Hitting rock bottom: Morphological response of upland bedrock-confined streams to catastrophic flooding

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Hitting rock bottom: Morphological response of upland bedrock-confined streams to catastrophic flooding

Abstract
The process-based classification of upland drainage networks and the response of bedrock channels to extreme events has attracted significant attention in the recent literature. The acknowledgement of the importance of headwater reaches to catchment-scale ecological and geomorphological processes highlights the need for process-based studies in such settings and an examination of how such settings respond to big flood events. A catastrophic flood event in the Lockyer Valley in 2011 resulted in significant geomorphic changes across the catchment, particularly in bedrock-confined reaches. This study assesses the post-flood channel morphology in three reaches and examines the response of such settings to the catastrophic 2011 flood and subsequent flooding in 2013. Field-survey data, multi-temporal LiDAR analysis, flood frequency analysis and sediment entrainment threshold calculations were used to investigate the reach-scale morphological response of steep, bedrock-confined channels.

The results indicate that the three study reaches underwent catastrophic stripping during the 2011 flood with large-scale destruction of channel units and in-channel vegetation to create a highly disorganised channel morphology. The flood frequency analysis demonstrates that the 2011 flood is the largest on record and represents a ~50-yr recurrence interval (ARI). The extent of geomorphic change due to this extreme event increased with stream order (catchment area), evidenced through volumetric analysis of alluvium eroded. However, net erosion per unit area was the greatest in the steepest (smallest catchment area) reach. The longitudinal profiles and channel cross-sections in all three reaches show extensive channel lowering and widening with erosion to bedrock occurring along much of the valley floor. Channel cross sections expanded by up to 220% and longitudinal profiles experienced significant reductions in morphological variance with the loss of vertical variability. It is estimated that this event, with an estimated discharge range of 415-897 m$^3$/s and an estimated unit stream power range of 616-1077 W/m$^2$, mobilised the entire grain-size population from sand to boulders up to 1670mm in diameter. Channel recovery through vertical accretion of sedimentary material and channel narrowing has occurred to some extent following the 2011 event, most likely the function of a ~6-yr ARI event in 2013. However, modern channel morphologies do not reflect existing classification frameworks for mountain stream morphology due to the disturbance of sediment supply and transport capacity conditions during this event. It is hypothesised that rare, large magnitude floods dominate the episodic morphological evolution of such settings with the recovery of in-channel units (e.g. pools and riffles) dependent on the subsequent frequency of bedload transporting events.

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Hitting Rock Bottom

Morphological Response of Upland Bedrock-Confined Streams to Catastrophic Flooding

Markus Baggs Sargood

Research report submitted in partial fulfilment of the requirements for the award of the degree of Bachelor of Environmental Science (Honours)

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The information in this thesis is entirely the result of investigations conducted by the author, unless otherwise acknowledged and has not been submitted in part, or otherwise, for any other degree or qualification.

Markus Baggs Sargood
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ABSTRACT
The process-based classification of upland drainage networks and the response of bedrock channels to extreme events has attracted significant attention in the recent literature. The acknowledgement of the importance of headwater reaches to catchment-scale ecological and geomorphological processes highlights the need for process-based studies in such settings and an examination of how such settings respond to big flood events. A catastrophic flood event in the Lockyer Valley in 2011 resulted in significant geomorphic changes across the catchment, particularly in bedrock-confined reaches. This study assesses the post-flood channel morphology in three reaches and examines the response of such settings to the catastrophic 2011 flood and subsequent flooding in 2013. Field-survey data, multi-temporal LiDAR analysis, flood frequency analysis and sediment entrainment threshold calculations were used to investigate the reach-scale morphological response of steep, bedrock-confined channels.

The results indicate that the three study reaches underwent catastrophic stripping during the 2011 flood with large-scale destruction of channel units and in-channel vegetation to create a highly disorganised channel morphology. The flood frequency analysis demonstrates that the 2011 flood is the largest on record and represents a ~50-yr recurrence interval (ARI). The extent of geomorphic change due to this extreme event increased with stream order (catchment area), evidenced through volumetric analysis of alluvium eroded. However, net erosion per unit area was the greatest in the steepest (smallest catchment area) reach. The longitudinal profiles and channel cross-sections in all three reaches show extensive channel lowering and widening with erosion to bedrock occurring along much of the valley floor. Channel cross sections expanded by up to 220% and longitudinal profiles experienced significant reductions in morphological variance with the loss of vertical variability. It is estimated that this event, with an estimated discharge range of 415-897 m³/s and an estimated unit stream power range of 616-1077 W/m², mobilised the entire grain-size population from sand to boulders up to 1670mm in diameter. Channel recovery through vertical accretion of sedimentary material and channel narrowing has occurred to some extent following the 2011 event, most likely the function of a ~6-yr ARI event in 2013. However, modern channel morphologies do not reflect existing classification frameworks for mountain stream morphology due to the disturbance of sediment supply and transport capacity conditions during this event. It is hypothesised that rare, large magnitude floods dominate the episodic morphological evolution of such settings with the recovery of in-channel units (e.g. pools and riffles) dependent on the subsequent frequency of bedload transporting events.
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1. INTRODUCTION

1.1 CONTEXT

The role of catastrophic flooding in the development of fluvial systems has received a significant amount of attention in the past five decades (e.g. Wolman & Miller 1960; Fuller 2008; Milan 2012). Large-scale, low frequency floods are a major vehicle of geomorphic change, resulting in extensive channel and floodplain adjustment (Croke et al. 2012). South-East Australian catchments experience unusually high flow variability in an international context as a result of alternating climatic ‘flood dominated regimes’ (FDR) and ‘drought dominated regimes’ (DDR) as outlined by Erskine & Warner (1998). This variability manifests itself in long periods of low-flow in fluvial systems during DDRs, which are interspersed with periods of FDRs, characterised by large flood events which can cause vast geomorphic change on very short time scales. The erosion associated with these geomorphically effective floods often causes damage to infrastructure, productive land and human lives. Due to the human interests which are dependent on alluvial floodplains and the dynamism of hydrological and sedimentary processes in lowland valleys, the majority of research has focused on these lower-catchment regions. The notion that upland streams represent little value to societies in terms of water resources or as fishery or agricultural resources, has resulted in a gap in academic research in the fluvial sciences regarding processes and morphology of upland channels (Halwas & Church 2002). Relatively recent recognition of the value of steep headwater channels as ecological habitats and sediment sources as well as their critical role in landscape evolution and transmission of disturbances throughout catchments has encouraged research in recent years, with a particular focus on process-based morphology (Montgomery & Buffington 1997).

Upland streams are often referred to as bedrock channels, which have been described as being ‘characterised by frequent exposures of bedrock in the bed and banks and a lack of a coherent blanket of sediment, even at low flow’ (Whipple & Tucker 2002). Toone et al. (2012) use the definition of ‘mixed bedrock-alluvial channels’ to characterise both the presence of alluvial channel units and strong bedrock control. These channels have a mixture of alluvial and non-alluvial features, but are delineated by the high sediment transport capacity of flows compared to sediment supply (Howard et al. 1994). Researchers have highlighted the amplified role of floods as agents of geomorphic change in high threshold, resistant bedrock-confined streams which maintain relatively uniform structure during ‘normal’ flow periods (Jansen 2006). In alluvial channels, relatively frequent, i.e. <10 year recurrence interval, flows have been identified as the primary mechanism for geomorphic change and sediment transport as they are capable of mobilising the majority of bedload sediment (Wolman & Miller 1960). Bedrock channels in small catchments have highly variable flows and resistant boundary conditions and as such, very low
frequency, high-discharge floods are the ‘geomorphically effective’ flows, as larger flows are required to mobilise sediment and propagate bedrock erosion and incision (Wolman & Miller 1960; Milan 2012). Due to the lack of in-channel or overbank areas for dissipation of flow, flooding in bedrock channels is usually associated with highly concentrated in-channel flows, resulting in erosion, channel scour and incision (Jansen 2006). The morphological evolution of steep, confined channels has been described as a stochastic process, with periods of aggradation, or alluvial development, interrupted by large, rare floods which strip channels of alluvium and ‘reset the clock’ of bedrock-confined channels (Nanson 1986; Benda 1990).

A number of geomorphologists have used field surveying, remote sensing data and statistical methods to inform classifications and models of in-channel morphology of bedrock-confined mountain stream reaches (Montgomery & Buffington 1997; Thompson et al. 2006; Wohl & Merritt 2008). The degree of structural control imposed on fluvial processes by bedrock increases the relevance of local geology for specific reach-scale morphology and sediment supply. There has been an increasing interest in categorising and understanding such channels in terms of process based morphology across a number of continents, based primarily on a pioneer study by Montgomery and Buffington (1997) which proposed a classification framework for upland streams. By applying process and setting based classification systems to representative channel reaches, the form and process of montane channels, including response to disturbances such as floods, can be better understood, tracked and quantified to inform effective management (Golden & Springer 2006).

Advances in remote sensing technologies and techniques in recent years, in particular airborne Light Detection and Ranging (LiDAR), has increased the ability of geomorphologists to assess channel and floodplain morphology over extensive or remote study regions. Field-surveying of extensive and remote fluvial settings is often prohibitively costly and time-consuming, while desktop analyses are efficient and relatively low-cost, where sufficient data and expertise exists. Due to the high spatial resolution of modern LiDAR imaging, in-channel features can be mapped through the creation of digital elevation models (DEMs) and temporal changes can be quantified using multi-temporal DEMs of difference (DODs) (Croke et al. 2013a). The use of LiDAR derived DEMs for mapping and assessing temporal changes to in-channel morphology has been employed effectively by a number of geomorphologists in recent years (Charlton et al. 2003). Of particular note to this study is the use of LiDAR to assess the erosion and deposition of in-channel and floodplain sediments in the Lockyer Creek catchment (Thompson & Croke 2013; Croke et al. 2013a). In addition to LiDAR, aerial photography and spectral reflectance data has proven effective in fluvial geomorphology due to the abundance and low cost of satellite-derived spectral data. The applicability and benefits of remote-sensing analysis in fluvial geomorphology has been
demonstrated in a number of studies, where both discrete and catchment-scale analysis has been carried out (Winterbottom & Gilvear 1997; Grove et al. 2013).

The importance of headwater processes to local aquatic and terrestrial ecosystems and landscape evolution, as well as downstream fluvial and geomorphological processes has come to the fore in recent decades. A number of researchers have highlighted the need for greater understanding and research in the processes and morphology types which characterise steep, upland streams (Hodge et al. 2011; Milan 2012).

