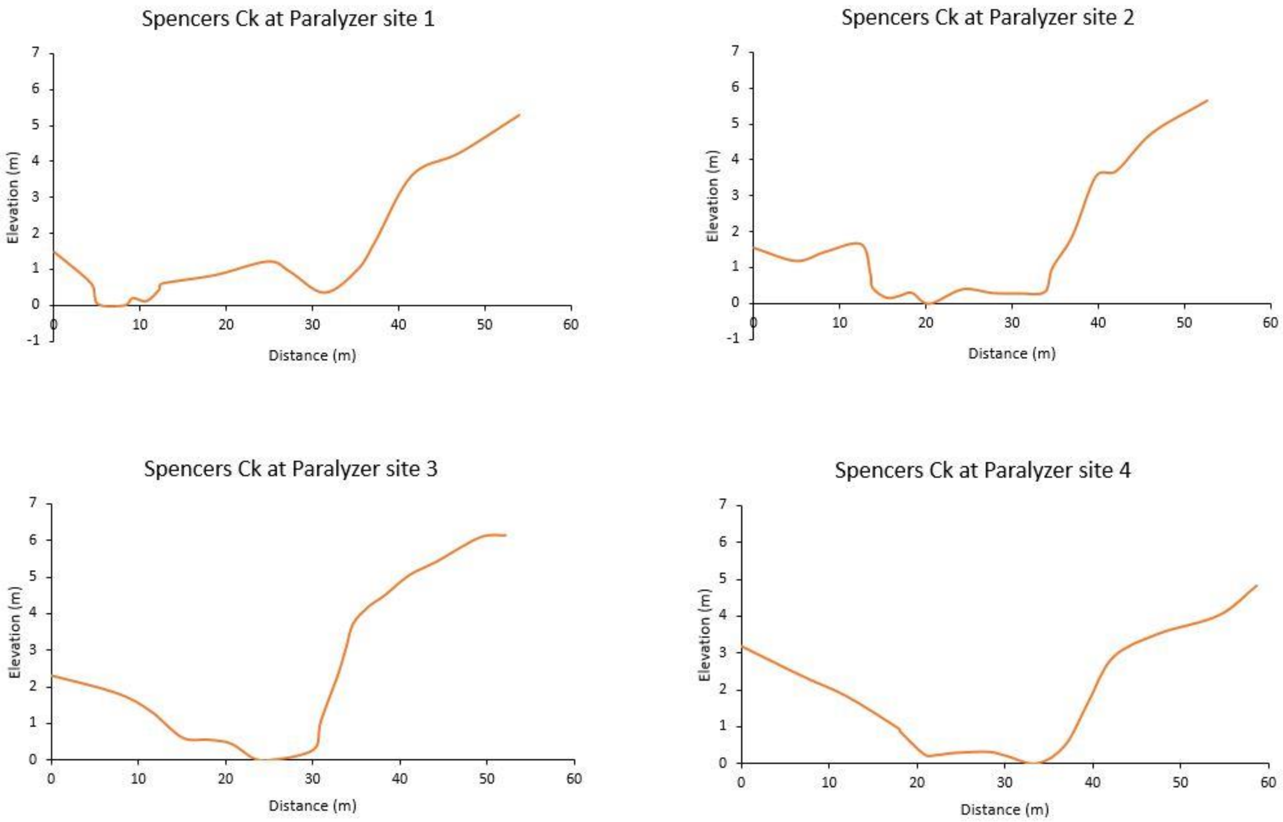


Appendix 2 continued. The site Snowy River at Guthrie with field surveyed cross-sections and the view upstream and downstream of site 1.

g)

Appendix 2 continued. Overview of the site Snowy River at Guthrie (Google and DigitalGlobe 2016).

h)

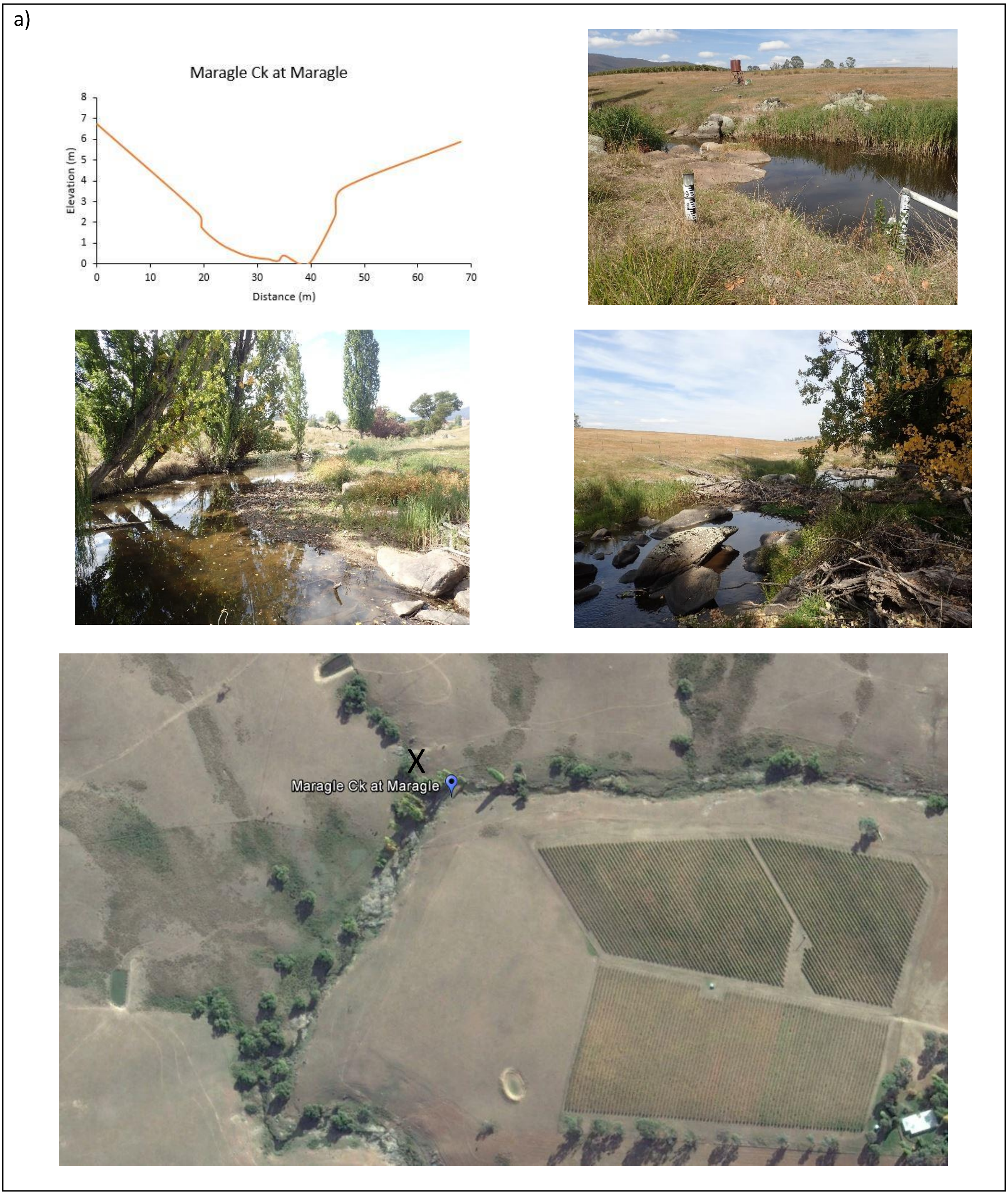


Appendix 2 continued. h) Field surveyed cross-sections for Spencers Ck at Paralyzer

i)

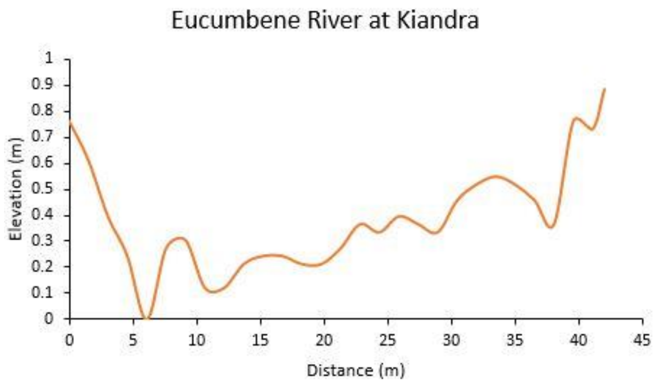
Appendix 2 continued. i) The site Spencers Ck at Paralyzer, looking upstream and downstream from site 1, the survey locations and overview with the location of the cross-sections (Google and DigitalGlobe 2016)

Appendix 3. NSW Office of Water and Snowy Hydro sites

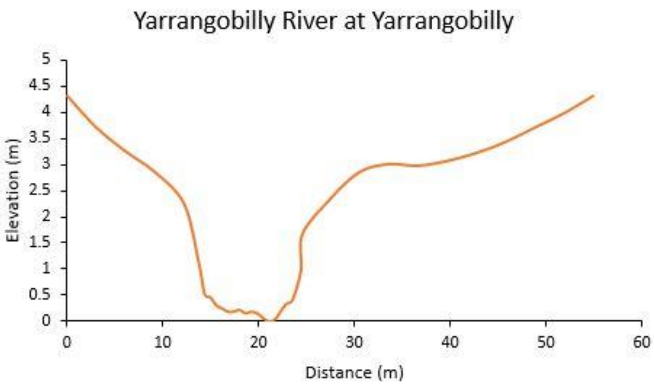


Appendix 3. a) The cross-section at the site Maragle Creek at Maragle by NSW Office of Water, the location by the stage boards, looking upstream and downstream from the gauges and aerial view. Gauge location marked with an X (Google and DigitalGlobe 2016)

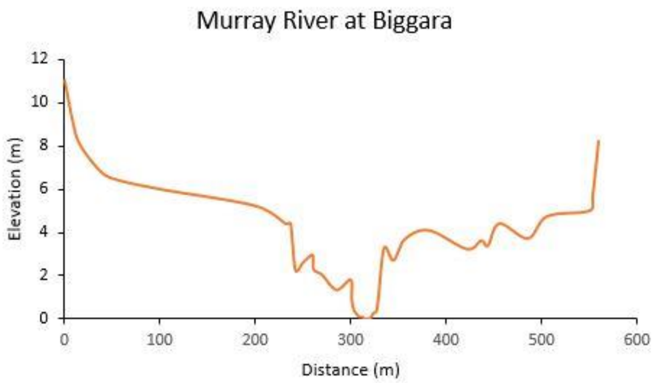
b)



c)

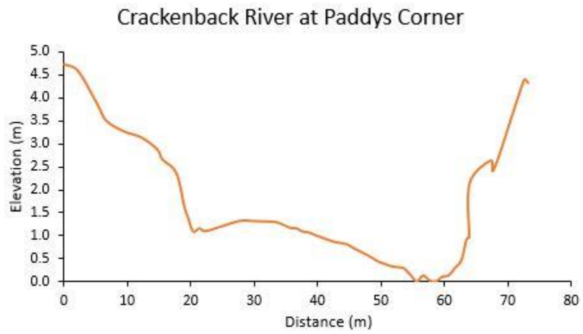


d)



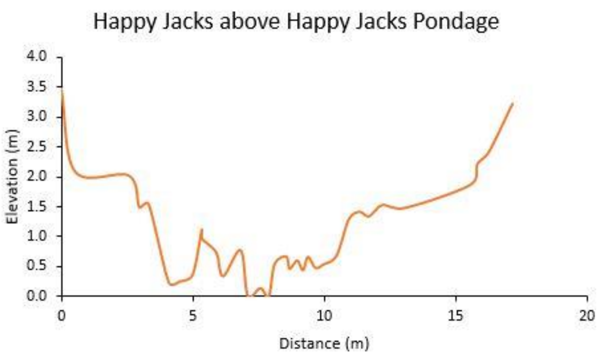
Appendix 3 continued. b) Cross-section, overview and upstream and downstream of the site Eucumbene River at Kiandra. Cross-sections and overviews for c) Yarrangobilly River at Yarrangobilly and d) Murray River at Biggara. Cross-sections provided by the NSW Office of Water, overviews by Google Earth (Google and DigitalGlobe 2016).

e)



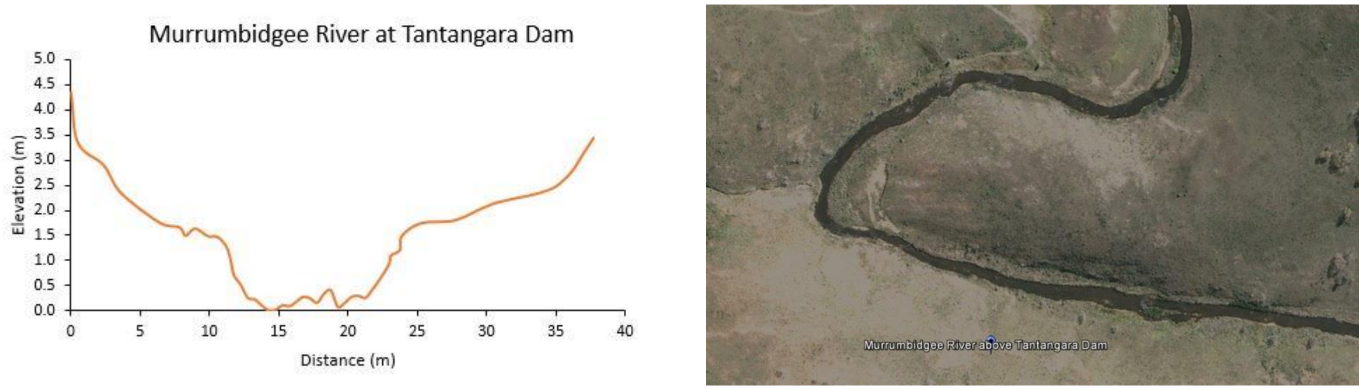
f)

g)

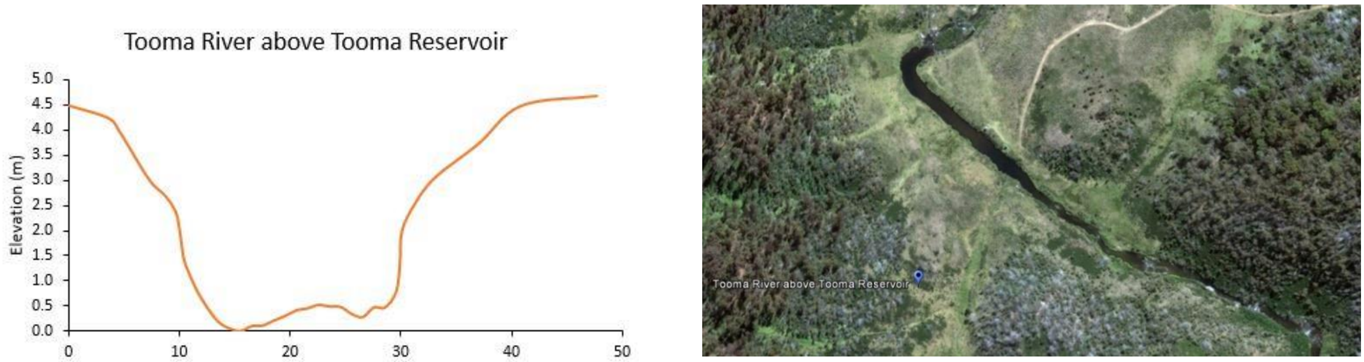


Appendix 3 continued. e) Cross-section, overview and the gauge location (marked X) at the site Crackenback River at Paddys Corner. Cross-sections and overviews for f) Geehi River at Geehi and g) Happy Jacks River at Happy Jacks Pondage. Cross-sections provided by the NSW Office of Water, overviews by Google Earth (Google and DigitalGlobe 2016).

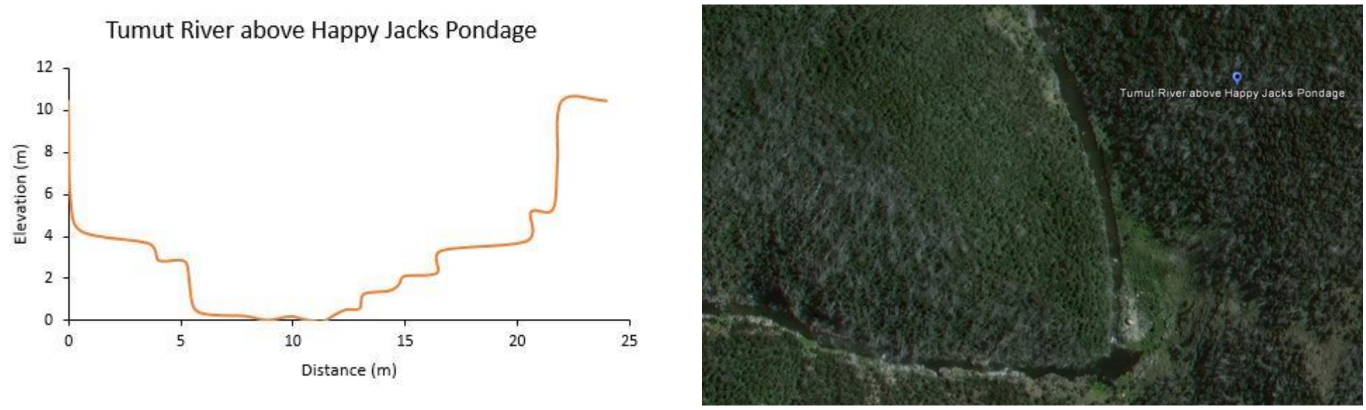
h)



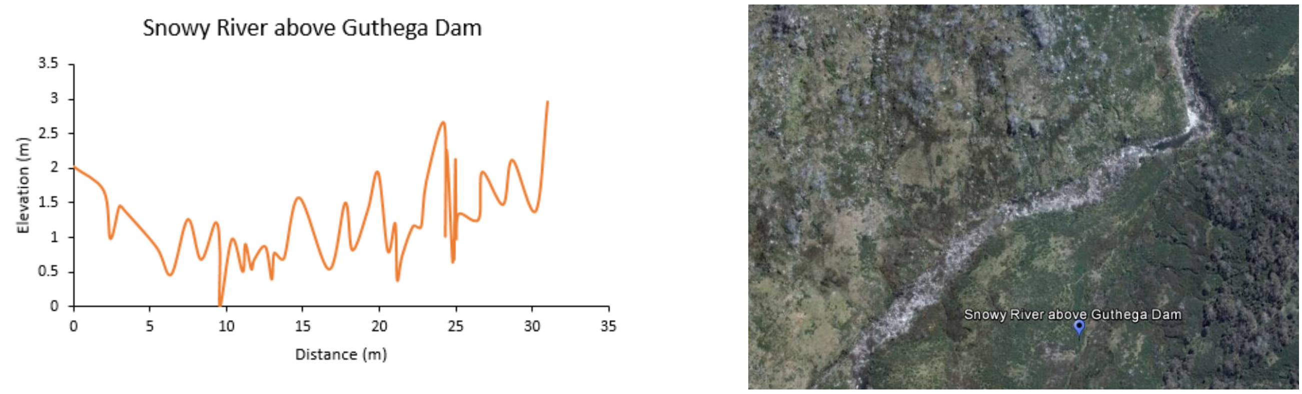
i)



j)

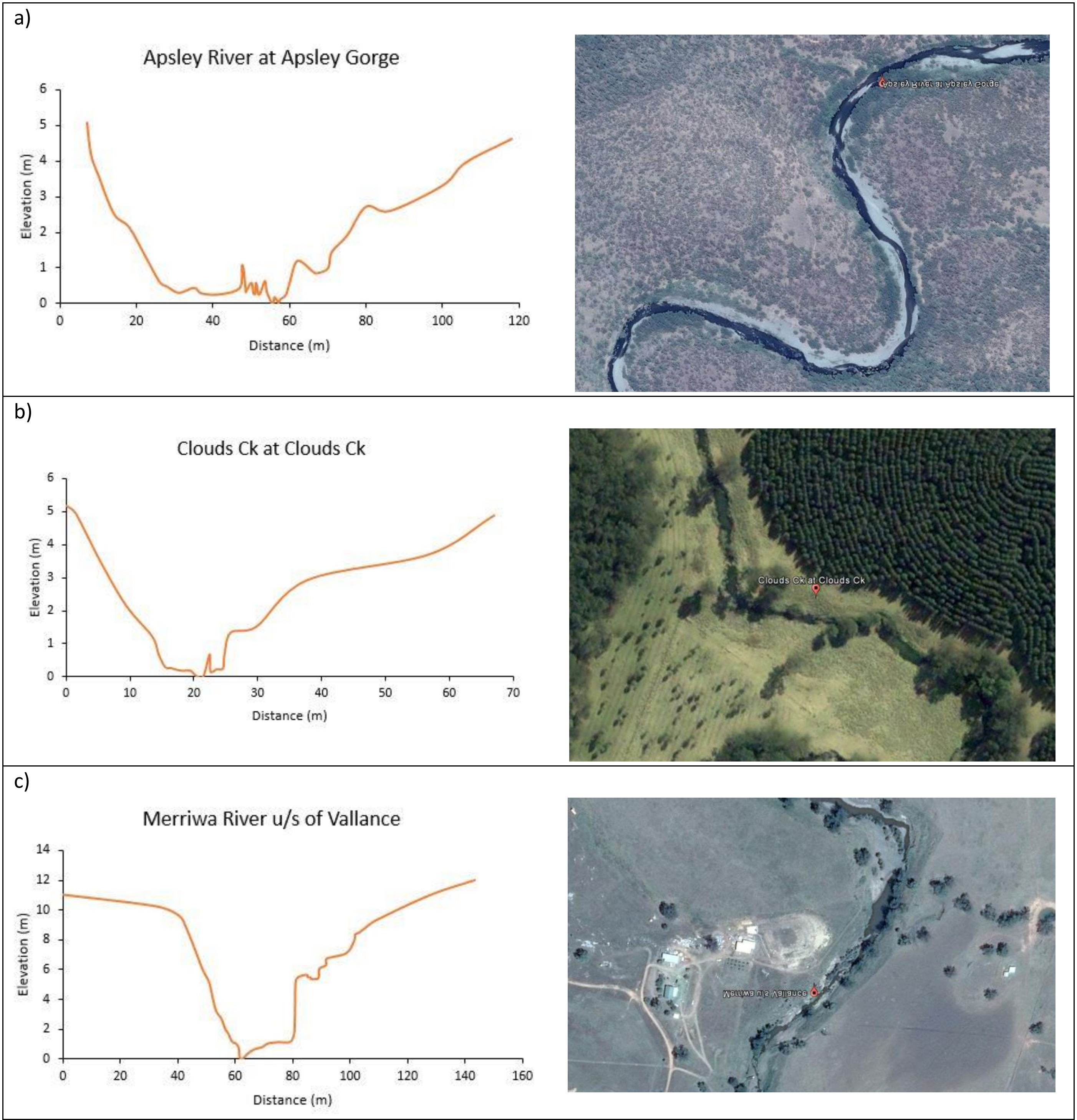


k)



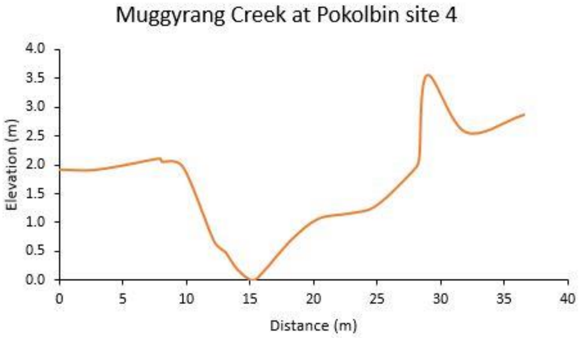
Appendix 3 continued. h-k) Approximate locations for the Snowy Hydro Limited site cross-sections with overview images (Google and DigitalGlobe 2016)

Appendix 4. East coast non-snowmelt rivers



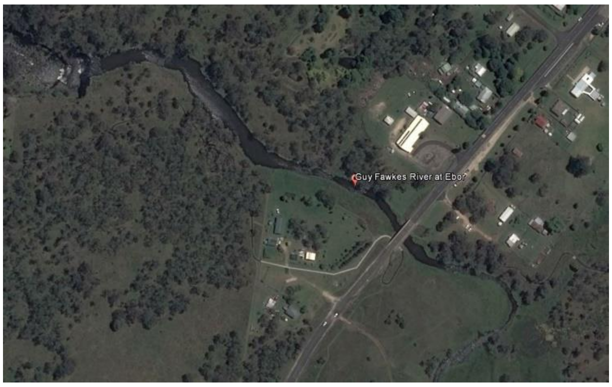
Appendix 4. The approximate locations for the east coast river cross-sections available from the NSW Office of Water and the corresponding overviews from Google Earth (Google and DigitalGlobe 2016). a) Apsley River at Apsley Gorge, b) Clouds Creek at Clouds Creek, c) Merriwa River Upstream of Vallance

d)



e)

f)