1.2 AIMS AND OBJECTIVES

The 2011 flood event in the Lockyer Catchment had a catastrophic impact in terms of damage to human life, resources and infrastructure as well as wreaking immense geomorphic and environmental change throughout much of the catchment (Croke et al. 2012). The headwaters of the catchment, which reside in the foothills of the Great Dividing Range, underwent immense geomorphic change during the event and the enormity of flows in this region contributed to the propagation of disastrous flooding effects downstream. In 2013, a second event of lesser magnitude caused widespread flooding throughout the catchment, further influencing fluvial systems and human interests. The upland streams of the Lockyer Catchment demonstrate the way in which floods of varying magnitude may result in specific types of geomorphic responses. As mentioned, there is a lack of quantitative research of erosional processes and channel evolution in bedrock settings (Howard 1998), which strengthens the impetus to study and empirically quantify such responses. These two subsequent events present a unique opportunity to assess the extent of geomorphic change in the headwaters of the catchment as a result of extrinsic climatic events using field sampling, remote sensing and Geographic Information Systems.

This study aims to investigate bedrock-confined channels in an upland setting, characterise their response to flood events and test the applicability of existing classification schemes in describing the channels of the upper Lockyer. The modern channel morphology of three bedrock-confined channels in the upper Lockyer valley will be characterised in terms of physical and morphological characteristics in order to allow a comparison of the upland settings of this catchment to those described in the scientific literature. An assessment of the applicability of existing classification schemes for upland channels will be undertaken to determine the nature of post-flood channels.

Through the use of field survey techniques, multi-temporal LiDAR and satellite imagery, this study will investigate the response of the study reaches to the 2011 and 2013 flood events, characterising changes in process-based morphology. Quantitative spatial analysis will be carried out to describe the role of large, rare flood events for reach-scale channel evolution and long-term episodic landscape evolution.
Flood-frequency analysis of local stream-gauge data and evidence of long-term climatic trends will be used to characterise the variability of discharge regimes in the Lockyer Catchment and the role of climate on fluvial processes and thus landscape change.

Explicitly, this study will:

1. Characterise the modern channel morphology of three study reaches of the upper Lockyer Valley according to physical setting, visual morphology and flood history.
2. Assess modern morphology according to the existing classification framework for south-east Australian upland streams developed by Thompson et al. (2006) and determine the applicability of morphological classifications in such settings.
3. Investigate the hydrological characteristics of the upper Lockyer drainage network based on flood frequency analysis
4. Evaluate and quantify the reach-scale channel response to the 2011 and 2013 flood events through use of multi-temporal LiDAR, field survey data and spatial analysis
5. Assess the geomorphic effectiveness of the 2011 and 2013 flood events and determine the role of extreme events in bedrock-confined channel evolution

1.3 Thesis Structure

The research report presents a review of literature focusing on the morphology of upland bedrock channels and the geomorphic effect of flooding on such channels. The response of upland streams to geomorphic change and channel evolution is also discussed. Chapter 3 places the study area in a regional and climatic context as well as discussing the human factors which exist in the catchment including settlement, land-use and anthropogenic changes to the fluvial network. The subsequent chapter is a description of the methods used in fieldwork and analysis to collect data and integration of primary fieldwork with existing data. Chapter 5 includes the presentation of the results of fieldwork and desktop analysis, which are focused on the morphological nature of the study reaches and quantifying the response of these reaches to recent flooding. Chapter 6 discusses the results and implications of the study in reference to existing research and literature in Australia and internationally, including a comment on the limitations of the methods and analyses used in this thesis. Concluding the report is a chapter which outlines recommendations for future research and the implications of this study in understanding and managing upland rivers.
2. LITERATURE REVIEW

This chapter will review past and current literature regarding bedrock-channel processes and morphology and investigate the importance of large flood events in dictating reach-scale characteristics of upland, bedrock-confined channels. The importance of geomorphically effective flows and in particular, catastrophic flooding, to bedrock channel morphology is discussed including theories of upland channel evolution.

2.1 BEDROCK CHANNEL PROCESSES AND FEATURES

2.1.1 SEDIMENT ENTRAINMENT THEORY

Critical to understanding and predicting the nature of channel processes, as well as the response of channel features to certain discharges is sediment entrainment theory. Sediment entrainment theory outlines the critical conditions required for mobilising certain fractions of the sediment store within a channel (Bathurst 1987). A number of flume and field studies have been undertaken to determine the discharge conditions required for entrainment of certain channel bed sediment populations (Bathurst 1987; Komar 1996; Thorne et al. 1997). Experiments in controlled flume environments with relatively uniform sediment size led to the creation of a number of sediment entrainment curves based on empirical relationships between grain size and flow characteristics such as velocity or bed stress. Perhaps the most prominent is the Shields Curve, which describes a ‘universal’ threshold for the initiation of movement of bed load according to shear stress and grain size (Shields 1936), based on an extensive range of flume experiments using various sediment materials and flow regimes (Equation (1)). Such empirical relationships are limited in their real-world application as they are based on sediment deposits of uniform size and density.

Various researchers have attempted to account for differences in entrainment thresholds between types of natural channels. Komar & Carling’s (1991) research on the use of reference particles for entrainment analysis led to the development of an equation for the entrainment of bed material in steep channels with unsorted coarse bedload, given below as Equation (2) (U.S. Department of Agriculture 2008).

$$\tau_* = \frac{\tau_c}{(\gamma_s - \gamma)} D$$ (1)

Where $\tau_c$ = critical shear stress; $\gamma_s$ = specific weight of bed material; $\gamma$ = specific weight of water; $D$ = bed material particle diameter and $\tau_*$ = dimensionless Shields parameter.
Where \( \tau_{cl} \) = critical shear stress for particle of interest to move; \( \tau_{c50}^* \) = dimensionless Shields parameter for \( D_{50} \), \( D_l \) = diameter of particle size of interest and \( D_{50} \) = diameter of the median particle size of the channel bed.

Empirical entrainment threshold curves show that in sand-sized sediment deposits, larger particles are selectively entrained due to greater cohesiveness in smaller-grained deposits. Conversely, in gravel entrainment from mixed deposits, the greater the flow strength, the coarser the material entrained from the bed (Komar 1996). Bathurst (1987), found that in deposits of non-uniform grain size, particles smaller than a reference size (approximately \( D_{50} \)) require larger discharges to initiate movement, while the reverse is true of particles larger than the reference size. This is attributed to the protection of smaller particles by larger ones and the increased vulnerability of large particles which project into the stream flow.

In the case of upland streams, sediment size is typically variable due to the input of alluvial and non-alluvial sediment and seasonal changes in discharge, affecting sediment sorting and transport regimes. A study by Hodge et al. (2011) found that the exposure of bedrock along the channel bed reduces the size-dependence of bedload sediment entrainment. As a result, the proportion of a channel which is mantled by sediment has a direct impact on the entrainment of certain clast sizes. From this it can be inferred that the degree of mantling will determine how such a channel responds to extreme events. While many entrainment relationships involve the use of shear stress as the primary variable for delineating thresholds, in bedrock streams it becomes untenable due to the low depth to particle size ratios. This has led to the creation of equations specific to steep boulder-bed streams with non-uniform sediment distributions which employ unit discharge rather than shear stress as the delineating variable. Bathurst (1987) created a set of equations for calculating critical conditions for particle movement thresholds in steep channels with non-uniform, coarse bed material which accommodate the effects of grain protection and exposure in mixed-size deposits. Equations (3), (4) and (5) allow the calculation for bedload entrainment based on unit discharge.

\[
q_c = 0.15 \, g^{0.5} \, D^{1.5} \, S^{-1.12} \tag{3}
\]

Where \( q_c \) = critical water discharge per unit width; \( g \) = acceleration due to gravity; \( D \) = diameter of particle size of interest and \( S \) = slope.
\[ q_{ci} = q_{cr} \left( \frac{D_i}{D_r} \right)^b \] (4)

Where \( q_{ci} \) = critical unit discharge for the movement of particles of size \( D_i \); \( q_{cr} \) = critical unit discharge for the reference particle size \( D_r \) and \( b \) = an exponent (derived from equation (5))

\[ b = 1.5 \left( \frac{D_{84}}{D_{16}} \right)^{-1} \] (5)

These entrainment variables and thresholds are vital to understanding both fluvial processes and the in-channel morphological characteristics of bedrock upland channels as they directly influence the way in which sediment is arranged into morphological units and the overall characteristics of upland catchments. Studies into the accuracy of mathematical entrainment equations have found mixed results, with over- and under-estimation of different transport thresholds in step-pool channels being presented by Zimmerman & Church (2001). However, due to the impracticability of physically measuring bedload entrainment during high flow events, mathematical surrogates for entrainment thresholds present a tenable methodology for estimation of the geomorphic effectiveness of given discharges.

2.1.2 CHANNEL UNITS IN BEDROCK SETTINGS

The morphology of most fluvial channels is the result of hierarchical arrangement of sediment particles into bedforms or channel units, which form sequences that characterise stream morphology (Shields 1936). The processes which lead to the distribution of alluvial substrate into channel units are fundamental to understanding the variables influencing fluvial geomorphology and the response of channel reaches to particular flow events. Physical processes are the result of a suite of variables, foremost; geology, climate and land use; which in turn drive the topography, discharge, sediment characteristics and the influence of vegetation. These factors exert control over the geomorphic variables including channel dimensions, slope, bed-form and planform (Buffington et al. 2003). The processes and unit-scale morphology of lowland river systems are well-defined due to a long history of study, yet the processes and physical variables of such systems differ significantly from those of upland, bedrock-confined channels (Montgomery & Buffington 1997).

A universal nomenclature of channel units and reach-scale morphology for bedrock streams does not exist in literature. However, the majority of modern studies follow a set of criteria for identifying channel units similar to that outlined by Grant et al. (1990), as summarised in Table 1.
Table 1: Channel units typical of upland streams, based on Grant et al. (1990)

<table>
<thead>
<tr>
<th>Channel Unit</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pools</td>
<td>Areas of slow, subcritical flow typically with high relative depth and substrate coverage at low-flow. Often deepest immediately at their upstream extent.</td>
</tr>
<tr>
<td>Riffles</td>
<td>Areas of dominantly subcritical flow with local instabilities and hydraulic jumps, often over bed elements. Velocity is greater, relative depth lower than pools. Limited lateral organisation of substrate.</td>
</tr>
<tr>
<td>Rapids</td>
<td>Areas of both subcritical and supercritical flow characterised by organisation of boulders lateral to flow into ‘ribs’. Pocket pools may intersperse ribs.</td>
</tr>
<tr>
<td>Cascades</td>
<td>Steep units with dominantly supercritical flow over large boulder or bedrock steps. Steps are separated by small, short pools into a staircase-like arrangement.</td>
</tr>
<tr>
<td>Steps</td>
<td>Short (&lt;1 channel width) features of bedrock, boulders or logs forming discrete falls. Often due to immovable hillslope boulders, tree falls or bedrock outcrops.</td>
</tr>
</tbody>
</table>

A number of conceptual and mathematical theories have been proposed in fluvial research to describe the nature of self-formed channels and arrangements of channel units in terms of height, frequency and spacing and in turn, general stream morphology (Huang & Nanson 2000). The maximum friction factor (MMF) hypothesis put forward by Davies & Sutherland (1983) has been widely applied in bedrock channel morphology, postulating that the arrangement of sediment in fluvial systems is directed towards a state of maximum resistance to flow. This concept has both empirical and logical coherence in alluvial transport, as any threshold discharge will act upon channel morphology in a way that increases frictional resistance. In simple terms, this means that the channel boundary – and thus sedimentary units - will be reshaped during formative flows towards a more resistant arrangement. The MMF hypothesis has proven applicable to both alluvial and bedrock settings, as even in systems where sediment supply is limited relative to transport capacity, the geometry of channel reaches will still adjust to maximise resistance to flow energy (Abrahams et al. 1995; Wohl & Merritt 2008). The practical implication of this model is that steep headwater reaches will move towards the most variable bed which can be achieved within the constraints of the system, particularly gradient, discharge and sediment supply (Wohl & Merritt 2008).

It has been argued that the use of extremal hypotheses such as MMF is arbitrary and has a somewhat tentative foundation in physics (Nanson & Huang 2008). Due to the fact that extremal hypotheses deal only with excess energy, Nanson & Huang (2008) propose the least action principle (LAP) as a more complete theory explaining channel adjustments and energy consumption in fluvial systems. In terms of channel morphology, the LAP states that channels are self-adjusting systems which undergo change in a way which emits any surplus energy through
available processes and conserves energy if insufficient energy exists. Upland streams that are characteristically confined by bedrock or steep valleys have much less scope for adjustment in comparison to the alluvial channel to which this principle has been frequently applied. While alluvial channels have malleable boundaries and lateral space for channel adjustments, the space available for adjustment in bedrock-confined streams is primarily vertical. Huang & Nanson (2000) impress the usefulness of extremal theories in understanding certain aspects of fluvial dynamics, yet link their premise to the LAP. These theories of channel adjustment and evolution are further discussed in Section 2.4.

Inputs of colluvium, large woody debris and bedrock exposures can ‘force’ morphological development of bedrock streams as they are non-alluvial under normal flow conditions (Buffington et al. 2002). A number of studies have found that exogenous bodies on channel boundaries exert a strong influence over the development of channel units including steps, pools and riffles (Shields 1936; Buffington et al. 2002; Thompson 2012). These obstructions can cause the development of ‘forced’ morphologies in atypical settings, such as forced pool-riffle or step-pool sequences, in which channel morphology is the result of flow divergence around large woody debris or colluvial boulders (Montgomery et al. 1996).

The organisational structure of channel units is often viewed on a broader scale in order to analyse ‘reach morphology’. Due to the influence of discrete exogenous bodies and localised factors on channel units, it is often useful to subdivide channels into reaches tens of metres to ten of kilometres in length, which represent sections of a stream containing a sequence of channel units throughout which morphology is relatively consistent (Wohl & Merritt 2001; Brardinoni & Hassan 2007). The use of channel reaches of at least 10 – 20 channel widths in length has become the standard in literature regarding upland stream morphology analysis, within which the nature of channel units and physical variables are used to characterise process-based reach morphology (Montgomery & Buffington 1997).

2.2 BEDROCK STREAM MORPHOLOGY AND CLASSIFICATION

There is no infallible set of physical conditions which has been found to reliably predict reach-scale morphology in bedrock-confined rivers, yet a range of studies in recent years have described a variety of morphology types and provided general relationships between catchment characteristics and morphology for discrete regions. Literature in fluvial geomorphology highlights the role of physical setting, including landscape characteristics, vegetation and drainage area in influencing the presence of certain morphologies (Hack & Goodlett 1960). The nature of ‘macrochannels’ have been highlighted as an important morphological concept in various reach types, particularly in assessing flood processes (Reinfelds & Nanson 2004). Macrochannels are
described by Croke et al. (2013) as larger channels operating as a conduit for high magnitude floods (>100-yr ARI) which accommodate a small inner channel and associated benches that carry frequent flows and smaller floods (~20-yr ARI). In Australian channels, alluvial macrochannels are often bounded by high elevation ‘apparent floodplains’, while structurally confined macrochannels are bounded by bedrock valleys (Erskine & Livingstone 1999).

Recent interest in upland channels has led to an increasing amount of research into trends in upland stream morphology, resulting in a number of conceptual morphological classification models for mountain streams (Wohl & Merritt 2001). Montgomery & Buffington (1997) produced an important contribution which outlined a framework for reach-scale classification of upland streams into visually identifiable and physically distinct categories. While based on channels in the Pacific Northwest of America, the framework has been applied and modified in a number of subsequent studies to be appropriate in an international context, although the author stresses that no single classification system can be considered applicable in all contexts (Montgomery & Buffington 1997).

The Montgomery and Buffington (1997) reach classification includes 6 channel classes which are delineated as an idealised downstream progression of morphologies; colluvial, bedrock, cascade, step pool, plane bed, pool riffle and dune ripple (Brardinoni & Hassan 2007), as depicted in Figure 1.

![Figure 1: Idealized valley profile showing distribution of channel types and controls on processes in mountain basins. From Montgomery and Buffington (1997).](image)

The morphologies are identifiable based on visual characteristics and the combination of geomorphic variables which influence processes and thus morphology. An extensive range of consequent studies have found that the framework outlined in Figure 1 is widely applicable to upland regions of catchments around the world, with local conditions influencing the parameters within which certain morphologies exist and how frequently they occur (Harvey 1991; Halwas &

Church 2002; Golden & Springer 2006; Thompson et al. 2006; Vianello & D'Agostino 2007; Wohl & Merritt 2008). The plot of drainage area vs. slope (Figure 2) is commonly used to present the continuum of mountain stream morphologies according to these key parameters, with the relationship between reach slope and drainage area providing a good degree of separation between morphology classes (Brardinoni & Hassan 2007).

![Figure 2: Drainage area versus reach slope for channels in the Finnery Creek watershed, Washington, from Montgomery and Buffington (1997).](image)

The pivotal characteristic which influences reach-scale morphology is the relationship between sediment supply and sediment transport capacity. This ratio is derived from a range of contributing sub-variables such as slope, discharge, sediment size distribution and drainage area. In general terms, transport capacity declines downstream due to slope decreasing more rapidly than depth, while sediment supply generally increases with drainage area, as depicted in Figure 3 (Montgomery & Buffington 1997; Thompson et al. 2006). A study by Gomi et al. (2003) discusses the dominance of hillslope processes in high gradient upland streams, with a progression downstream to morphologies resulting from fluvial processes as gradient decreases.

![Figure 3: Generalised relative trends in sediment supply (Qs) and transport capacity (Qc) in mountain drainage basins. From Montgomery & Buffington (1997)](image)
A study on local variations in physical watershed characteristics and their influence on morphology is presented by Addy et al. (2011) in deglaciated terrain. A longitudinal progression of channels occurs and morphological properties of classes conform to the existing framework of Montgomery and Buffington (1997), yet the gradient at which each reach type occurs is significantly lower. This demonstrates the effect of sediment supply and transport ratios on upland stream morphology as de-glaciated landscapes house fluvial systems characterised by low sediment supply, which reduces the capacity of the stream bed to generate channel units usually associated with certain gradients (Addy et al. 2011). Golden & Springer (2006) quantified the degree to which multiple lithologies affect mountain channel morphology as a function of varying resistance. Given lithologies were found to promote certain morphologies and rock type strongly controlled grainsize, which in turn influences resistance. However no significant relationship existed between lithology and morphology, leading to the conclusion that while lithology impacts on channel characteristics, this impact is indirect (Golden & Springer 2006).

Montgomery & Buffington (1997) also propose a number of intermediate channel morphologies which fall between major morphology classes. The classification system is centred on characterising the morphological variables which are associated with each visually-identifiable reach type and where significant overlap exists, intermediate morphologies are described. This approach has been utilised by a number of subsequent studies to define streams which are common or unique in a particular catchment or stream network (Thompson et al. 2006; Addy et al. 2011).

In an Australian context, Thompson et al. (2006) used the ratio of sediment transport capacity \( Q_c \) to sediment supply \( Q_s \) and reach-scale gradient to delineate different types of mountain streams in south-eastern Australia. This ratio has been shown to exert control over channel features such as slope, depth and median particle size, which are key factors in determining bed morphology.

The study used the framework developed by Montgomery and Buffington (1997) to describe local stream types, adjusting the classification to accommodate intermediate reaches which are the result of local geology and processes, with a number of reach types found to be landscape dependent. This modified classification system of reach types is depicted schematically in Figure 4. The Australian study area did not exhibit a downstream continuum of reach morphologies as described by previous studies (Montgomery & Buffington 1997) due to discontinuities in the gradient of some downstream reaches compared to their upstream counterparts. (Thompson et al. 2006). The gradient of discrete reaches was found to reliably differentiate grain size, roughness and thus reach type (Thompson et al. 2006).
Any channel morphology at a discrete point in time is the result of ongoing channel evolution, which occurs through bedrock erosion and the entraining and deposition of bed material. Channel reaches move towards a steady state where the discharge can mobilise all upstream sediment without net sediment flux (Turowski et al. 2008). The state of a channel at any given time is strongly influenced by the disturbance regime and the lag-time since the most recent disturbance (Montgomery & Buffington 1997).

2.3 GEOMORPHIC EFFECTIVENESS OF FLOWS

‘Geomorphic effectiveness’ is a term used in fluvial geomorphology to describe discharges which actively change the morphology or nature of a given channel. Wolman & Gerson (1978) pioneered the use of ‘effectiveness’ in assessing the impact of climatic elements on geomorphology, defining it as ‘the ability of an event or combination of events to affect the shape or form of the landscape’. In fluvial systems, this change primarily occurs through the transportation of sediment and subsequent rearrangement, destruction or creation of channel units. The question of whether fluvial systems evolve as the result of frequent events involving small forces or are primarily worked by very rare, extreme flows has been a topic of much debate since it was posed in the 1960’s (Wolman & Miller 1960). While large discrete events may cause a large amount of sediment flux very rapidly, the infrequent nature of such floods means that higher frequency floods of lesser magnitude may exert greater control over morphology in the long-term (Milan 2012). Due to the fact that individual settings exhibit vastly different characteristics in terms of bedform resistance, the frequency of effective processes and rates of recuperative processes, the actual magnitude of a discharge is only one factor in determining the type and
extent of changes caused by an event (Costa 1974). The literature regarding geomorphic responses to disturbance indicates that floods of similar scale and frequency can produce vastly different changes to channel morphology (Costa & O’Connor 1995).