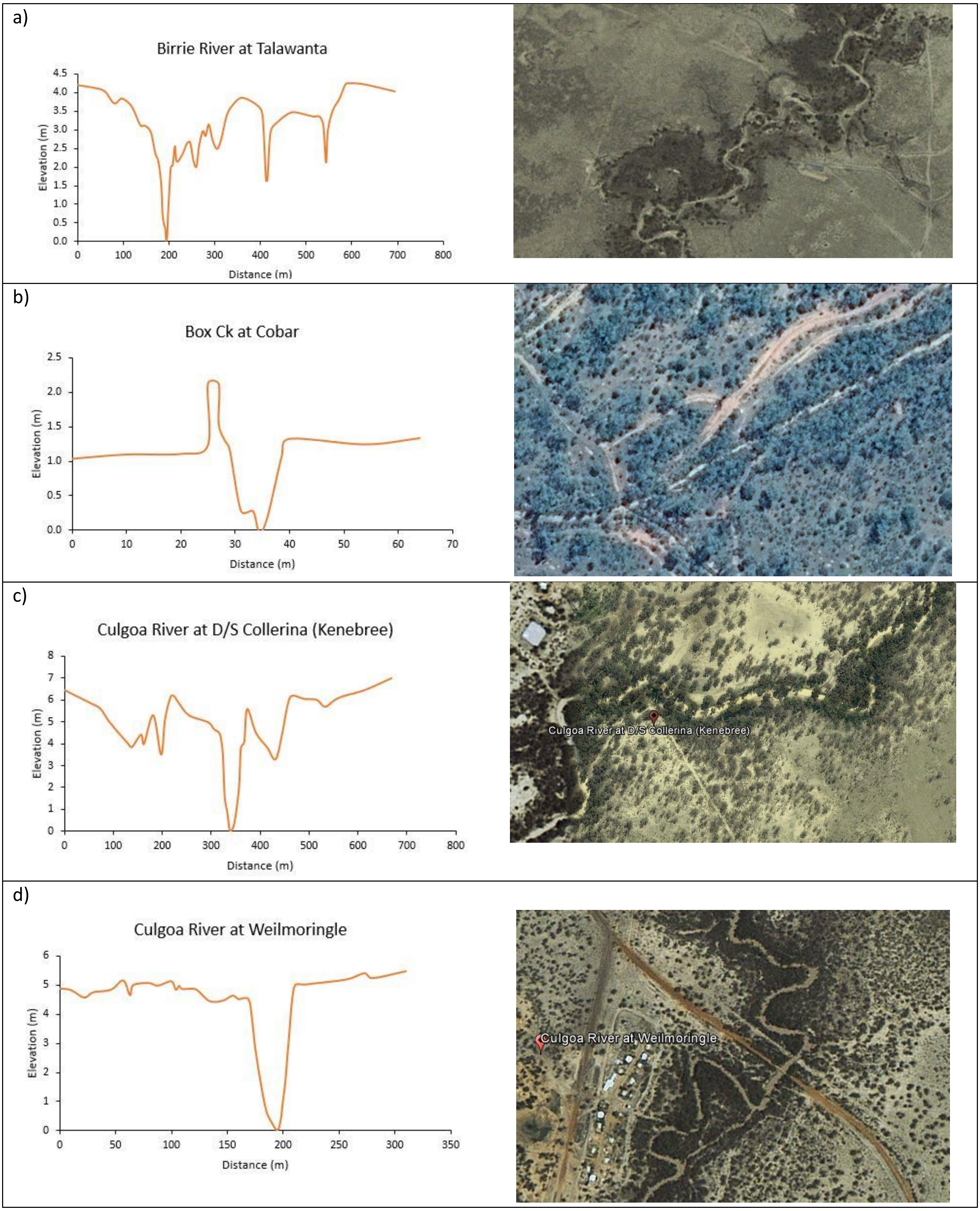
g)

h)

i)

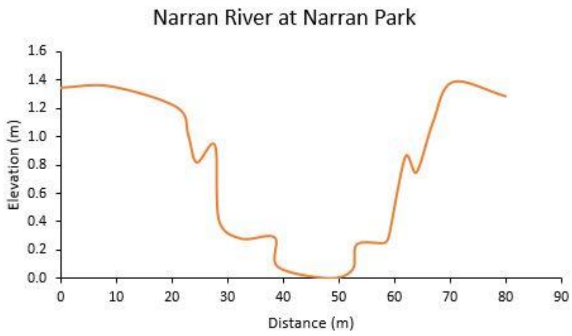
Appendix 4 continued. The approximate locations for the east coast river cross-sections available from the NSW Office of Water and the corresponding overviews from Google Earth d) Muggyrang Creek at Pokolbin and e) Timbarra River at Billyrimbah. Overview images of sites without cross-sections f) Guy Fawkes River at Ebor, g) Munmurra Brook at Tomimbil, h) Shoalhaven River at Warri and i) Warrah Creek at Old Warrah (Google and DigitalGlobe 2016).

Appendix 5 Semi-arid rivers

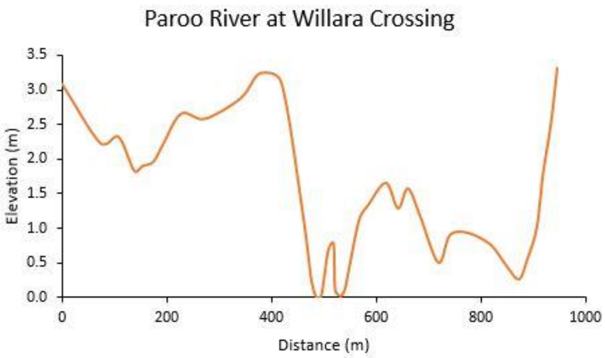


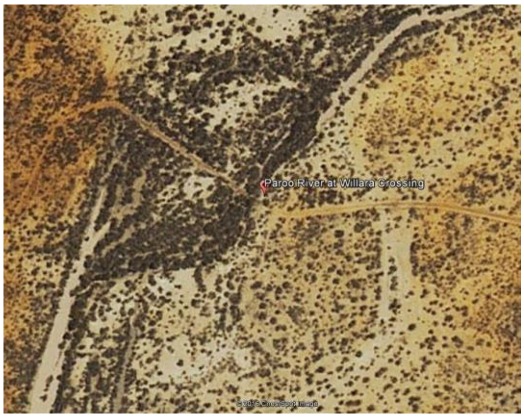
Appendix 5. Cross-sections provided by NSW Office of Water for the semi-arid sites, and Google Earth screen shots to provide an overview of the approximate gauge location (Google and DigitalGlobe 2016). a) Birrie River at Talawanta, b) Box Creek at Cobar, c) Culgoa River at downstream Collerina, d) Culgoa River at Weilmoringle

e)

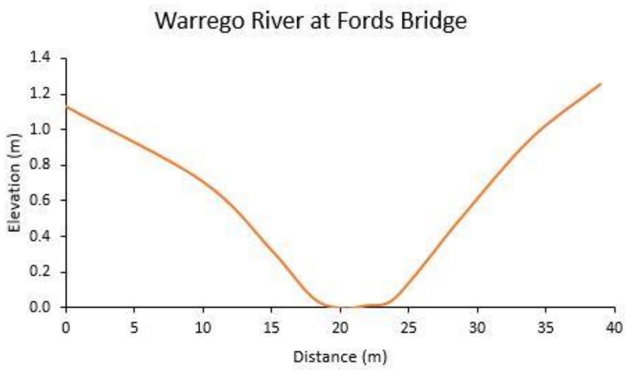


f)





g)

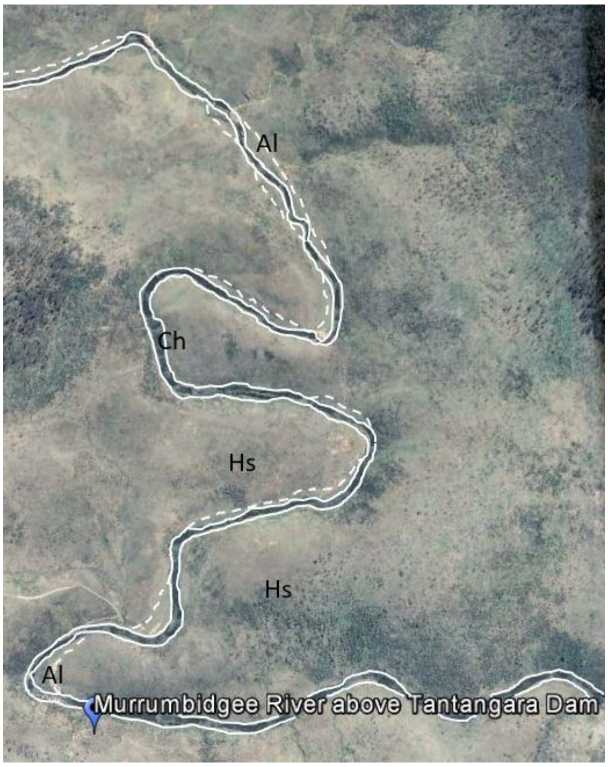


h)

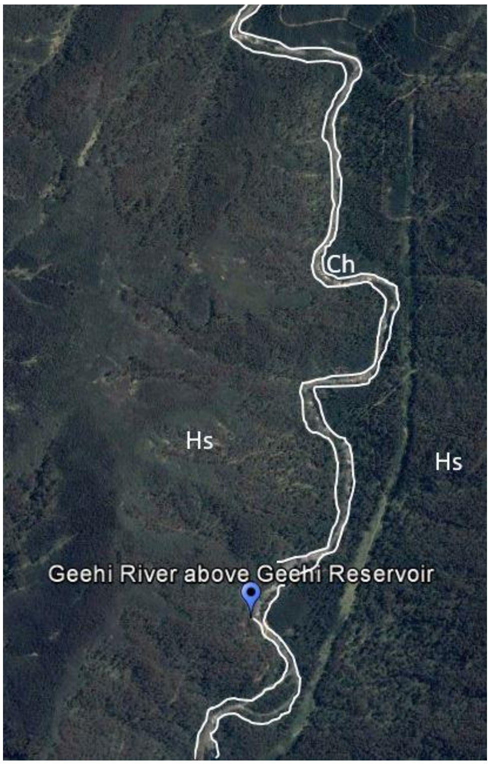
Appendix 5 continued. Cross-sections provided by NSW Office of Water for the semi-arid sites, and Google Earth screen shots to provide an overview of the approximate gauge location (Google and DigitalGlobe 2016). e) Narran River at Narran Park, f) Paroo River at Willara Crossing, g) Warrego River at Fords Bridge and h) Paroo River at Wanaaring.

Appendix 6. Valley Confinement

a)

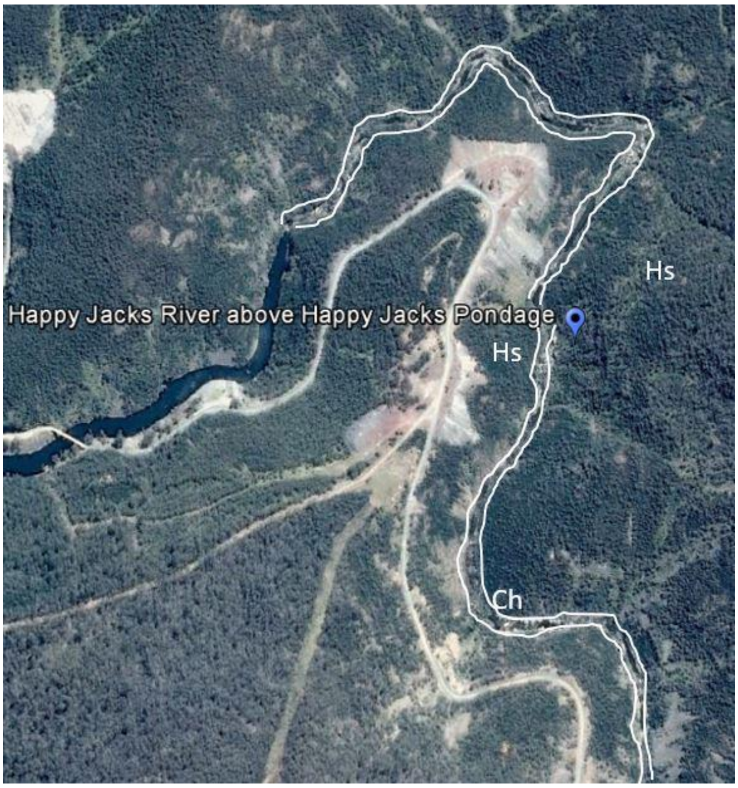


b)



c)

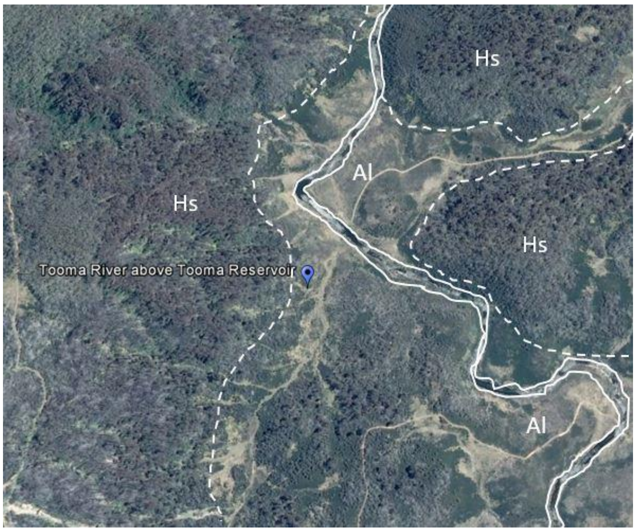
d)



Appendix 6. The location of the channel, alluvial deposits and hillslopes for the Snowy Mountain river study sites a) Murrumbidgee River at Tantangara Dam, b) Geehi River above Geehi Reservoir, c) Spencers Ck at Paralyzer, d) Happy Jacks River above Happy Jacks Pondage. (Images by Google and DigitalGlobe 2016).