The inapplicability of discharge alone in determining geomorphic effectiveness has led to researchers investigating the phenomenon of episodic erosion and deposition using ‘threshold’ values which determine the competence of flows to entrain sediment or erode bedrock and thus facilitate geomorphic change (Costa & O’Connor 1995). The ability of a discrete run-off event in a watershed to cause change is directly controlled by the geomorphic thresholds of the channels which drain the catchment. (Schumm 1979). Geomorphic effectiveness can occur due to the exceedence of intrinsic or extrinsic thresholds. Intrinsic thresholds refer to parameters overcome without forcing by an external variable, while extrinsic thresholds are only overcome when a system responds to an external influence which is significant enough to exceed an internal threshold (Schumm 1979). Floods are representative of extrinsic threshold events, in which internal resistance is overcome by large discharges of water from run-off, or sediment inputs such as landslides or debris flows. It is extrinsic threshold breaches which typically produce significant and persistent changes to channel morphology (Milan 2012).

Thresholds are by definition limits of system sensitivity or resistance, which are a function of lithology, confinement, slope and sediment characteristics, that is, the boundary conditions of a channel (Wohl 2007). Critical to boundary conditions is the extent and nature of riparian vegetation, which can exert very strong controls on hydrology, sediment supply and bank stability (Fuller 2008), as well as land-use, large woody debris and the time delay since the previous significant flood event (Wohl 2007; Dean & Schmidt 2013). The frequency of floods has been seen to exert a strong influence on geomorphic effectiveness. Baker (1977) states that flood-frequency variability gives more detailed estimates of the geomorphic impact of floods than discharge alone. Studies of upland channels in northern England showed that rare floods of comparable magnitude exhibited vastly different geomorphic effects based on their temporal proximity to a very large threshold-exceeding flood (Milan 2012).

Fluvial geomorphic thresholds have been considered in terms of a number of mathematically measurable values including; Froude and Reynolds numbers, shear stress and stream power (Nanson 1986; Costa & O’Connor 1995; Miller 1995). In approaching the issue of geomorphic effectiveness between events of comparable magnitude, Costa and O’Connor (1995) assessed a number of large magnitude floods in the United States using a ‘time over threshold’ technique where estimated thresholds of geomorphic work are plotted against time (Figure 5). The authors concluded that maximum discharge is a poor indicator of geomorphic effectiveness, and postulated that the amount of time which a discharge remains above estimated geomorphic
thresholds best predicts the amount of geomorphic work. Floods (a) and (b) in Figure 5 have comparable maximum discharges, yet (b) has considerably more energy available for geomorphic change due to a longer flood peak. Such models help to explain the variation in morphological response to floods of similar magnitude (Costa & O'Connor 1995). The definition of geomorphic effectiveness as the duration of flow exceeding erosional resistance of channel boundaries is widely used in subsequent literature to describe and quantify channel responses to flood events (Wohl 2007).

Figure 5: Conceptual plot of stream power vs. time indicating geomorphic effectiveness of different flood types. Modified from Costa & O'Connor (1995) by Wohl (2007)

Given that the effectiveness of floods is dependent on a balance between the amount of energy available to achieve geomorphic change and the resistance of a particular reach to change as a function of boundary conditions (Wohl 2007), there are some conclusions which can be drawn about the response of different kinds of channels to geomorphically effective flood events. Alluvial channels are malleable by relatively frequent discharges as a result of largely deformable boundaries, whereas bedrock-confined channels may be dominantly shaped by rare, high-magnitude flood events which are capable of overcoming channel-boundary resistance (Wohl & Merritt 2001). In general terms, mountain streams existing in narrow, steep valleys have resistant boundaries and little accommodation space for flow dissipation, leading to long-lasting change due to rare, high magnitude floods. Lower gradient, broad lowland valleys possess space for lateral flow dissipation over extensive floodplains, which allows significant energy expenditure during large flows (Miller 1995). This trend has been discussed in a range of literature and is summarised by Wohl (2007) in Figure 6. It appears that small upland drainage basins with highly variable discharge magnitudes show a greater potential for a catastrophic geomorphic response than their lowland counterparts (Baker 1977).
As landscape evolution operates as a continual progression of formative and destructive processes, geomorphic effectiveness must also take into account the persistence of morphological changes, which is a function of recovery rates and frequency of ‘effective’ events (Wolman & Gerson 1978; Schumm 1979). ‘Persistent’ effects of geomorphic change are defined by Brunsden & Thornes (1979) as formations which remain intact until a subsequent event of comparable magnitude. Those features which are malleable by smaller consequent events are referred to as ‘transient’. Recent studies suggest that catchment systems can adjust to major flood events and maintain similar morphologies throughout subsequent floods, in what is referred to as a flood-dominated morphology (Fuller 2008).

2.4 RESPONSE TO DISTURBANCE AND UPLAND CHANNEL EVOLUTION

The scope of changes due to disturbance in fluvial systems is vast, spanning from complete bedform destruction and wholesale channel reorganisation to minor changes to channel dimensions which do not effect overall processes (Thompson et al. 2006). As mentioned in the previous section, large floods in narrow and steep mountain watersheds result in a larger degree of geomorphic change relative to similar discharges in low-land alluvial valley environments (Miller 1995). Upland reaches, generally defined by high flow variability and significant confinement, are geomorphically controlled by large, low frequency floods. The effect of a disturbance is the combined result of hillslope and channel coupling, the nature of upstream channels and site-specific channel morphology (Montgomery & Buffington 1997). In terms of physical parameters,
sediment supply and transport capacity relationships are key indicators of channel form and stability. Changes to the relationship between these two values will cause instability through either aggradation or erosion (Jansen & Nanson 2010). In a southeast Australian context, the cyclical flood and drought dominated regimes described by Erskine & Warner (1998) could directly influence sediment supply and transport capacity ratios and thus the morphological nature and evolution of channels under this climatic regime (Thompson et al. 2008).

Central to the study of channel response to flood events and morphological evolution of fluvial systems is the concept of ‘equilibrium states’. The applicability of such an empirical theory to natural systems has faced some resistance due to the difficulty of predicting channel form and response based on equilibrium models. However, fluvial geomorphologists have described equilibrium in terms of long term fluxes and time-averaged erosion and deposition, rather than discrete measurements, to assess changes to morphology over time (Nanson & Huang 2008). According to the model of equilibrium states, a channel can exist in one of three states; stable, neutral or unstable. In the context of the LAP, an unstable channel will adjust to increase the efficiency of the system by expending energy on the most available processes. Given a disturbance which moves a reach to an unstable state, iterative adjustments will occur, according to available energy and sediment, making directional changes towards the most stable planform within the context of the recently ‘disturbed’ physical conditions (Nanson & Huang 2008). The type of change which occurs is dictated by the space available for channel adjustments, which in the case of upland streams, is predominantly vertical, resulting in energy expenditure in step-pool sequences or braiding rather than the meander bends typical of alluvial systems (Huang et al. 2004).

The theory of equilibrium in channel morphology assumes that under a particular climatic regime and suitable time-scale, a fluvial system of a given nature will form which responds to changes in discharge, sediment supply and biological activity (Wolman & Gerson 1978). Given a period of time throughout which no major disturbance occurs, a channel or reach will make iterative adjustments towards this stable form. Due to the strong geomorphic control of mountain streams by rare, large magnitude floods, disturbances in these environments are typically geomorphically intensive, resulting in long recovery times to return to a ‘stable’ channel form. Nanson (1986) describes an evolutionary model for bedrock-confined channels in which episodic vertical accretion and catastrophic stripping of floodplains characterises morphological responses to disturbance. Figure 7 shows the catastrophic stripping of alluvial material from the macrochannel due to a large flood, followed by a period of alluvial aggradation leading up to the next geomorphically effective flood.
A similar conceptual model proposed by Benda (1990) for a mountain drainage network in the United States outlines stochastic cycling between sediment aggradation and catastrophic stripping leading to unstable morphologies as a result of rare, effective disturbances. The fact that upland stream morphology is largely dominated by rare, large magnitude floods implies that evolution of these channels is dependent on events which occur on a longer time-scale than for alluvial systems, leading to an episodic cycle of slow aggradation of alluvial material punctuated by rare, unpredictable events of catastrophic erosion. This process is not described by the conventional theories of equilibrium states, rather being described as ‘episodic disequilibrium’ (Nanson 1986). Such discontinuous evolution is a function of the highly variable sediment-transport regimes that are typical of upland streams, including those of eastern Australia (Nanson 1986).

Extreme flood events in upland reaches create an unstable and highly dynamic fluvial environment, with channel scouring and removal of erosion mobilising large volumes of sediment and making remaining deposits of unconsolidated alluvium vulnerable to entrainment. Milan (2012) highlights the role of large floods as not only the cause of initial erosion, but also in creation of a ‘relaxation phase’ during which time large amounts of sediment are redistributed through the system by subsequent, smaller floods. The response-time of such channels to return to a more stable morphology is directly influenced by the rate of revegetation, which stabilises channel banks and channel-adjacent units (Milan 2012; Smith 2013). Rapid revegetation of in-channel and riparian sediment decreases the likelihood of sediment mobilisation by subsequent floods, increasing the resilience of the system to later floods and contributing to a more stable channel morphology (Wolman & Gerson 1978).
3. **REGIONAL SETTING**

The Lockyer Valley lies east of Toowoomba and west of Brisbane in South-east Queensland, Australia and is one of the most productive agricultural regions in Queensland, with much of the lower alluvial plains being cultivated by intensive horticulture. The upper Lockyer region is dominated by grazing for livestock (Galbraith 2009), with the southern and western extents of the catchment being steep and forested (BMT WBM Pty Ltd 2011). The Lockyer Valley catchment has a catchment area of 2600km², comprising approximately a quarter of the Brisbane catchment (Croke et al. 2012). Figure 8 shows the position of the study area in a catchment and continental context.

![Regional Setting Diagram](image)

*Figure 8: Regional setting of study area showing the position of the Brisbane and Lockyer Catchments, stream network and location of the study area.*

The study reaches of Paradise Creek, Fifteen Mile Creek and Murphys Creek are part of the upland stream network forming the headwaters of the Lockyer Creek, which flows into the Brisbane River. In terms of relative stream order, Paradise Creek is a tributary of Fifteen Mile Creek, which itself is a tributary of Murphys Creek, becoming Lockyer Creek at the confluence of
Murphys Creek and Alice Creek (Figure 8). The study reaches are approximately 1 kilometre in length, with their general attributes being summarised in Table 2.