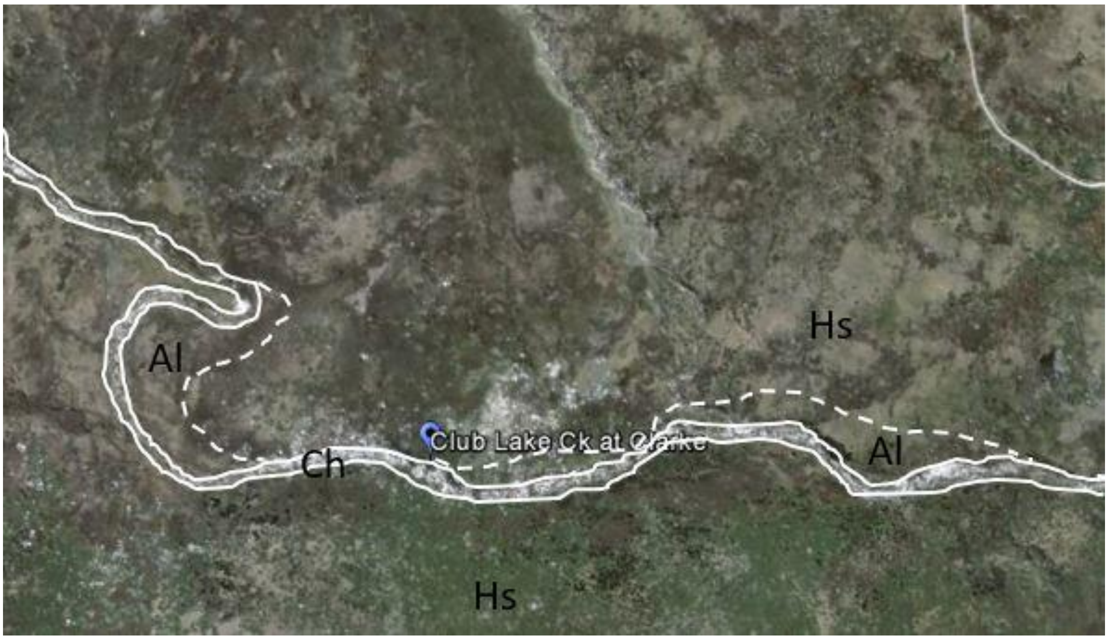
e)

f)



g)

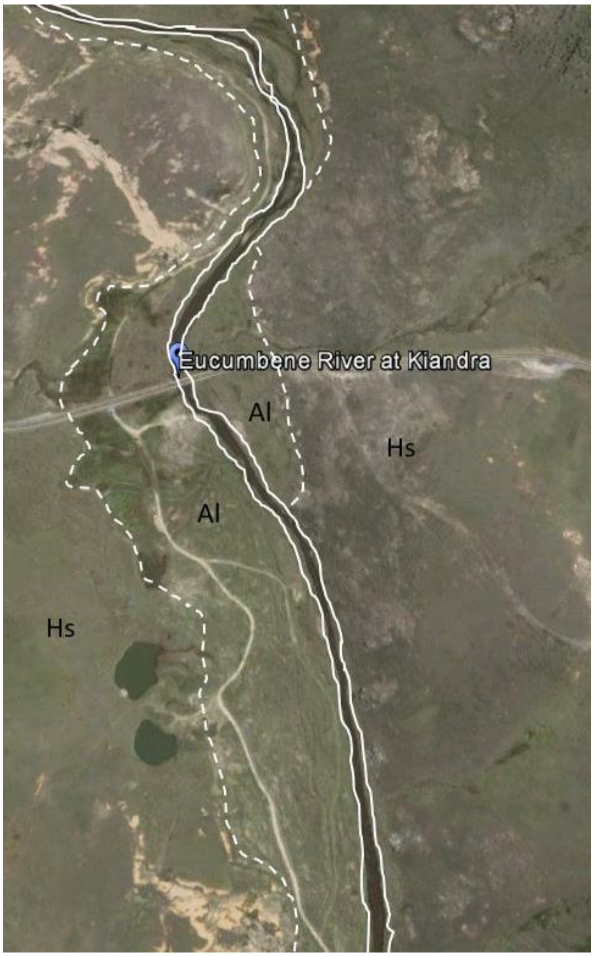
h)



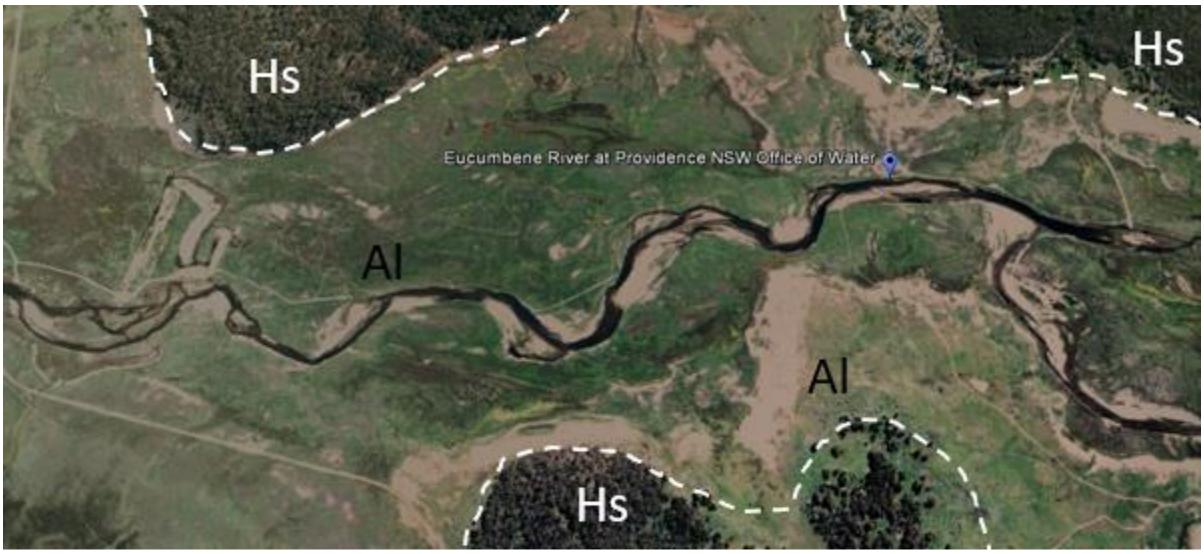
Appendix 6 continued. The location of the channel, alluvial deposits and hillslopes for the Snowy Mountain river study sites e) Tumut River above Happy Jacks Pondage, f) Tooma River above Tooma Reservoir, g) Yarrangobilly River at Yarrangobilly, h) Club Lake Ck at Clarke. (Images by Google and DigitalGlobe 2016).

i)

j)

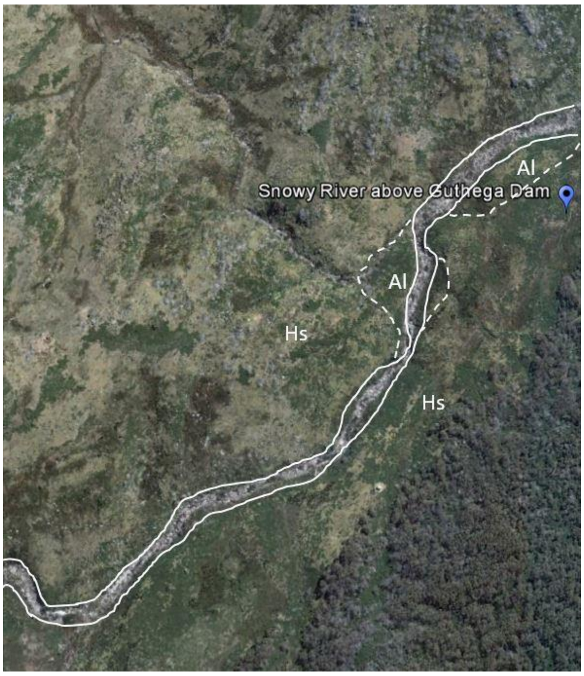


k)



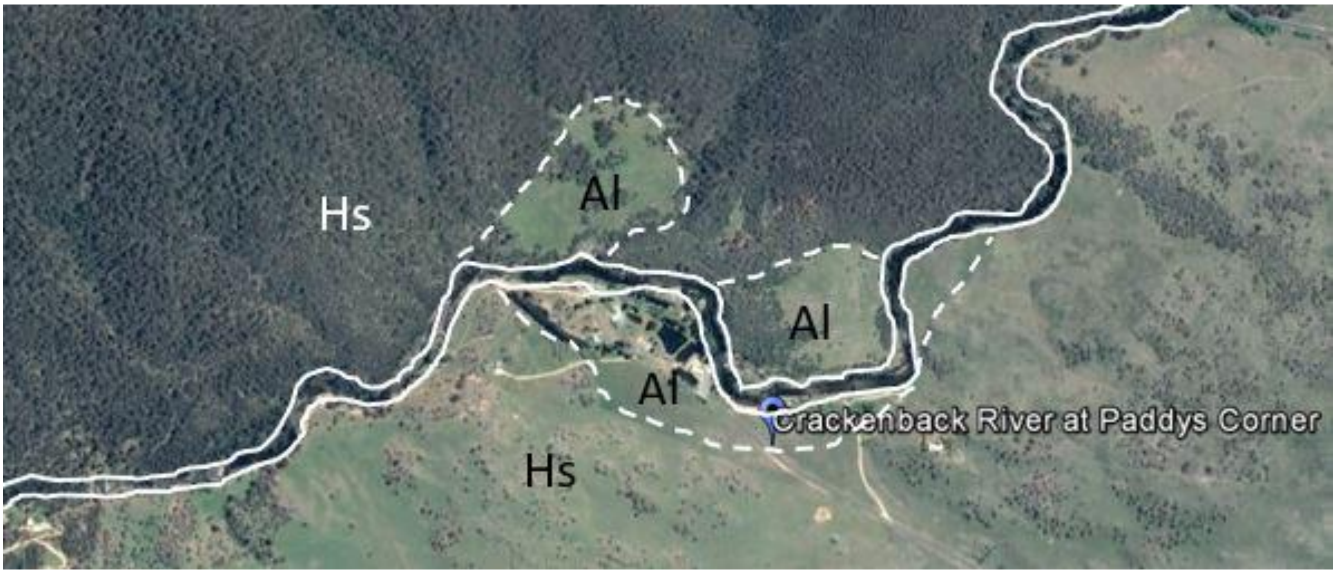
Appendix 6 continued. The location of the channel, alluvial deposits and hillslopes for the Snowy Mountain river study sites i) Perisher Ck at Blue Cow, Eucumbene River at j) Kiandra and k) Providence. (Images by Google and DigitalGlobe 2016).

l)



m)

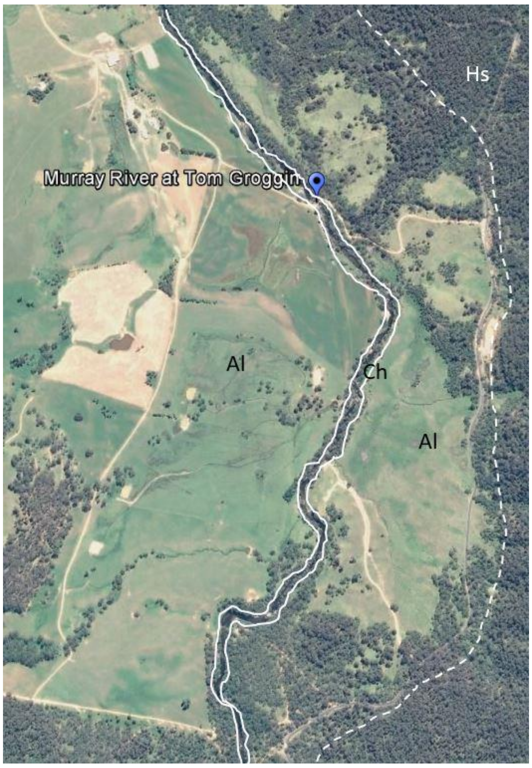
n)



Appendix 6 continued. The location of the channel, alluvial deposits and hillslopes for the Snowy Mountain river study sites Snowy River l) above Guthega Dam and m) at Guthrie, n) Crackenback River at Paddys Corner. (Images by Google and DigitalGlobe 2016).

o)

p)



q)

Appendix 6 continued. The location of the channel, alluvial deposits and hillslopes for the Snowy Mountain river study sites Murray River at o) Biggara and p) Tom Groggin, q) Maragle Ck at Maragle. (Images by Google and DigitalGlobe 2016)

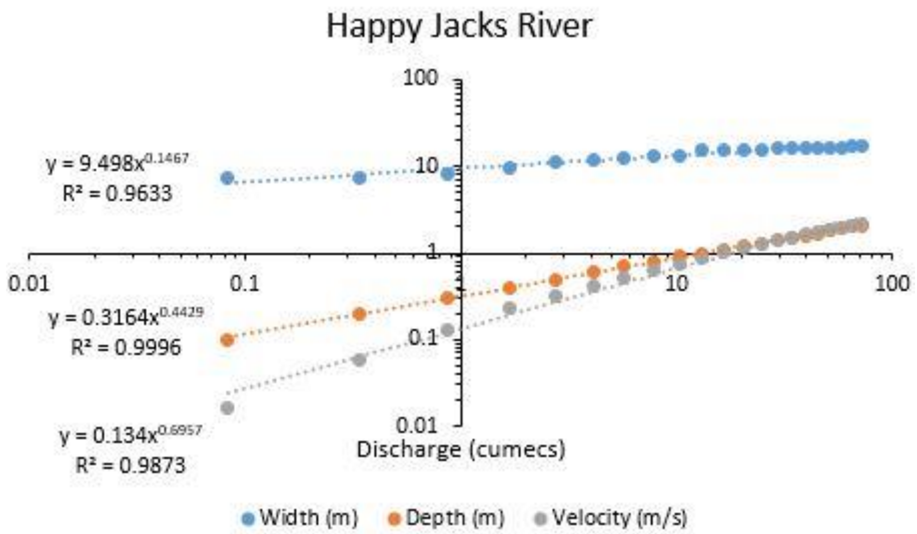
Appendix 7. River and reach channel slope

Appendix 7. DEM-derived channel slope from furthest upstream point of river to the field site for each Snowy Mountain river

River	Max elevation (m)	Min elevation (m)	rise (m)	run (m)	slope (m/m)
Club Lake Ck at Clarke	2053.54	1769.90	283.64	3395.34	0.084
Cootapatamba Ck at Ramshead	2123.05	1901.21	221.84	3425.82	0.065
Eucumbene River at Kiandra	1470.95	1336.08	134.87	15474.70	0.009
Eucumbene River at Providence	1470.95	1180.24	290.71	28112.21	0.010
Maragle Ck at Maragle	1121.98	384.52	737.46	34282.38	0.022
Murray River at Biggara	1486.99	513.09	973.89	115093.36	0.008
Murray River at Tom Groggin	1486.99	315.99	1171.00	80798.12	0.014
Perisher Ck at Blue Cow	1888.14	1616.24	271.90	8519.41	0.032
Snowy River at Guthrie	2116.86	1656.94	459.92	11640.71	0.040
Spencers Ck at Paralyzer	2020.18	1727.05	293.13	6797.86	0.043
Yarrangobilly River at Yarrangobilly	1481.99	1006.77	475.23	18107.57	0.026
Snowy above Guthega Dam	2117.30	1595.14	522.15	14738.44	0.035
Crackenback at Paddys Corner	1552.62	902.00	650.62	33966.75	0.019
Tooma above Tooma Reservoir	1828.64	1223.74	604.90	24983.73	0.024
Geehi above Geehi Reservoir	1493.66	1121.54	372.11	11240.78	0.033
Tumut above Happy Jacks Reservoir	1349.52	1207.26	142.26	7206.37	0.020
Happy Jacks above Happy Jacks Reservoir	1636.87	1219.65	417.21	17996.14	0.023
Murrumbidgee above Tantangara Dam	1344.71	1234.08	110.64	29230.39	0.004

Appendix 8. Hydraulic geometry

Unfortunately, the hydraulic geometry calculations were unusable because the given velocity data was taken from the rating analysis and represented the mean velocity of flow for the given gauge height. Therefore, instead of the velocity being measured on site through a variety of flood stages, the data was a rearrangement of Q=AV becoming V=Q/A. This resulted in inaccurate hydraulic geometry calculations rendering this portion of the analysis useless.



Appendix 8. An example of the inaccurate at-a-station results for Happy Jacks River, obtained from the hydraulic geometry analysis where the exponent values don't sum to 1 because of derived rather than measured velocity values.

Appendix 8. Results for hydraulic geometry analysis demonstrating unusable results caused by derived velocity

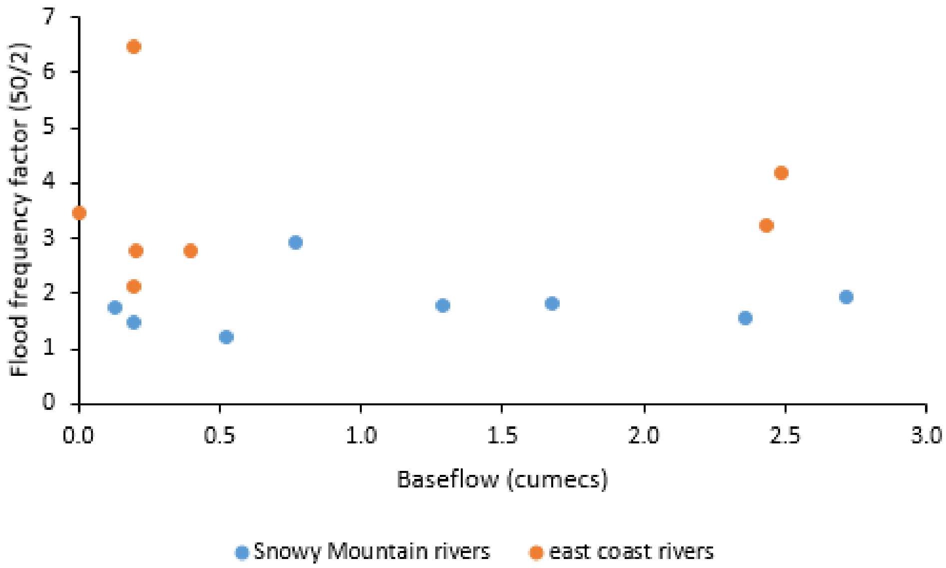
River	**Width**	**Depth**	**Velocity**	**Total**
Eucumbene at Providence (SH)	0.2722	1.0808	0.5466	1.8996
Tooma above Tooma Reservoir	0.0798	0.3737	0.7671	1.2206
Tumut above Happy Jacks Reservoir	0.1553	0.3302	0.6438	1.1293
Happy Jacks above Happy Jacks Reservoir	0.1467	0.4429	0.6957	1.2853
Murray at Biggara	0.4724	0.4299	0.2833	1.1856
Maragle Ck at Maragle	0.2791	0.3079	0.195	0.7820
Geehi above Geehi Reservoir	0.089	0.4116	0.6771	1.1777
Murrumbidgee above Tantangara Dam	0.1828	0.3282	0.5869	1.0979
Crackenback at Paddy's Corner	0.1761	0.5161	0.4808	1.1730
Snowy above Guthega Dam	0.6008	0.1386	0.4293	1.1687

Appendix 9. Flash flood magnitude index, Coefficient of variation and baseflow index

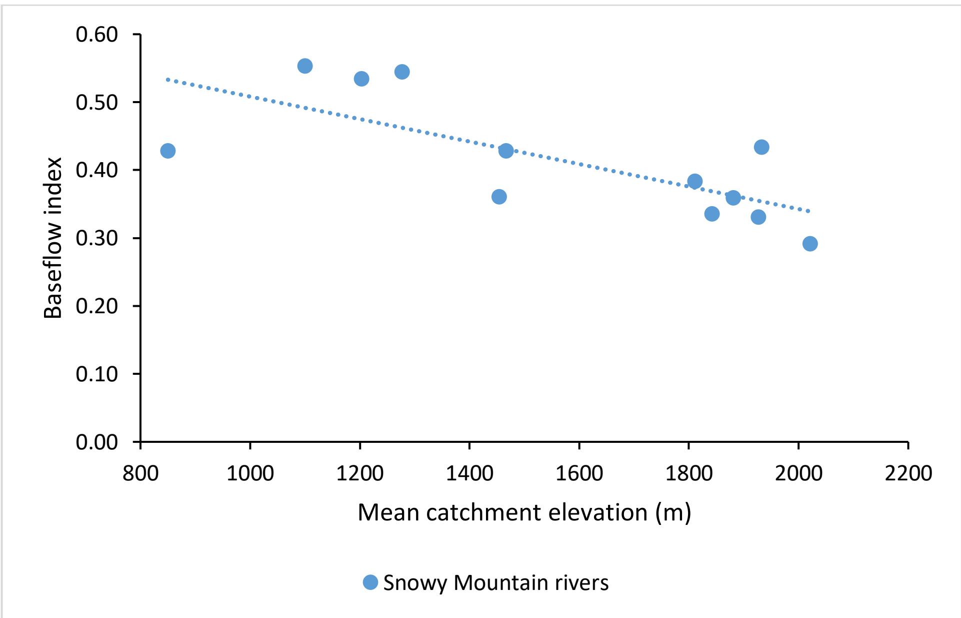
Appendix 9. The flash flood magnitude index, coefficient of variation and baseflow index for all rivers with sufficient ML/d data

Gauge	River	Flash flood magnitude index	Coefficient of variation	Baseflow Index	Mean daily baseflow (ML/d)	
222527	Snowy River above Guthega Dam	0.22		0.36	203.79	Snowy Mountain rivers
222541	Crackenback River at Paddys Corner	0.20				
401554	Tooma River above Tooma Reservoir	0.27				
401560	Geehi River above Geehi Reservoir	0.28				
410533	Tumut River above Happy Jacks Reservoir	0.30				
410534	Happy Jacks River above Happy Jacks Reservoir	0.29				
410535	Murrumbidgee River above Tantangara Dam	0.32				
222522	Eucumbene River at Providence (N.O.W.)	0.28	0.39	0.43	234.76	
401009	Maragle Creek at Maragle	0.37	0.69	0.43	66.67	
401012	Murray River at Biggara	0.25	0.49	0.55	1031.41	
401514	Murray River at Tom Groggin	0.18	0.56	0.53	568.64	
222513	Perisher Creek at Blue Cow	0.21	0.29	0.38	28.15	
410010	Yarrangobilly River at Yarrangobilly	0.30	0.52	0.54	111.51	
222501	Snowy River above Jindabyne 1902-1955	0.21				
222517	Club Lake Creek at Clarke		0.20	0.33	16.70	
401508	Cootapatamba Creek at Ramshead		0.22	0.29	11.30	
222507	Eucumbene River at Kiandra		0.36	0.36	108.94	
222508	Snowy River at Guthrie		0.21	0.43	144.78	
222509	Spencers Creek at Paralyzer		0.31	0.34	45.27	
210066	Merriwa River upstream of Vallance	0.93	1.00	0.19	17.22	East Coast rivers
210086	Munmurra Brook at Tomimbil	0.58	0.86	0.27	16.82	
419076	Warrah Creek at Old Warrah	1.29	1.19	0.21	6.13	
206033	Apsley River at Apsley Gorge	0.50	0.90	0.32	214.46	
204008	Guy Fawkes River at Ebor	0.61	0.51	0.34	34.01	
204037	Clouds Creek at Clouds Creek	0.69	0.92	0.30	17.85	
204033	Timbarra River at Billyrimbah	0.59	0.83	0.32	209.99	
210069	Muggyrang Creek at Pokolbin site 4	0.85	1.17	0.10	0.08	
215002	Shoalhaven River at Warri	0.63	1.02	0.16	207.13	
424001	Paroo River at Wanaaring		1.26			Semi-arid rivers
424002	Paroo River at Willara Crossing	0.53	1.16	0.09	99.92	
425016	Box Creek at Cobar	0.70	1.10			
412093	Naradhan Creek at Naradhan		1.79			
422017	Culgoa River at Weilmoringle	0.64	1.26	0.19	186.89	
422006	Culgoa River at downstream Collerina (Kenebree)	0.52	1.21	0.34	720.85	
423001	Warrego River at Fords Bridge	0.72	1.65			
422010	Birrie River at Talawanta		1.64	0.15	34.72	
422029	Narran River at Narran Park		1.60	0.22	47.75	

Appendix 10. Baseflow



Appendix 10. The difference between flood flow and baseflow for Snowy Mountain and east coast rivers demonstrates that Snowy Mountain rivers have lower F values that are closer in size to the mean daily baseflow across all sites. Calculated using the flood frequency factor F=Q50/Q5 (Malamud and Turcotte 2006)



Appendix 10. The baseflow index was found to decrease with mean catchment elevation

Appendix 11. Flood frequency ratio curves

Appendix 11. Flood frequency calculations in cumecs for Snowy Mountain rivers with complete ML/d data