<table>
<thead>
<tr>
<th>Reach Length (m)</th>
<th>Murphy's Creek</th>
<th>15 Mile Creek</th>
<th>Paradise Creek</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1203</td>
<td>1199</td>
<td>1173</td>
</tr>
<tr>
<td>Greatest Elevation (MASL)</td>
<td>195.93</td>
<td>228.29</td>
<td>248.31</td>
</tr>
<tr>
<td>Lowest Elevation (MASL)</td>
<td>189.69</td>
<td>215.72</td>
<td>235.23</td>
</tr>
<tr>
<td>Change in Elevation (m)</td>
<td>6.24</td>
<td>12.57</td>
<td>13.08</td>
</tr>
<tr>
<td>Reach Slope (m/m)</td>
<td>0.0055</td>
<td>0.0083</td>
<td>0.0114</td>
</tr>
<tr>
<td>Catchment Area (km²)</td>
<td>168.1</td>
<td>89.1</td>
<td>26.3</td>
</tr>
<tr>
<td>Width of Valley Floor (m)</td>
<td>70</td>
<td>70</td>
<td>76</td>
</tr>
<tr>
<td>Reach Type</td>
<td>Bedrock-alluvial</td>
<td>Bedrock-alluvial</td>
<td>Bedrock-alluvial</td>
</tr>
</tbody>
</table>

3.1 Landuse in the Upper Lockyer Valley

The Lockyer Valley comprises an area of 2600km², and has a population of approximately 35,000 people (Australian Bureau of Statistics 2009). The valley’s major governmental and economic centre is Gatton, lying approximately 90km west of Brisbane with a population of 6000 (Croke et al. 2013a). Other major regional townships include Forest Hill, Grantham, Helidon, Laidley and Withcott (BMT WBM Pty Ltd 2011).

Settlement of the Lockyer Valley began in the 1840s, with early land-clearing being centred on the rich alluvial low-land floodplains of the Lockyer Creek. By the 1940s, much of the agriculturally productive floodplains of the catchment’s major tributaries had been cleared for cultivation, with ongoing land clearing resulting in the Lockyer region having the highest proportion of land used for intensive agriculture in South East Queensland (Galbraith 2009). The Lockyer Valley is one of the most productive agricultural areas of South East Queensland, due to the rich alluvial soils and the availability of water. Ongoing intensification of agriculture, particularly horticulture, has led to a strong reliance on irrigation from both surface-water and groundwater stores. The over-extraction of groundwater during times of drought has placed stresses on stores and led to water shortages (Galbraith 2009).

The major land cover types of the region are pasture (47%), woody vegetation (41%), and crops (11%) (Apan et al. 2002). Cleared land for crops and pasture exists in the mid to lower catchment, while the majority of remnant forest is located in steep upland areas of the Helidon Hills in the north-west and the south and eastern fringes of the catchment (Apan et al. 2002; Croke et al. 2013a). The upper Lockyer valley remains largely forested due to the lack of fertile soils and
steep topography, although some regions have been cleared for pasture (Galbraith 2009). The region north of Helidon where the study area is located is primarily forested, with rural residences, forestry and quarrying for sandstone comprising major anthropogenic land use.

3.2 GEOLOGICAL SETTING

The Upper Lockyer region lies on the eastern side of the Great Dividing Range, west of Brisbane. Topographically, the study area is a steep, forested post-orogenic upland region with altitudes between 190-250 MASL. The valleys and hill-slopes of the upper Lockyer valley form the western headwaters of the Lockyer Creek catchment (the largest tributary network of the Brisbane Basin) with the western fringes reaching elevations of over 700m AHD.

The lithology of the study area is dominated by sedimentary and metamorphosed sedimentary rocks of Jurassic-Triassic and Permian origin respectively (Figure 9). The major surface lithology across the region is derived from the Woogaroo Subgroup, consisting of Triassic sedimentary quartzose sandstone with interbedded siltstone, shale conglomerate and coal measures. Regions of metamorphosed Permian mudstone exist in the Buaraba Mudstone group, preserved in a number of valleys of the Upper Lockyer catchment. The valley floor of lower gradient, higher order streams further down the catchment are infilled to varying extents by Quaternary alluvium comprising clay, silt, sand, gravel and floodplain material. A number of significant faults run approximately north-south and east-west across the upland region (Geological Survey of Queensland 2011).

The Paradise Creek study reach has a lithology of Permian mudstones associated with the Buaraba Mudstone, while Fifteen Mile Creek and Murphys Creek are located over the Woogaroo Subgroup of Jurassic sandstone. Murphys Creek shows some valley fill of Quaternary alluvium according the most recent geological dataset (Figure 9), although the 2011 flood resulted in excavation of large volumes of sediment, exposing underlying bedrock.
In general terms, the upland streams of this region are bedrock-confined mixed bedrock-alluvial channels, with discontinuous mantling of bedrock by alluvial and non-alluvial material. Exposure of bedrock along the channel bed is common, particularly on the outside of channel bends. The nature and morphology of study reaches is discussed in Section 5.2.3.

Grain size throughout the reaches is highly variable and sedimentary deposits are very poorly sorted with particles ranging from fine sand (<1mm) to large boulders (>1024mm) existing in the same channel units.

3.3 CLIMATE AND HYDROLOGY

3.3.1 LONG-TERM CLIMATE AND HYDROLOGY

The climate of Eastern Australia is highly variable; with long-term precipitation patterns influenced by global-scale systems including the El Niño-Southern Oscillation (ENSO), the Subtropical ridge (STR) and the Indian Ocean Sea Surface Temperature patterns (Kirkup et al. 1998). The long-term pattern of rainfall in coastal catchments on the east coast of Australia are related to the strength and persistence of La Nina and El Niño events which create multi-year periods of above-average and below-average rainfall (Kirkup et al. 1998). In addition, decadal trends of above- and below-average rainfall across eastern Australia have been described in the literature as
flood and drought dominated regimes (Erskine & Warner 1998) and droughts and anti-droughts (McMahon & Finlayson 2003). Hydrologically, this is manifested in a high degree of stream flow variability in many parts of eastern Australia, particularly northern New South Wales and Southern Queensland (Rustomji et al. 2009). These regions show distinct coupling between variations in stream flow and ENSO values (Kiem et al. 2003).

In the South-East Queensland context, rainfall data for the past 100 years shows lower than average rainfall from 1920 – 1947 after which a high rainfall period lasted until about 1990. Since this time drier conditions have dominated, with wide-spread drought across the east of the Australian continent. Rainfall from 2008 – 2013 has been relatively high and the region has experienced two significant flood events in 2011 and 2013, which suggests a return to a wetter climatic period. These trends are visible in Figure 10, which presents yearly rainfall totals and a 10 year moving average for annual rainfall at Helidon in the upper Lockyer region.

The climate of the Lockyer Valley is sub-humid, subtropical and strongly seasonal, with 65-70% of total rainfall occurring between October and March (Table 3), due in part to higher precipitation intensities associated with summer storms generated by sub-tropical lows (Galbraith 2009). Total annual rainfall for the Lockyer Valley is low relative to surrounding areas and highly variable on a year-to-year basis. Average annual rainfall is 803mm at Helidon. The escarpment of the Great Dividing Range which forms the catchment’s Western boundary causes higher rainfall in the upper Lockyer region due to orographic precipitation.
Table 3: Monthly rainfall statistics for Helidon (mid-catchment) and Gatton (lower catchment)

<table>
<thead>
<tr>
<th>Station No.</th>
<th>40096</th>
<th>40082</th>
</tr>
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<tbody>
<tr>
<td>Station Name</td>
<td>Helidon Post Office</td>
<td>University of Queensland Gatton</td>
</tr>
<tr>
<td>Elevation (MASL)</td>
<td>155</td>
<td>89</td>
</tr>
<tr>
<td>Period of Record</td>
<td>1870 - Present</td>
<td>1897 - Present</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Average Rainfall</th>
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<td>January</td>
<td>118.6</td>
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<tr>
<td>February</td>
<td>109.2</td>
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<td>46.9</td>
</tr>
<tr>
<td>July</td>
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</tr>
<tr>
<td>August</td>
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</tr>
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<tr>
<td>October</td>
<td>61.9</td>
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<tr>
<td>November</td>
<td>80.5</td>
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<td>December</td>
<td>104.6</td>
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<tr>
<td>Annual</td>
<td>803.3</td>
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</tbody>
</table>

The hydrological state of upland channels is particularly dependent on these annual and decadal climatic cycles as they primarily transmit flows generated by precipitation. The study area of the upper Lockyer Valley is typical of this, in that the low-order streams have negligible or zero discharge during dry periods and comparably massive flows during years of higher than average rainfall (Galbraith 2009). The stream gauge data for Murphys Creek at Spring Bluff reflects this, with multiple weeks during the dry period from the early 1990s to the mid-2000s recording maximum daily discharges of less than 0.001 m$^3$/s.

Stream gauge records exist since 1987 on the Lockyer Creek at Helidon Number 3 (Station No. 143203C) and 1979 on Murphys Creek at Spring Bluff (Station No. 143219A) (Figure 11). The mean daily discharge is 0.812 m$^3$/s and 0.053 m$^3$/s at Helidon and Spring Bluff respectively. The largest flood on record at Helidon was on the 11/01/2011 with a discharge of 3643 m$^3$/s, with the largest flood on record at Spring Bluff also occurring on the 11/01/2011, having a discharge of 362 m$^3$/s.
3.3.2 THE 2011 FLOOD EVENT

The catastrophic flooding that occurred in the Lockyer Valley on the 10th and 11th of January 2011 was preceded by months of record-breaking rainfall across Queensland, triggered primarily by an extremely strong La Niña event with a SOI index of +27.1, the highest December value on record (National Climate Centre 2011). December 2010 yielded the highest average rainfall values across the state in over 110 years of records (BMT WBM Pty Ltd 2011). The long-term and consistent nature of this rainfall resulted in the saturation of the Lockyer Valley catchment, effectively creating run-off conditions whereby additional rainfall could not infiltrate the soil column and was transmitted directly to streams. The storm system which resulted in the extreme flood event originated from a low pressure system off the mid-south Queensland coast and persisted over the Lockyer Valley catchment for 3 days after moving onshore on the 9th of January and colliding with upper level and monsoonal troughs (BMT WBM Pty Ltd 2011). Significant precipitation over 24 hours across the Lockyer Catchment on the 9th of January further soaked the soil column. On the 10th of January the storm cell intensified under orographic uplift in the north and west of the catchment, resulting in extreme rain depths over a period of only a few hours in the upland bedrock-confined tributaries of the Lockyer Creek. Observations of water level rise were first
noted at 1320 at the stream gauge of Murphys Creek at Spring Bluff, peaking at 4.96m just 20 minutes later (Jordan 2011).

Heavy rain continued to fall across the catchment on the 11th of January with lesser intensity, but higher 24 hour values. The temporal progression of discharge peaks throughout the flood is presented in Figures 12 & 13 for Spring Bluff and Helidon stream gauges.

The extent to which this second storm event exacerbated flooding is unknown due to the widespread failure of stream gauges across the catchment. The precipitation in the upper catchment played a disproportionate role in the flooding due to the high intensity of localised rainfall in a very short period and the steep, confined nature of the upland streams which rapidly transmitted this water downstream. The most intense rainfall (~150mm in 2hrs) was experienced in the Fifteen Mile Creek and Alice Creek catchments of the upper Lockyer Valley (Rogencamp
& Barton 2012). The true intensity maximums of precipitation remain unknown due to the sparse rain gauge network present in upland areas (BMT WBM Pty Ltd 2011).