ARI	Murray River at Biggara	Maragle Creek at Maragle	Perisher Creek at Blue Cow	Eucumbene River at Providence (NOW)	Yarrangobilly River at Yarrangobilly 1911-1930	Crackenback River at Paddys Corner	Geehi River above Geehi Reservoir	Happy Jacks River above Happy Jacks Reservoir	Murrumbidgee River above Tantangara Dam	Snowy River above Guthega Dam	Tooma River above Tooma Reservoir	Tumut River above Happy Jacks Reservoir
1.001	12.73	1.11	4.88	6.28	2.44	15.31	16.46	3.90	2.12	16.96	5.08	7.37
1.01	21.65	2.37	6.19	11.13	3.83	23.24	23.15	6.57	5.40	31.62	9.81	12.64
1.1	41.78	6.19	9.10	23.20	6.72	39.75	38.99	13.16	15.53	64.32	21.74	25.99
1.25	57.02	9.85	11.37	33.23	8.80	51.67	52.20	18.66	24.50	87.64	31.41	37.42
1.5	73.32	14.40	13.93	44.69	10.94	64.16	67.71	25.01	34.63	111.05	42.11	50.84
1.75	85.18	18.12	15.90	53.48	12.47	73.16	80.00	29.94	42.17	127.14	50.06	61.39
2	94.72	21.34	17.55	60.80	13.68	80.35	90.52	34.09	48.25	139.54	56.52	70.34
5	152.93	45.19	29.09	110.11	20.85	124.01	168.34	62.86	84.45	206.20	96.83	133.93
10	194.28	66.30	39.02	149.58	25.78	155.12	239.63	86.88	108.29	245.92	125.89	188.50
20	235.41	90.58	50.52	192.22	30.60	186.35	325.71	113.71	130.17	280.55	154.86	250.64
50	290.45	128.04	68.76	254.36	36.95	228.69	467.90	154.27	156.63	320.82	193.54	346.42
100	332.94	160.82	85.33	306.16	41.80	261.88	601.74	189.29	175.03	348.04	223.23	430.57

Appendix 11 continued. Flood frequency calculations in cumecs for east coast rivers with complete ML/d data

ARI	Apsley River at Apsley Gorge	Clouds Creek at Clouds Creek	Guy Fawkes River at Ebor	Muggyrang Creek at Pokolbin site 4	Munmurra Brook at Tomimbil	Shoalhaven River at Warri	Timbarra River at Billyrimbah
1.001	13.270	0.020	0.064	0.000	0.438	0.634	0.565
1.01	23.624	0.177	0.435	0.001	1.436	3.320	3.031
1.1	58.463	2.056	3.539	0.058	6.926	23.192	20.876
1.25	98.112	5.829	8.476	0.260	15.246	55.549	48.789
1.5	156.548	12.757	16.186	0.774	29.532	109.921	93.807
1.75	211.682	19.835	23.204	1.406	44.292	163.471	136.598
2	264.975	26.782	29.585	2.094	59.305	215.420	177.021
5	828.460	91.337	78.056	9.819	234.463	710.051	530.778
10	1597.406	155.409	117.095	18.171	484.121	1244.929	876.984
20	2837.451	228.638	155.995	27.641	884.003	1919.125	1281.473
50	5613.488	334.602	205.321	40.639	1747.283	3023.842	1892.874
100	9036.853	418.657	240.222	50.187	2757.891	4019.146	2404.442

Appendix 11 continued. Flood frequency calculations in cumecs for semi-arid rivers with complete ML/d data

ARI	Birrie River at Talawanta	Culgoa River at downstream Collerina (Kenebree)	Culgoa River at Weilmoringle	Paroo River at Willara Crossing	Warrego River at Fords Bridge
1.001	0.00	0.93	0.00	13.61	0.10
1.01	0.00	3.19	0.00	18.81	0.22
1.1	0.00	14.09	2.25	35.50	0.74
1.25	1.26	28.01	9.57	54.02	1.50
1.5	3.66	48.42	22.50	81.30	2.88
1.75	5.95	66.87	34.93	107.30	4.40
2	8.13	83.90	46.48	132.72	6.04
5	26.83	229.22	134.81	419.89	30.68
10	44.36	374.10	202.56	854.12	79.10
20	63.95	550.65	265.66	1627.80	182.19
50	92.04	834.75	338.85	3590.10	493.58
100	114.32	1089.48	385.95	6325.70	992.88

Appendix 11 continued. Flood frequency ratio calculations for Snowy Mountain rivers with complete ML/d data

Qf/Q2	Murray River at Biggara	Maragle Creek at Maragle	Perisher Creek at Blue Cow	Eucumbene River at Providence (NOW)	Yarrangobilly River at Yarrangobilly 1911-1930	Crackenback River at Paddys Corner	Geehi River above Geehi Reservoir	Happy Jacks River above Happy Jacks Reservoir	Murrumbidgee River above Tantangara Dam	Snowy River above Guthega Dam	Tooma River above Tooma Reservoir	Tumut River above Happy Jacks Reservoir	Mean Snowy Mtn Rivers
1.001	0.13	0.05	0.28	0.10	0.18	0.19	0.18	0.11	0.04	0.12	0.09	0.10	0.13
1.01	0.23	0.11	0.35	0.18	0.28	0.29	0.26	0.19	0.11	0.23	0.17	0.18	0.22
1.1	0.44	0.29	0.52	0.38	0.49	0.49	0.43	0.39	0.32	0.46	0.38	0.37	0.41
1.25	0.60	0.46	0.65	0.55	0.64	0.64	0.58	0.55	0.51	0.63	0.56	0.53	0.57
1.5	0.77	0.68	0.79	0.73	0.80	0.80	0.75	0.73	0.72	0.80	0.74	0.72	0.75
1.75	0.90	0.85	0.91	0.88	0.91	0.91	0.88	0.88	0.87	0.91	0.89	0.87	0.89
2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5	1.61	2.12	1.66	1.81	1.52	1.54	1.86	1.84	1.75	1.48	1.71	1.90	1.73
10	2.05	3.11	2.22	2.46	1.88	1.93	2.65	2.55	2.24	1.76	2.23	2.68	2.31
20	2.49	4.25	2.88	3.16	2.24	2.32	3.60	3.34	2.70	2.01	2.74	3.56	2.94
50	3.07	6.00	3.92	4.18	2.70	2.85	5.17	4.53	3.25	2.30	3.42	4.93	3.86
100	3.52	7.54	4.86	5.04	3.05	3.26	6.65	5.55	3.63	2.49	3.95	6.12	4.64

Appendix 11 continued. Flood frequency ratio calculations for east coast rivers with complete ML/d data

Qf/Q2	Apsley River at Apsley Gorge	Clouds Creek at Clouds Creek	Guy Fawkes River at Ebor	Muggyrang Creek at Pokolbin site 4	Munmurra Brook at Tomimbil	Shoalhaven River at Warri	Timbarra River at Billyrimbah	Mean of non-snowmelt rivers
1.001	0.050	0.001	0.002	0.000	0.007	0.003	0.003	0.010
1.01	0.089	0.007	0.015	0.000	0.024	0.015	0.017	0.024
1.1	0.221	0.077	0.120	0.028	0.117	0.108	0.118	0.112
1.25	0.370	0.218	0.286	0.124	0.257	0.258	0.276	0.256
1.5	0.591	0.476	0.547	0.370	0.498	0.510	0.530	0.503
1.75	0.799	0.741	0.784	0.671	0.747	0.759	0.772	0.753
2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
5	3.127	3.410	2.638	4.689	3.954	3.296	2.998	3.445
10	6.029	5.803	3.958	8.678	8.163	5.779	4.954	6.195
20	10.708	8.537	5.273	13.200	14.906	8.909	7.239	9.825
50	21.185	12.494	6.940	19.407	29.463	14.037	10.693	16.317
100	34.105	15.632	8.120	23.967	46.504	18.657	13.583	22.938

Appendix 11 continued. Flood frequency ratio calculations for semi-arid rivers with complete ML/d data

Qf/Q2	Birrie River at Talawanta	Culgoa River at downstream Collerina (Kenebree)	Culgoa River at Weilmoringle	Paroo River at Willara Crossing	Warrego River at Fords Bridge	Mean arid rivers
1.001	0.00	0.01	0.00	0.10	0.02	0.03
1.01	0.00	0.04	0.00	0.14	0.04	0.04
1.1	0.00	0.17	0.05	0.27	0.12	0.12
1.25	0.15	0.33	0.21	0.41	0.25	0.27
1.5	0.45	0.58	0.48	0.61	0.48	0.52
1.75	0.73	0.80	0.75	0.81	0.73	0.76
2	1.00	1.00	1.00	1.00	1.00	1.00
5	3.30	2.73	2.90	3.16	5.08	3.44
10	5.46	4.46	4.36	6.44	13.09	6.76
20	7.87	6.56	5.72	12.26	30.15	12.51
50	11.32	9.95	7.29	27.05	81.69	27.46
100	14.07	12.99	8.30	47.66	164.33	49.47

Appendix 11 continued. Snowy Mountain rivers discharge (cumecs) of each ARI flood calculated using annual series

Gauge	River	Catchment area (km2)	1.1	2	5	10	20	50	100
222513	Perisher Creek at Blue Cow	12.07	9.10	17.55	29.09	39.02	50.52	68.76	85.33
222527	Snowy River above Guthega Dam	76.78	64.32	139.54	206.20	245.92	280.55	320.82	348.04
410010	Yarrangobilly River at Yarrangobilly 1911-1930	91.93	6.72	13.68	20.85	25.78	30.60	36.95	41.80
410534	Happy Jacks River above Happy Jacks Reservoir	108.99	13.16	34.09	62.86	86.88	113.71	154.27	189.29
401554	Tooma River above Tooma Reservoir	117.77	21.74	56.52	96.83	125.89	154.86	193.54	223.23
401560	Geehi River above Geehi Reservoir	124.11	38.99	90.52	168.34	239.63	325.71	467.90	601.74
410533	Tumut River above Happy Jacks Reservoir	129.91	25.99	70.34	133.93	188.50	250.64	346.42	430.57
222522	Eucumbene River at Providence	164.91	23.20	60.80	110.11	149.58	192.22	254.36	306.16
410535	Murrumbidgee River above Tantangara Dam	214.57	15.53	48.25	84.45	108.29	130.17	156.63	175.03
401009	Maragle Creek at Maragle	214.98	6.19	21.34	45.19	66.30	90.58	128.04	160.82
222541	Crackenback River at Paddys Corner	243.76	39.75	80.35	124.01	155.12	186.35	228.69	261.88
401012	Murray River at Biggara	1256.00	41.78	94.72	152.93	194.28	235.41	290.45	332.94
222501	Snowy River above Jindabyne 1902-1955	1848.40	175.98	358.69	543.02	667.57	787.55	943.30	1060.43

Appendix 11 continued. East coast rivers discharge (cumecs) of each ARI flood calculated using annual series

River	Catchment area (km2)	1.1	2	5	10	20	50	100
Muggyrang Creek at Pokolbin site 4	5	0.06	2.09	9.82	18.17	27.64	40.64	50.19
Guy Fawkes River at Ebor	31	3.54	29.59	78.06	117.10	156.00	205.32	240.22
Clouds Creek at Clouds Creek	62	2.06	26.78	91.34	155.41	228.64	334.60	418.66
Munmurra Brook at Tomimbil	606	6.93	59.31	234.46	484.12	884.00	1747.28	2757.89
Timbarra River at Billyrimbah	985	20.88	177.02	530.78	876.98	1281.47	1892.87	2404.44
Apsley River at Apsley Gorge	2406	58.46	264.98	828.46	1597.41	2837.45	5613.49	9036.85
Shoalhaven River at Warri	1450	23.19	215.42	710.05	1244.93	1919.13	3023.84	4019.15

Appendix 11 continued. Semi-arid rivers discharge (cumecs) of each ARI flood calculated using annual series

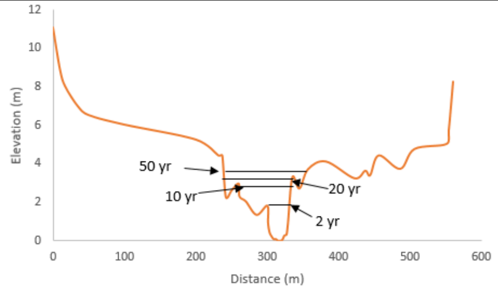
River	Catchment area (km2)	1.1	2	5	10	20	50	100
Paroo River at Willara Xing	not given	35.497	132.724	419.885	854.118	1627.795	3590.095	6325.704
Culgoa River at Weilmoringle	not given	2.247	46.478	134.808	202.562	265.655	338.848	385.952
Culgoa River at D/S Collerina (Kenebree)	51541	14.089	83.898	229.22	374.102	550.652	834.748	1089.483
Warrego River at Fords Bridge	60600	0.738	6.042	30.682	79.103	182.189	493.582	992.88
Birrie River at Talawanta	not given	0	8.128	26.831	44.36	63.954	92.036	114.322

Appendix 12. Inundation frequency at gauge cross-sections

Appendix 12. The height (m) of the calculated annual series floods (years) calculated using Log Pearson III plotted in surveyed Snowy Mountain river cross-sections a) Murray River at Biggara, b) Crackenback River at Paddys Corner, c) Maragle Creek at Maragle, d) Murrumbidgee River above Tantangara Dam, e) Eucumbene River at Providence (Snowy Hydro)

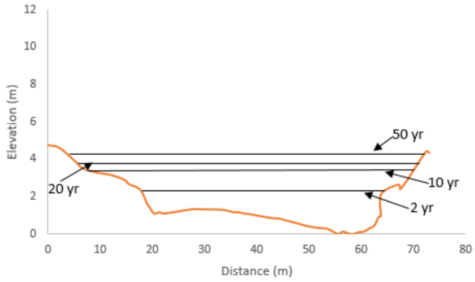
a)