The Helidon gauge is the only upper Lockyer station with a record longer than 100 years. The rainfall event which resulted in the 2011 flood represented an Annual Exceedence Probability (AEP) of greater than 2000 years in terms of rainfall intensity (mm/hr) over all timescales from 1HR to 48HR (Figure 14).

![Figure 14: AEP for rainfall intensity at Helidon during the 2011 storm event of 10/01/2011 (Bureau of Meteorology 2013)](image)

### 3.3.4 Flood History of the Lockyer Catchment

A discussion of the long term flood history of the upper Lockyer Catchment is inhibited somewhat by a sparse and prohibitively short record of stream gauge data across the region. The two primary recording stations for the upper Lockyer watershed are Murphys Creek at Spring Bluff and the Lockyer Creek at Helidon, for which data extends to 1979 and 1987 respectively. The use of palaeoflood deposits as indicators of flood history is hampered by the extent of channel stripping which occurs in confined channels during large floods, with much of the upper Lockyer valley stream network being eroded to bedrock in the 2011 event. Research by Sandercock (2012) used radiocarbon dating to determine ages of flood deposits in Fifteen Mile Creek. Deposits indicated ages of ~1881 and ~10693 years before present. However, it is concluded that floods are very likely to have occurred in subsequent years, with stratigraphic evidence destroyed by channel stripping during large floods (expanded in Section 6.3).

Data for the stage height of the Brisbane River has been continuously collected since 1841 and flooding in the Brisbane River is a descriptive surrogate for the flood history of the Lockyer Catchment. In the period from 1841 – 1900, severe floods in the Brisbane catchment were
relatively frequent, with 23 floods exceeding 2.74m in this 59 year period and particularly extensive flooding in 1841 and 1893, when 4 separate floods were recorded (Figure 15). In contrast, just 13 floods, none of comparable magnitude to the larger floods of the previous century, occurred from 1900 – 1974 (Bureau of Meteorology 1974).

A flood event in January 1974 resulted in high flood-levels in Brisbane and higher 24 hour rainfall maximums than the 2011 storm across all sub-catchments of the Brisbane Basin, including the Lockyer Valley (National Climate Centre 2011). It was the largest flood event in the Brisbane catchment of the twentieth century (Bureau of Meteorology 1974) and had a higher flood peak in Brisbane than the 2011 flood. However, in the context of the upper Lockyer Valley, the 1974 flood was focused closer to the coast and did not penetrate as far west as the Great Dividing Range. While gauge data for the Lockyer catchment does not exist for 1974, anecdotal evidence and rainfall intensity data suggest that the valley was not as severely impacted as in 2011.

Heavy rainfall throughout the summer of 2013 across coastal Queensland and New South Wales resulted in flooding throughout the Lockyer and Brisbane catchments, with the highest 1-day rainfall between 22nd and 28th of January being the sixth-highest on record since 1900 (Bureau of Meteorology 2013). While flooding throughout the valley was extensive, the upper Lockyer valley experienced much less severe rainfall intensities and flooding than in 2011.
4. METHODS

4.1 FLOOD FREQUENCY ANALYSIS

Analysis of historical discharge was undertaken using maximum daily discharge data from 2 stream gauges. Murphys Creek at Spring Bluff is upstream of the study reaches considered here, above the confluence of Murphys Creek and Fifteen Mile Creek. The gauge on the Lockyer Creek at Helidon lies immediately downstream of the study reaches below the confluence of Murphys Creek and Alice Creek (Figure 11). Stream gauge data for the upper Lockyer Valley has a limited record of less than 35 years, which requires analysis of flood regimes to be extrapolated from a small suite of measurements. The stream gauge at Spring Bluff has been operating near-continuously since 1979 (431 days of no data) and at Helidon since 1987 (125 days of no data).

Annual recurrence intervals for maximum daily discharge at Spring Bluff at Murphys Creek and Helidon at Lockyer Creek were calculated using ‘FLIKE V4.50’. In addition, a partial series analysis was carried out, with a discharge threshold magnitude of the 2-yr ARI from the annual series. Bankfull discharge, an oft-used threshold for geomorphic effectiveness, has a recurrence interval of 1-2 years, as identified by Wolman and Leopold (1957). Flood independence was determined by the criteria created for small catchments in Eastern NSW by Potter and Pilgrim (1971), of flood peaks being separated by at least 3 days.

There has been some discussion in literature as to the most appropriate statistical technique for estimating flood recurrence intervals for hydrological events in Eastern Australia due to the region’s high flow variability. The nationally established industry method is the Log Pearson III model (Pilgrim 1987), however the Generalised Pareto distribution has been found to be preferable for modelling flood frequency curves in some high flow variability catchments of Eastern Australia (Rustomji et al. 2009). Due to a lack of consensus in the literature and the fact that the variability of flow in the Lockyer Valley is not as extreme as nearby catchments such as the Burnett and Fitzroy catchments, the annual and partial series analysis was carried out using both Log Pearson III and Generalised Pareto statistical models.

4.2 FIELD SURVEY

The longitudinal channel profiles and cross-sections for this study were derived from survey measurements collected with real time kinematic (RTK) survey equipment (Trimble R7 and R8 GNSS System). Measurements were taken using GDA94 MGA Zone 56 and AHD71. Due to the remote location of the study site, no state survey marks existed and as such measurements are relative to the approximated base station location. The field survey was conducted in a single fieldwork period in April 2013. Due to the erosion and channel scouring caused by recent
flooding (2011), the lack of vegetation in the macro-channel allowed use of RTK equipment for all measurements.

Channel profile measurements were taken along the low-flow channel of an approximately 1 km stretch at 3 representative reaches in settings of varying contributing area and gradient; Murphys Creek, Fifteen Mile Creek and Paradise Creek (Table 2). Noteworthy in-channel features were recorded (bars, riffles, pools, cascades, boulder deposits) as well as the presence, location and height of flood marks from the 2011 flood, including flood debris and eucalypt scarring along the boundaries of the macro-channel. Examples of these flood height indicators are shown in Figure 16.

![Figure 16: Flood height indicators; A) Eucalypt scarring; B) Flood debris](image)

Cross sections of channel dimensions were surveyed within 100m of the upstream and downstream extents of each study reach, with heights of 2011 flood marks recorded in each case.

Grain-size data was collected using a modified Wolman (1954) method for sampling coarse river-bed material. Two 50m transects on sedimentary bars were sampled at each study reach with 100 particles measured for b-axis using a measuring tape at each site.
4.3 **Spatial Analysis**

Field survey data and remote sensing data was integrated using ArcGIS 10 (ESRI 2010) software. The Digital Elevation Model (DEM) datasets used in analysis were derived from air-borne LiDAR, with an average error of ± 0.2m and a spatial resolution of 2m. Two DEMs were used for the study area, flown in 2010 and 2011. Satellite imagery of the area used in spatial analysis was collected in 2009 and 2011 and has a spatial resolution of 0.5m and 0.15m respectively. Catchment area was calculated using a drainage network dataset derived from a catchment DEM with a spatial resolution of 20m.

4.3.1 **Temporal Landscape Analysis**

Field data was normalised to LiDAR height datum for analysis between LiDAR derived and RTK derived longprofiles and cross-sections. Due to the unavailability of state survey marks in the area and field limitations, RTK height data was inconsistent with existing LiDAR measurements. In order to normalise field data, an average height displacement was calculated from georeferenced field data points assumed not to have changed elevation from 2011 and corresponding LiDAR pixel values from the most recent 2011 DEM. This allowed for direct comparison between field and spatial data, whilst maintaining the relative values of field data points.

Multi-temporal longprofiles and cross sections of the channels were derived from the 2010 and 2011 DEMs using the 3D Analyst tool in ArcGIS 10 and plotted with field data points. In order to quantify variability, residuals were calculated from a linear regression through each longprofile data set (i.e. 2010, 2011, and 2013). Changes to the cross-sectional area of the pre-flood low-flow channel were quantified by determining the maximum height of sedimentary units adjacent to the 2010 low-flow channel and calculating cross-sectional area below this height for 2010 and 2011 cross-sections.

4.3.2 **Volumetric Analysis**

Quantifying the changes to channel sediment stores during the 2011 flood event was carried out by creating a DEM of difference (DOD) from the 2010 and 2011 DEMs, portraying differences in height per pixel. Consideration of error is critical to the analysis of DEMs to assess geomorphic change (Milan et al. 2011; Croke et al. 2013a). The DEMs used in this analysis were post-processed by Croke et al. (2013a) to account for elevation discrepancies caused by interference by vegetation. This was achieved by normalising the DEMs across major and minor road surfaces for which elevation remained constant subsequent to the 2011 flood event. The 2010 DEM is derived from LiDAR flown while significant vegetation existed in the drainage network channel, contributing to an average error of ±0.2m. Error after post-processing for the 2011 DEM is negligible as in-channel areas were devoid of vegetation following the 2011 flood. Due to the
small scale of analysis on a reach-by-reach basis, this existing consideration of error in creating the DEMs is sufficient for the purposes of analysis in this study.

The DOD created from the temporal DEMs was used to render raster layers attributing volumetric change per pixel within the macrochannel boundary of each reach. This allowed the calculation of total sediment volume change for each reach and derivation of volume change per unit area.

4.4 SEDIMENT SUPPLY AND SEDIMENT TRANSPORT CAPACITY \( (Q_c - Q_s) \)

The ratio between sediment transport capacity and sediment supply are commonly used to characterise physical controls on upland streams, as detailed in section 2.2. Quantifying these values in the field is not feasible and as such, surrogates derived from fluvial hydrodynamics are used to approximate the relationship between these two factors and create regime diagrams. Calculations in this study followed the methodology of Thompson et al. (2006), which draws on the work of Buffington et al. (2003). A recent publication by Thompson & Croke (2008) highlights issues with some constants used in Thompson et al. (2006) and as such, the improved equations are specified below.

Dimensionless bedload transport \( (q_b^*) \) is employed as a surrogate for sediment supply, calculated using a modified version of the Meyer-Peter & Müller (1948) equation formulated by Wong (2003).

\[
q_b^* = 4.93(\tau^* - \tau_{c50}^*)^{1.6} \quad (6)
\]

Where \( \tau_{c50}^* \) is the Shields stress to mobilise the median grain size, set to 0.03 and \( \tau^* \) is bankfull Shields stress;

\[
\tau^* = dS_b/D_{50}s \quad (7)
\]

Where \( d \) = mean bankfull depth (m); \( S_b \) = mean reach bed slope (m/m) and \( s \) = submerged specific gravity of sediment, set to 1.65.