ARI	Stage
2	1.85
10	2.83
20	3.18
50	3.63



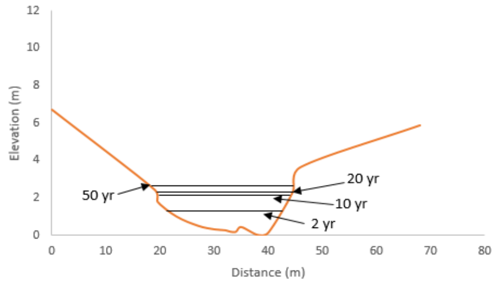
b)

ARI	Stage
2	2.33
10	3.46
20	3.85
50	4.33



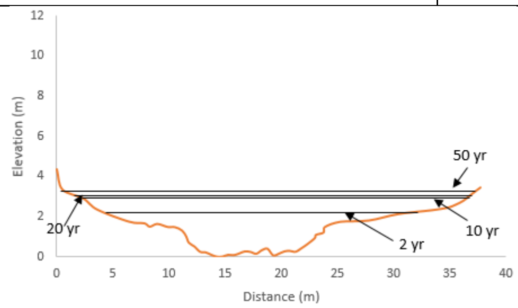
c)

ARI	Stage
2	1.38
10	2.06
20	2.31
50	2.64



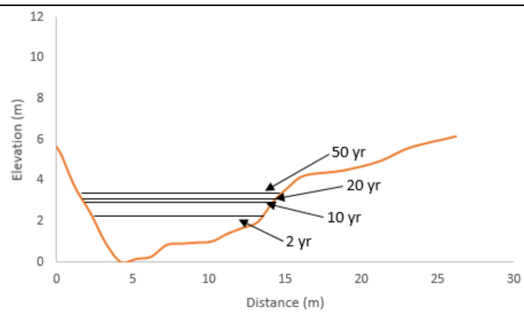
d)

ARI	Stage
2	2.18
10	2.96
20	3.17
50	3.41



e)

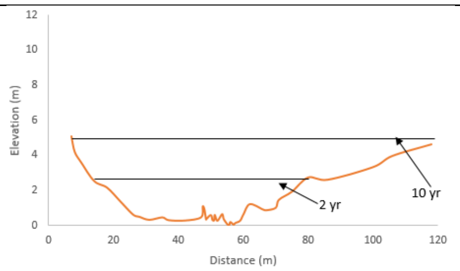
ARI	Stage
2	2.28
10	2.95
20	3.12
50	3.31



Appendix 12 continued. The height (m) of the calculated annual series floods (years) calculated using Log Pearson III plotted in surveyed east coast river cross-sections a) Apsley River at Apsley Gorge, b) Clouds Creek at Clouds Creek, c) Merriwa River u/s Vallance, d) Muggyrang Creek at Pokolbin site 4, e) Timbarra River at Billyrimbah

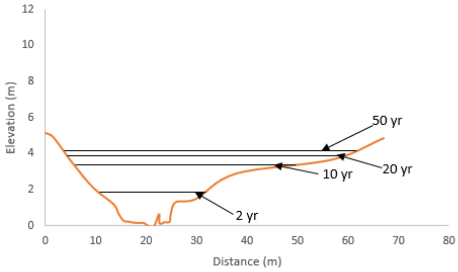
a)

ARI	Stage
2	2.68
10	5.10
20	6.20
50	7.79



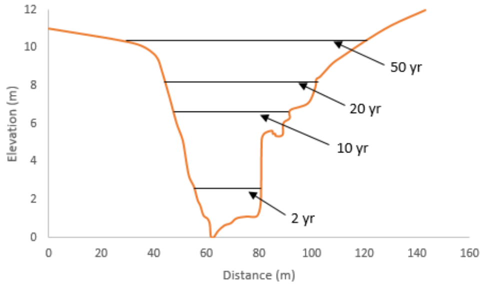
b)

ARI	Stage
2	1.99
10	3.53
20	3.92
50	4.29



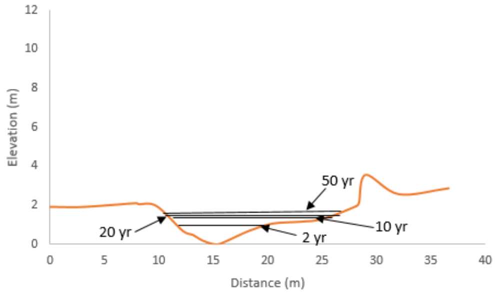
c)

ARI	Stage
2	2.62
10	6.58
20	8.24
50	10.42



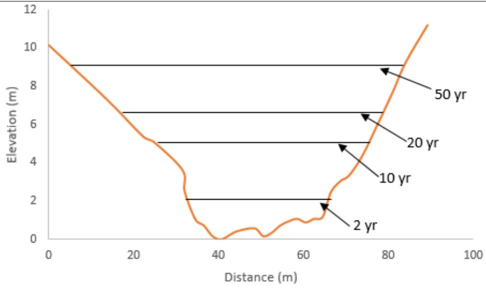
d)

ARI	Stage
2	0.98
10	1.37
20	1.47
50	1.56



e)

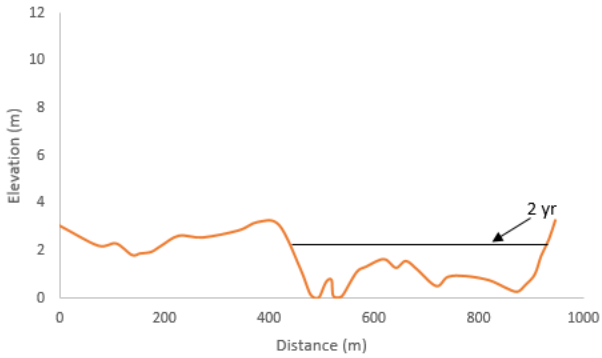
ARI	Stage
2	2.10
10	5.13
20	6.71
50	9.16



Appendix 12 continued. The height (m) of the calculated annual series floods (years) calculated using Log Pearson III plotted in surveyed semi-arid river cross-sections a) Paroo River at Willara Crossing, b) Culgoa River at d/s Collerina

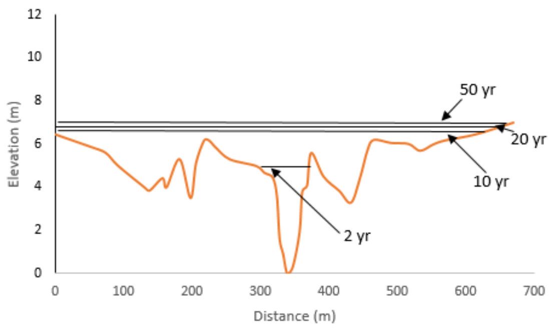
a)

ARI	Stage
2	2.37
10	3.92
20	4.54
50	5.36



b)

ARI	Stage
2	4.94
10	6.59
20	6.81
50	6.96



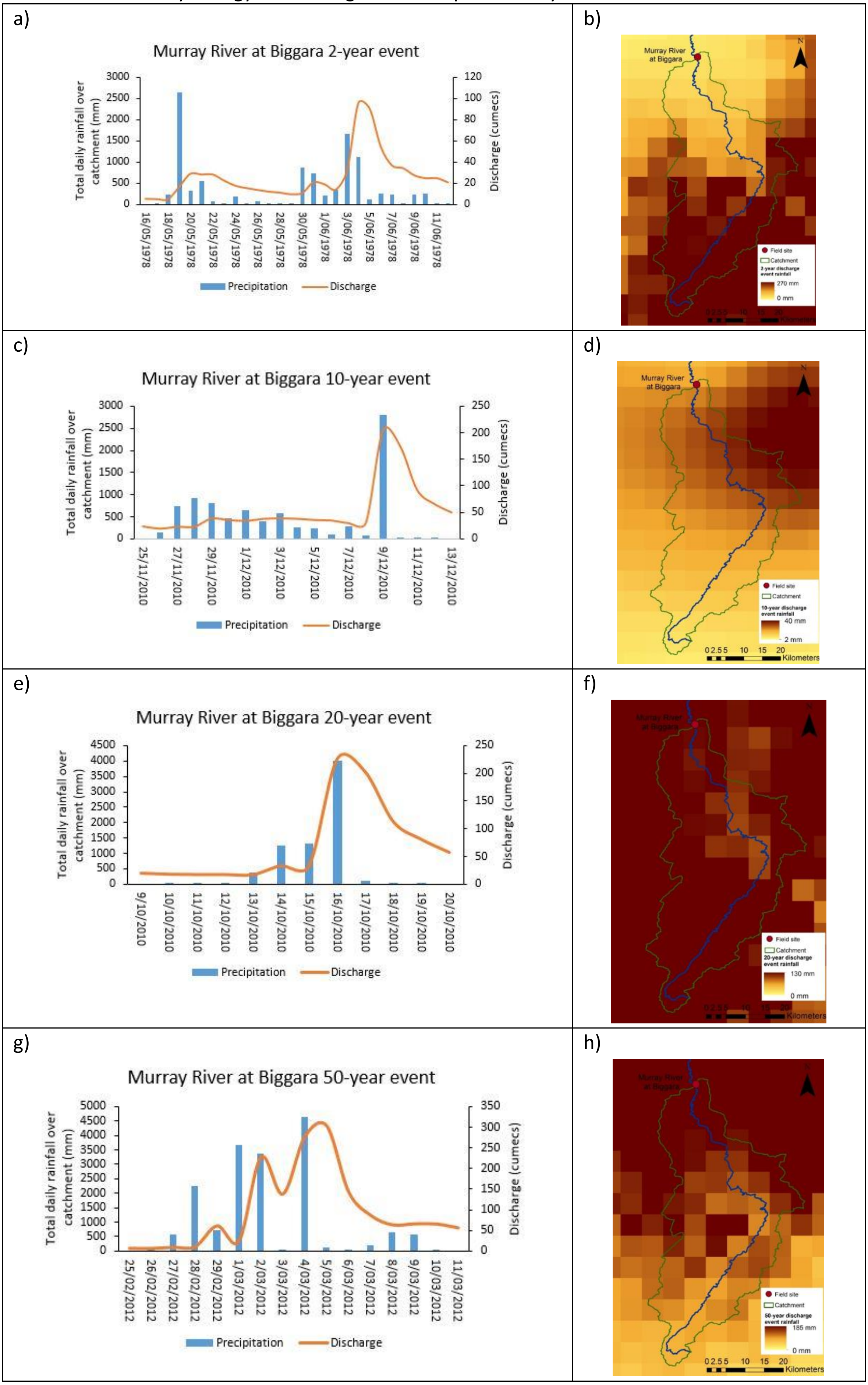
Appendix 13. Event-based runoff coefficients

Appendix 13. Precipitation and event based runoff coefficient analysis for Snowy Mountain rivers