Dimensionless discharge \( (q^*) \), is employed as a surrogate for transport capacity, defined by Buffington et al. (2003) as

\[
q^* = ud/[(sgD_{50})^{0.5}D_{50}] \quad (8)
\]

Where \( u \) = vertically averaged velocity (m/s) defined by
\[ u = (u^*/k) \ln(0.4d/z_0) \quad (9) \]

Where \( k \) = the von Karman’s constant (0.408); \( z_0 \) = height above the bed where velocity equals 0, approximated by 0.1 \( D_{94} \) and \( u^* \) = shear velocity, equal to \((\tau/\rho)^{0.5}\). \( \tau \) is the boundary shear stress;

\[ \tau = \rho g d S_b \quad (10) \]

These dimensionless values are then used to quantify the relationship between sediment transport capacity and sediment supply by calculating the ratio, \( q_r = Q_c/Q_s \).

### 4.5 Sediment Entrainment Threshold Calculations

The determination of entrainment threshold conditions for the 2011 flood across the three study reaches was carried out using equations tailored to the calculation of hydrological parameters for upland streams outlined in Section 2.1.1 (Equation 1 – 5). The program ‘Channel v0.07’ was used to derive cross-section-dependent variables for application in calculations.

Manning’s \( n \) was derived for each reach using equations (11) and (12). Yen (1992) provides an equation which is applicable for natural mountain channels with cobble or boulder-bed material in clearwater flow.

\[ n = 0.32 S^{0.38} R^{-0.16} \quad (11) \]

Where \( n \) = Manning’s roughness coefficient; \( S \) = slope and \( R \) = hydraulic radius in metres.

In assessing the sediment entrainment thresholds of floods however, Meyer-Peter & Müller’s (1948) research led to the derivation of equation (12) to account for the increased turbulence of deep-water flow associated with large flood events in mountain channels.

\[ n = ((D_{90})^{1/6}) / 26.0 \quad (12) \]

Where \( D_{90} \) = particle size representing the 90\(^{th}\) percentile of bedload

Estimates of sediment entrainment thresholds for each reach were calculated using equations (1), (2), (3), (4), (5) & (12) based on the work of Shields (1936), Komar & Carling (1991) and Bathurst (1987), as described in section 2.1.

It has not been possible to evaluate the bedload portion which underwent entrainment in the 2013 flood due to scarcity of stream gauges in the upper Lockyer valley and lack of geomorphic and biological evidence of water surface height during this event.
5. RESULTS

5.1 HYDROLOGY AND FLOOD-FREQUENCY

5.1.1 FLOOD HYDROLOGY
The characteristics of flood hydrology were assessed using high-water marks (Figure 16) and reach characteristics calculated from field survey data and LiDAR derived DEMs, as described in Sections 4.2 and 4.3. Table 4 outlines the predicted Manning’s n, discharge (Q), unit stream power (ω) and unit shear stress (τ) values for the 2011 flood at each study reach. These variables are further implemented in Section 5.3.1. Predicted discharges calculated with the use of Manning’s n according to equation (12) were used in further hydraulic analysis as they provide a more realistic estimate of discharge in deep-water conditions (See Section 4.5).

Table 4: Hydrological values calculated for the 2011 flood. \(n_1/Q_1/ω_1\) represent values calculated with equation (11), \(n_2/Q_2/ω_2\) represent values calculated with equation (12).

<table>
<thead>
<tr>
<th>Creek</th>
<th>Area (km²)</th>
<th>Slope (m/m)</th>
<th>(n_1)</th>
<th>(n_2)</th>
<th>(Q_1) (m³/s)</th>
<th>(Q_2) (m³/s)</th>
<th>(ω_1) (W/m²)</th>
<th>(ω_2) (W/m²)</th>
<th>(τ) (N/m²)</th>
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</thead>
<tbody>
<tr>
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<td>2989</td>
<td>897</td>
<td>2299</td>
<td>690</td>
<td>286</td>
</tr>
<tr>
<td>Fifteen Mile Creek</td>
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<td>0.04</td>
<td>0.1</td>
<td>2332</td>
<td>933</td>
<td>2693</td>
<td>1077</td>
<td>388</td>
</tr>
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<td>Paradise Creek</td>
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<td>0.05</td>
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<td>747</td>
<td>415</td>
<td>1108</td>
<td>616</td>
<td>277</td>
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</table>

5.1.2 FLOOD FREQUENCY ANALYSIS
The flood frequency analysis for the annual series indicates that the 2011 flood had a recurrence interval of ~59 and 45 years at Spring Bluff and Helidon respectively. In contrast the 2013 flood represented a greater frequency event of 8 and 5-yr ARI for Spring Bluff and Helidon respectively (Figure 17 & Figure 18).

A comparison of the annual series results utilising the Log Pearson III model and the Generalised Pareto analysis for each stream gauge is presented in Table 5, showing the greater recurrence interval rating of the Log Pearson III analysis for comparable flows. Table 6 is the analysis of partial flood series based on a flood independence criteria of 3 days between flood peaks (Pilgrim 1987). The Log Pearson III and Generalised Pareto analyses exhibit a similar trend to the annual series, with a given ARI being attributed to a greater discharge in the Generalised Pareto model.
Figure 17: Annual series for Lockyer Creek at Helidon Number 3 - Log Pearson III analysis

Figure 18: Annual series for Murphys Creek at Spring Bluff - Log Pearson III analysis
### Table 5: Annual series analysis for stream gauges of upper Lockyer catchment, Log Pearson III and Generalised Pareto analysis. Discharge in m$^3$/s.

<table>
<thead>
<tr>
<th>ARI</th>
<th>Expected Parameter Quantile Log Pearson III</th>
<th>Expected Parameter Quantile Generalised Pareto</th>
<th>ARI</th>
<th>Expected Parameter Quantile Log Pearson III</th>
<th>Expected Parameter Quantile Generalised Pareto</th>
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<td>0.0</td>
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</tr>
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<td>0.0</td>
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<td>1.01</td>
<td>0.1</td>
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<tr>
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<td>1.0</td>
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<td>17.5</td>
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</table>

### Table 6: Partial series analysis for stream gauges of upper Lockyer Catchment, Log Pearson III and Generalised Pareto analysis. Discharge in m$^3$/s

<table>
<thead>
<tr>
<th>ARI</th>
<th>Expected Parameter Quantile Log Pearson III</th>
<th>Expected Parameter Quantile Generalised Pareto</th>
<th>ARI</th>
<th>Expected Parameter Quantile Log Pearson III</th>
<th>Expected Parameter Quantile Generalised Pareto</th>
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</thead>
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<tr>
<td>1.001</td>
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<td>0.2</td>
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<td>7.0</td>
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<td>120.4</td>
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<td>3564.3</td>
<td>100</td>
<td>360.3</td>
<td>287.3</td>
</tr>
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</table>
5.2 Channel Morphology and Characteristics

5.2.1 Grainsize Analysis

The median grain size for the study area is 79mm, with a $D_{\text{max}}$ of 1670mm (Table 7). When combined, the three reaches exhibit a general trend of coarsening grain size downstream, with increasing catchment area (Table 7). Grainsize range showed a large degree of variation, from coarse sand to large boulder clasts, with a unimodal distribution (Figure 19). The bars on which field work was carried out had no substantial vegetation growth, with grasses and young *casuarina* saplings less than three years old colonising alluvium. This indicates that the bars were recently deposited or the vegetation on surviving sediment stores was removed by the flood event of 2011.

![Figure 19: Grainsize frequency distribution for Murphys Creek, Fifteen Mile Creek and Paradise Creek study reaches](image)

Table 7: Grainsize characteristics from line-transect sampling using modified Wolman Method (Wolman 1954). B-axis (mm) of 100 particles

<table>
<thead>
<tr>
<th></th>
<th>Murphys Creek (168km²)</th>
<th>Fifteen Mile Creek (89km²)</th>
<th>Paradise Creek (26km²)</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_5$</td>
<td>17</td>
<td>12</td>
<td>13</td>
<td>12</td>
</tr>
<tr>
<td>$D_{16}$</td>
<td>29</td>
<td>21</td>
<td>26</td>
<td>24</td>
</tr>
<tr>
<td>$D_{35}$</td>
<td>58</td>
<td>52</td>
<td>47</td>
<td>51</td>
</tr>
<tr>
<td>$D_{50}$</td>
<td>85</td>
<td>85</td>
<td>67</td>
<td>79</td>
</tr>
<tr>
<td>$D_{84}$</td>
<td>310</td>
<td>288</td>
<td>170</td>
<td>220</td>
</tr>
<tr>
<td>$D_{95}$</td>
<td>500</td>
<td>505</td>
<td>236</td>
<td>454</td>
</tr>
<tr>
<td>$D_{\text{max}}$</td>
<td>1670</td>
<td>1088</td>
<td>492</td>
<td>1670</td>
</tr>
</tbody>
</table>
5.2.2 Sediment Supply and Sediment Transport

Mathematical surrogates calculated to represent the relationship between sediment supply \((Q_s)\) and sediment transport capacity \((Q_c)\) are represented in Table 8.

Table 8: Dimensionless transport rate \(q_b^* (Q_s)\) and dimensionless discharge per unit width \(q^* (Q_c)\) for study reaches based on approach of Thompson et al. (2006). \(q_r\) = ratio of dimensionless supply to dimensionless transport. See Section 4.4 for full definition of methods.

<table>
<thead>
<tr>
<th></th>
<th>Area (km²)</th>
<th>Slope (m/m)</th>
<th>(Q_s (q_b^*))</th>
<th>(Q_c (q^*))</th>
<th>(q_r)</th>
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<tr>
<td>Murphys Creek</td>
<td>168</td>
<td>0.0055</td>
<td>3.84</td>
<td>4.60</td>
<td>1.20</td>
</tr>
<tr>
<td>Fifteen Mile Creek</td>
<td>89</td>
<td>0.0083</td>
<td>6.08</td>
<td>4.58</td>
<td>0.75</td>
</tr>
<tr>
<td>Paradise Creek</td>
<td>26</td>
<td>0.0114</td>
<td>7.99</td>
<td>2.73</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Values for each dimensionless parameter are significantly larger than those compiled by Thompson et al. (2006) (Figure 20), which is most likely a factor of the measure of bankfull depth used in calculations in this analysis (i.e. the use of the 2011 flood depth). The extent of channel scour during the 2011 flood event has resulted in the study reaches having few consolidated morphological units such as bars, which typically inform bankfull depth estimates. As a result, the bankfull depth was determined by flood markers from the 2011 flood, which represents extreme depth values. While this may compromise the integrity of \(Q_s\) and \(Q_c\) values, as bankfull depth is a variable in calculation of both parameters, the value of \(q_r\) still informs the relationship between sediment supply and transport capacity.

![Figure 20: Plot of \(q_b^*\) vs. \(q^*\) from Thompson et al. (2006) for Australian mountain streams. Data calculated for the upper Lockyer Valley study reaches plotted in red.](image)

According to calculations, Paradise Creek and Fifteen Mile Creek are transport limited, while Murphys Creek is supply limited, with \(q_r\) decreasing with stream order. These values are opposite
to the generalised trends by Montgomery & Buffington (1997) (Figure 1 & Figure 3, Section 2.2). Steeper reaches generally have a greater transport capacity than sediment supply due to high gradients and small drainage areas, however, the results calculated in Table 8 indicate that this trend is reversed in the upper Lockyer study reaches. The implications of these findings are discussed in Section 6.