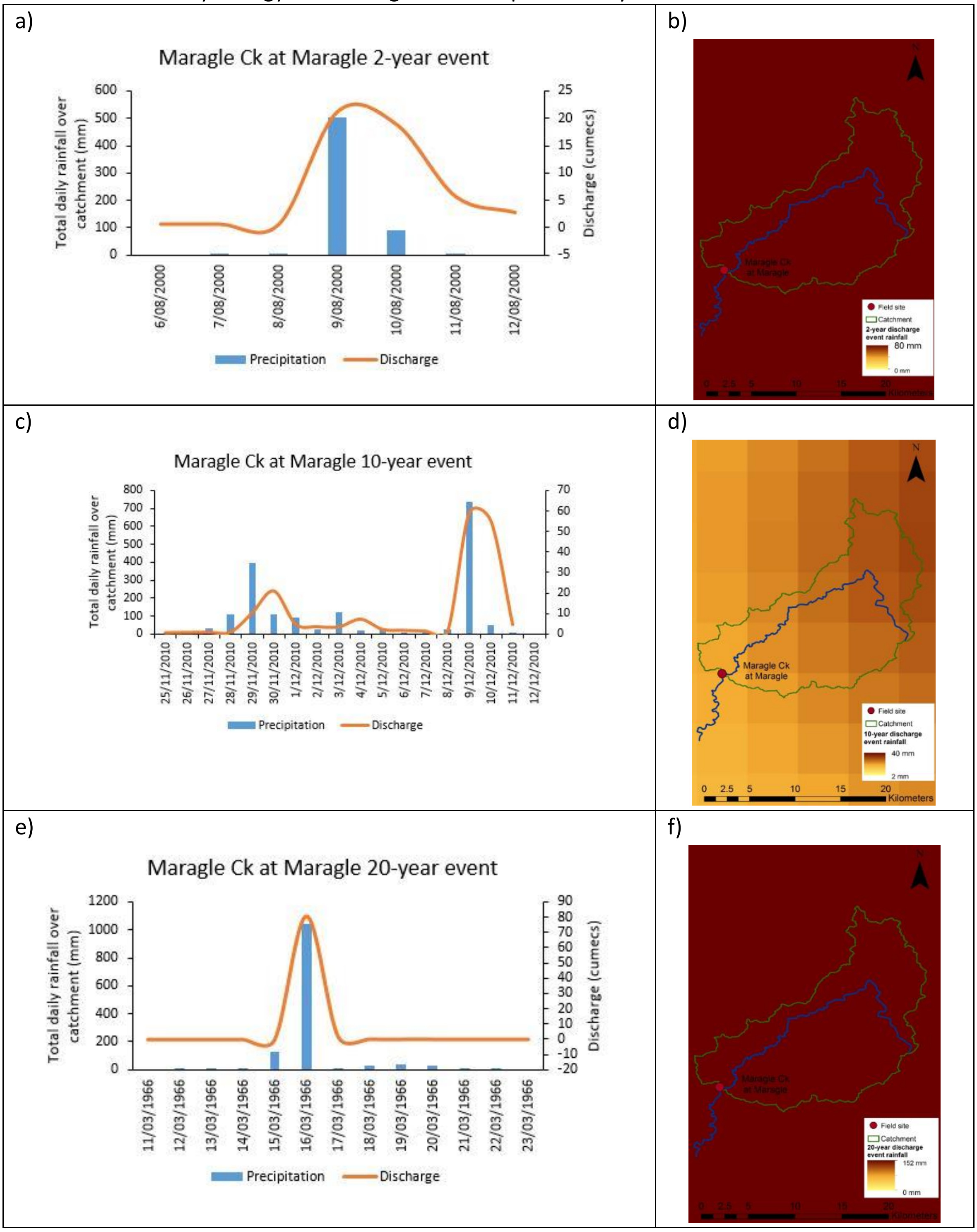
River	**Murray River at Biggara**				**Maragle Ck at Maragle**				**Mean Snowy Mtn rivers**			
Flood event (ARI years)	**2**	**10**	**20**	**50**	**2**	**10**	**20**	**50**	**2**	**10**	**20**	**50**
Max daily precipitation (mm)	96.5	83.6	121.0	170.4	73.3	89.4	124.3	na	56.8	86.5	122.7	170.4
Precipitation rate (mm/hour)	4.0	3.5	5.0	7.1	3.1	3.7	5.2	na	2.4	3.6	5.1	7.1
Number of days till max precip	4	14	7	8	3	14	5	na	11	14	6	8
Mean period discharge (ML)	1914	3564	4748	5806	308	357	69	na	1111	1960.5	2408.5	5806
Mean period runoff (mm)	1.52	2.84	3.78	4.62	1.43	1.66	0.32	na	1.48	2.25	2.05	4.62
Mean period rainfall (mm)	7.33	8.92	11.91	21.11	13.4	12.3	13.2	na	10.5	11.1	13.7	24.1
Mean rainfall depth over catchment over the rain event (mm)	205	170	143	338	67	196	145	na	136.0	183.0	144.0	338.0
Event based runoff coefficient	0.21	0.32	0.32	0.22	0.15	0.15	0.03	na	0.18	0.24	0.17	0.22

Appendix 13 continued. Precipitation and event based runoff coefficient analysis for east coast rivers

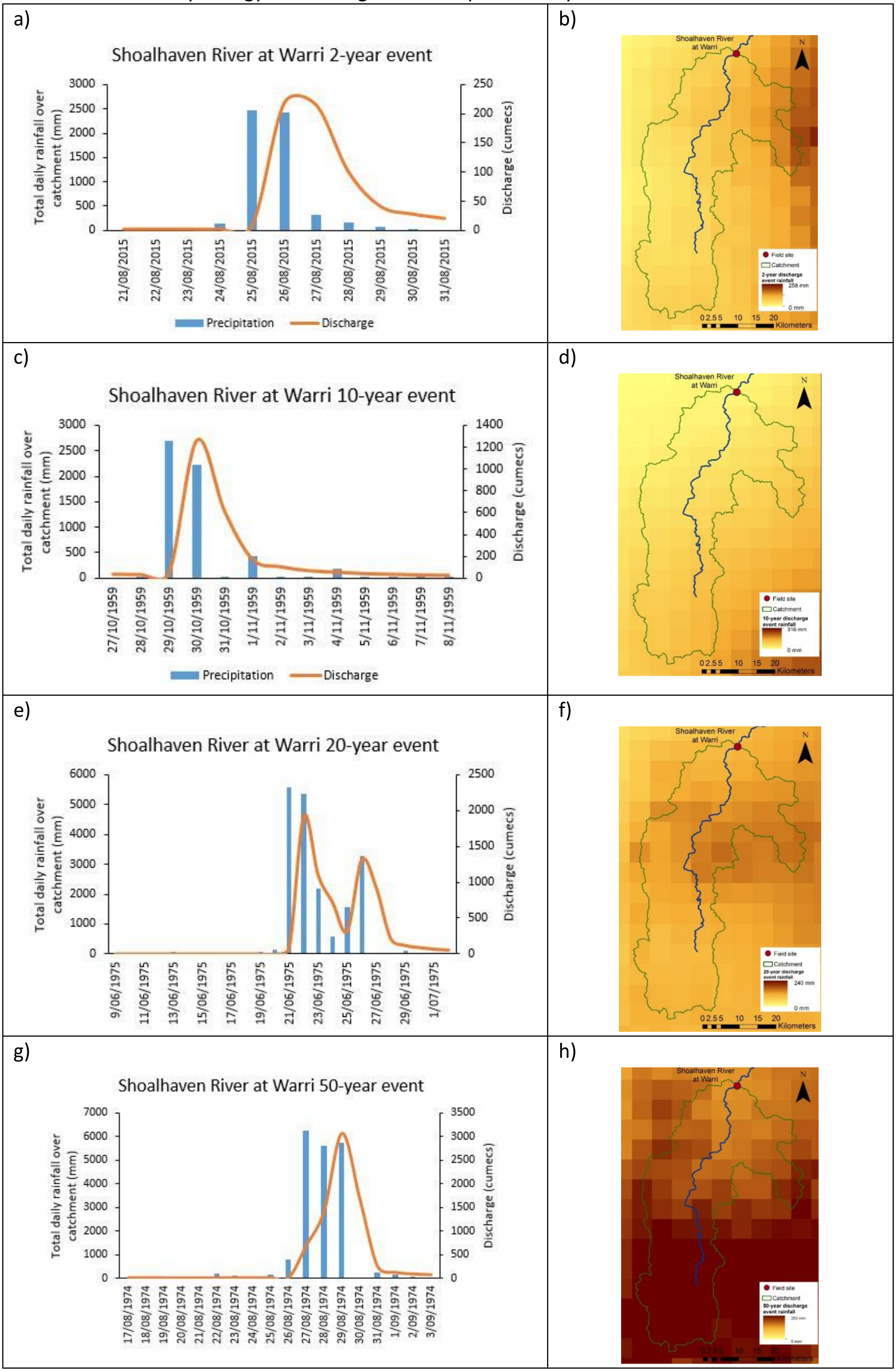
River	**Shoalhaven River at Warra**				**Timbarra River at Billyrimbah**				**Mean east coast rivers**			
Flood event (ARI years)	**2**	**10**	**20**	**50**	**2**	**10**	**20**	**50**	**2**	**10**	**20**	**50**
Max daily precipitation (mm)	117.2	74.9	132.8	158.4	53.9	160.1	205.2	na	85.5	117.5	169.0	158.4
Precipitation rate (mm/hour)	4.9	3.1	5.5	6.6	2.2	6.7	8.5	na	3.6	4.9	7.0	6.6
Number of days till max precip	5	3	13	10	9	11	4	na	7.0	7.0	8.5	10.0
Mean period discharge (ML)	3312	10380	16779	21642	1006	6629	1006	na	2159	8504.5	8892.5	21642
Mean period runoff (mm)	2.28	7.16	11.57	14.93	1.02	6.73	1.02	na	1.65	6.945	6.295	14.93
Mean period rainfall (mm)	11.0	14.7	15.2	21.4	8.5	17.6	31.0	na	9.8	16.2	23.1	21.4
Mean rainfall depth over catchment over the rain event (mm)	99	98	335	342	171	317	279	na	135.0	207.5	307.0	342.0
Event based runoff coefficient	0.25	0.95	0.83	0.79	0.13	0.40	0.42	na	0.19	0.67	0.62	0.79



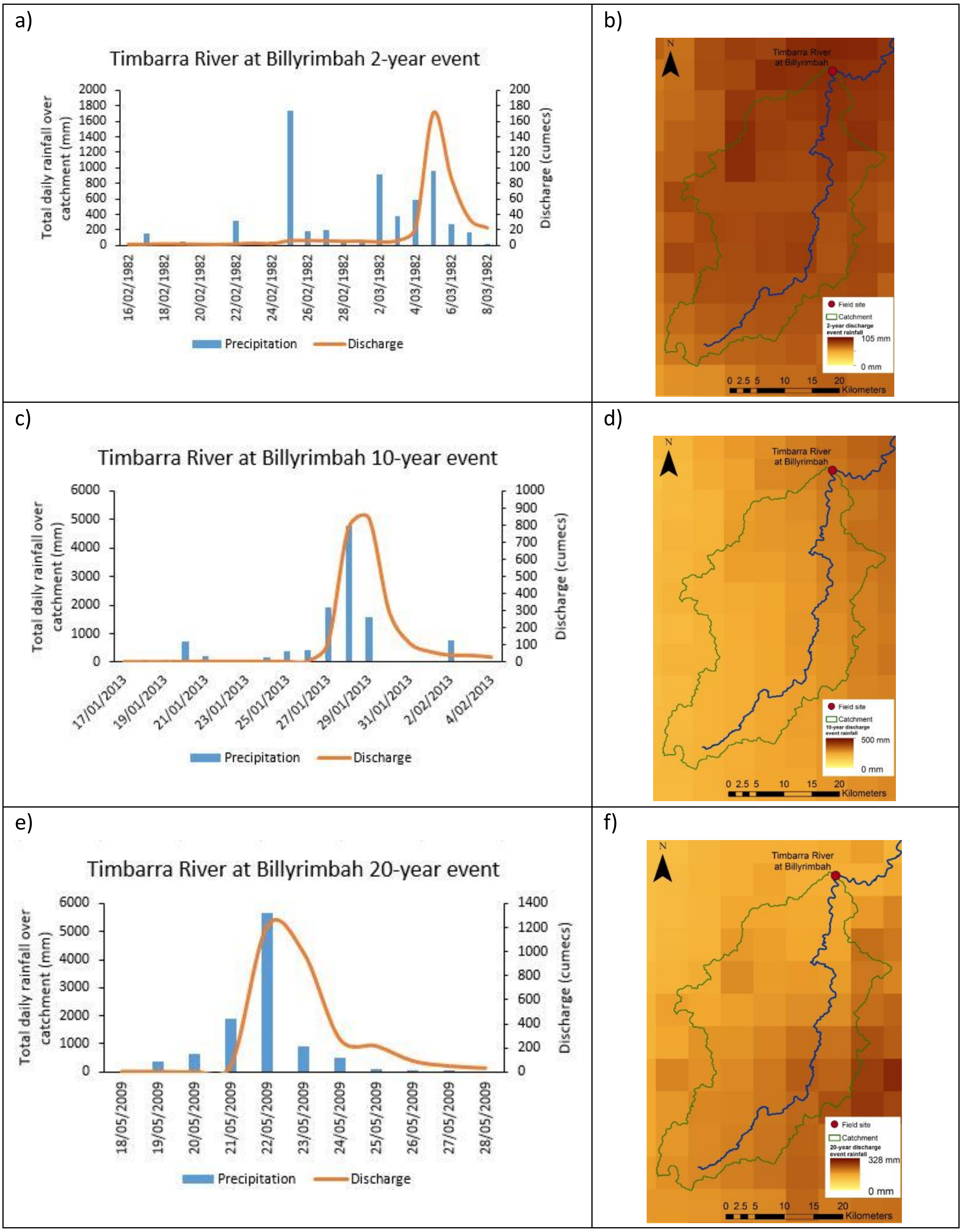
Appendix 13 continued. The hydrograph and associated rainfall for the 2, 10, 20 and 50-year flood events at Murray River at Biggara. The date of maximum rainfall totals for each storm is shown on each rainfall map. Calculated using BOM gridded data, ArcGIS and NSW Office of Water discharge data



Appendix 13 continued. The hydrograph and associated rainfall for the 2, 10, 20 and 50-year flood events at Maragle Creek at Maragle. The date of maximum rainfall totals for each storm is shown on each rainfall map. Calculated using BOM gridded data, ArcGIS and NSW Office of Water discharge data



Appendix 13 continued. The hydrograph and associated rainfall for the 2, 10, 20 and 50-year flood events at Shoalhaven River at Warri. The date of maximum rainfall totals for each storm is shown on each rainfall map. Calculated using BOM gridded data, ArcGIS and NSW Office of Water discharge data



Appendix 13 continued. The hydrograph and associated rainfall for the 2, 10, 20 and 50-year flood events at Timbarra River at Billyrimbah. The date of maximum rainfall totals for each storm is shown on each rainfall map. Calculated using BOM gridded data, ArcGIS and NSW Office of Water discharge data

Appendix 14. 8asm conference proceedings paper

Flood frequency and flow scaling in Snowy Mountain rivers

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Key Points

- Low hydrologic variability is demonstrated in Snowy Mountain rivers 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.