5.2.3 Modern Channel Morphology and Classification

Annotated longprofiles, presented in Figure 23, Figure 24 and Figure 25, were produced using field observations and visual analysis of the bed profiles. These are accompanied by reach-scale maps of channel units, based on definitions by Grant et al. (1990) and Montgomery & Buffington (1997), which indicate the location of the low flow channel within the macrochannel and spatial orientation of channel units.

The classification schemes of Montgomery & Buffington (1997) and Thompson et al. (2006) explain visually identifiable morphologies as a function of their physical characteristics including grain size, slope, width, drainage area and channel unit spacing. Two of the three reaches in this study, with the exception of Paradise Creek, have lower gradients than those expressed by the classification system outlined by Thompson et al. (2006), yet all three reaches exhibit both physical and morphological characteristics comparable to steeper channels. Figure 21 presents the slope/area relationships of the three study reaches in the context of previous classification studies compiled by Thompson et al. (2006).

![Figure 21: Slope/area plot with slope normalised by catchment area showing distribution of a number of field studies compiled by Thompson et al. (2006). Data from upper Lockyer Valley study reaches plotted in red.](image-url)
Each of the study reaches exhibit morphologies which are the direct result of the major flood in 2011 and the subsequent 2013 flood, which complicates the analysis in terms of existing morphology frameworks which are geared towards stable channel morphologies. Figure 22 represents the relatively featureless macrochannel form evident in parts of all three reaches, with a wide, flat channel bed accommodating flow across much of the valley floor even in conditions of low discharge.

Figure 22: Example of channel morphology at Paradise Creek. View is downstream.

5.2.2.1 Murphys Creek

Murphys Creek, with a catchment area of 168 km$^2$ and a slope of 0.0055, has a valley floor width of ~70m (Table 2). Despite having the shallowest gradient of the three study reaches, it exhibits the greatest degree of profile variability along the length of the reach (Figure 23). The general morphology of the reach is an alternating sequence of pools and riffles and bedrock steps. The only deep pools occur where bedrock constriction constrains discharge. The bed of the channel is primarily mantled with cobble to boulder sized alluvium, with sand-sized materials in pools and stretches of the reach flowing over bedrock where bedrock steps exist. The low-flow channel abuts exposed bedrock strath or the bedrock valley margin along the entire length of the reach, with outcropping bedrock making up a large proportion of the valley floor (Figure 23). Vegetative cover of in-channel bars is immature and dominated by primary colonisers, particularly grasses and casuarina saplings. Sediment sorting of channel units is poor, with bars accommodating particles ranging from sand to large boulders.

The Murphys Creek reach does not comply well to any of the mountain stream classes proposed by Thompson et al. (2006). Based on the relationship between slope and catchment area (Figure 21), the reach falls into the pool-riffle domain of the classification system. However, the strong
control of bedrock over the morphology of the reach and the presence of multiple bedrock steps is not consistent with this class. The reach shows some characteristics of bedrock reaches, although according to the classification system, bedrock reaches exhibit <10% alluvial cover and occur at gradients of greater than 3%.

5.2.2.2 Fifteen Mile Creek

Fifteen Mile Creek, with a catchment area of 89km² and a slope of 0.0083, also has a valley floor width of ~70m (Table 2). This reach has diverse channel morphology with long sections of planebed channel interspersed with riffles, pools and bedrock steps. Planebed sections are characterised by a cobble-sized channel bed which is considerably wider than other sections of the reach. Riffles of cobble to boulder sized clasts exist immediately downstream of both planebed sections, representing a marked increase in gradient. No deep pools exist in the reach, with the most significant pool existing on the outside of the sharp bedrock-controlled bend immediately downstream of a sequence of bedrock steps and riffles (Figure 24). Two major bars of over 10 channel widths in length occur on the inside of channel bends, with bedrock strath surfaces and the walls of the bedrock valley forming the outer channel margin along the entire length of the reach (Figure 24). A boulder bar showing significantly larger grain size than the reach average is a notable channel unit, occurring at the downstream extent of the reach adjacent to a large bedrock step.

Based on the classification system of Thompson et al. (2006), the Fifteen Mile reach shows many of the characteristics of the intermediate riffle-step morphology class, but falls within the riffle-pool domain of the slope/area analysis. Riffle-step reaches are characterised by a planebed-step-pool morphology (Figure 4), however the Fifteen Mile Creek reach exhibits bedrock steps rather than boulder steps (Figure 24).

5.2.2.3 Paradise Creek

Paradise Creek, with a catchment area of 26km² and a slope of 0.0114, has a valley floor width of ~76m (Table 2). This reach exhibits a dominantly planebed morphology with localised riffle-pool sequences and bedrock steps representing the only profile variability. Pools identified in the upstream section of the reach are classified as such due to differences in flow turbulence according to Grant et al. (1990), forming minor intra-riffle pools rather than significant deep-channel units. The low-flow channel is mantled by cobble-sized clasts and has a high width to depth ratio. Exposure of bedrock is minimal compared to the downstream reaches, with the valley floor accommodating significant sediment in the form of cobble-boulder mantle which is continuous throughout the reach. Bedrock control is exerted primarily on the outside of channel bends, where bedrock step-pool sequences occur. Pools downstream of bedrock steps are short and deep, with a thin sand-sized alluvial mantle.
The Paradise Creek reach falls into the classification of planebed reaches as described by Thompson et al. (2006), characterised by armoured cobble channel beds without marked lateral or vertical oscillations. The reach is within the slope/area region attributed to planebed channels and it exhibits minimal bedrock control, with bedrock exposures only occurring on the outside of tight channel bends.
Figure 23: Annotated long profile of the study reach at Murphys Creek and reach map of geomorphic in-channel units and features. Reach map flow direction is from top to bottom.
Figure 24: Annotated longprofile of the study reach at Fifteen Mile Creek and reach map of geomorphic in-channel units and features. Reach map flow direction is from top to bottom.
Figure 25: Annotated long profile of the study reach at Paradise Creek and reach map of geomorphic in-channel units and features. Reach map flow direction is from top to bottom.
5.3 CHANNEL RESPONSE TO 2011 FLOOD

5.3.1 SEDIMENT ENTRAINMENT THRESHOLDS

Field observations and analysis of spatial data following the 2011 flood event clearly indicate that the entire bedload fraction (i.e. $D_{\text{MAX}}$) was mobilised during the flood, indicating flows competent of transporting sediment with a $b$-axis of at least 1670mm (Table 9 & Table 10). The fact that the channel was densely vegetated before the 2011 flood makes the speculation of whether specific voluminous clasts were mobilised impossible based on satellite imagery. However, based on the creation of volumetric change maps (See Section 5.3.3) and anecdotal information from local residents, it is probable that clasts of diameters of up to 4820mm (Figure 26 B) underwent mobilisation during the 2011 flood. In addition, the fact that boulders were clean of any lichen or moss growth suggests that they have not been exposed in their current position for a significant time (Milan 2012). The large boulder in Figure 26 B was reportedly located approximately 100m upstream of its current position in 2010 prior to the flood. The boulder bar sampled at the Fifteen Mile Creek study reach (Figure 26 A) has a $D_{50}$ of 2325mm and maps of volumetric change (Section 5.3.3) show that significant deposition occurred in that area as a result of the 2011 flood.

The purpose of this section is to test the applicability of commonly used sediment entrainment relationships for upland streams in catastrophic flood events. As discussed in Section 2.1, a variety of modified shear stress equations exist for the calculation of entrainment thresholds (Buffington & Montgomery 1997). The Shields parameter, a modification of this based on research by Komar & Carling (1991) and a set of equations developed by Bathurst (1987) were applied here.

Manning’s $n$ was calculated according to equations (11) and (12). Final values presented in this section were calculated using a Manning’s $n$ value from equation (12), as the 2011 flood had predicted flow depths of 4-8m throughout the study reaches (See Section 4.5).
Calculation of sediment entrainment thresholds for the study reaches revealed different results according to the empirical equations used in the analysis. Predicted values for discharge and shear stress are presented in Table 4 (Section 5.1.1). The use of the dimensionless Shields parameter (1936) resulted in the overestimation of entrainment thresholds for larger particles. Bedrock streams with large variation in sediment size distribution do not fit well to generic entrainment relationships such as the Shields parameter, with entrainment of larger clasts not predicted (Table 9). The Komar & Carling (1991) equation yielded similar values for the entrainment of D_{50}, as the calculation of this is based on the Shields parameter. However, the predicted shear stresses capable of mobilising larger clasts are considerably lower, resulting in prediction of entrainment

Table 9: Sediment entrainment thresholds calculated using a shear stress approach. Red shading indicates insufficient shear stress for predicted mobilisation, green indicates predicted mobilisation. Bold values represent reach average values.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>τ_c (d_{50})</td>
<td>τ_c (d_{95})</td>
</tr>
<tr>
<td>Murphys Creek</td>
<td>68.79</td>
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<tr>
<td>Upstream</td>
<td>100.36</td>
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<tr>
<td>Downstream</td>
<td>55.03</td>
<td>172.52</td>
</tr>
<tr>
<td>Fifteen Mile Creek</td>
<td>68.79</td>
<td>408.83</td>
</tr>
<tr>
<td>Upstream</td>
<td>73.65</td>
<td>205.60</td>
</tr>
<tr>
<td>Downstream</td>
<td>64.34</td>
<td>253.22</td>
</tr>
<tr>
<td>Paradise Creek</td>
<td>54.22</td>
<td>191.32</td>
</tr>
<tr>
<td>Upstream</td>
<td>64.75</td>
<td>149.34</td>
</tr>
<tr>
<td>Downstream</td>
<td>50.18</td>
<td>127.55</td>
</tr>
</tbody>
</table>

Table 10: Sediment entrainment thresholds calculated using a unit discharge approach. Red shading indicates insufficient unit discharge for predicted mobilisation, green indicates predicted mobilisation. Bold values represent reach average values.

<table>
<thead>
<tr>
<th></th>
<th>Bathurst (1973)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>q_{ci} (d_{50})</td>
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<tr>
<td>Upstream</td>
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</tr>
<tr>
<td>Downstream</td>
<td>2.83</td>
</tr>
<tr>
<td>Fifteen Mile Creek</td>
<td>2.49</td>
</tr>
<tr>
<td>Upstream</td>
<td>2.76</td>
</tr>
<tr>
<td>Downstream</td>
<td>2.25</td>
</tr>
<tr>
<td>Paradise Creek</td>
<td>1.22</td>
</tr>
<tr>
<td>Upstream</td>
<td>1.59</td>
</tr>
<tr>
<td>Downstream</td>
<td>1.09</td>
</tr>
</tbody>
</table>
of $D_{\text{MAX}}$ during the 2011 flood (Table 9). Using a unit discharge approach, the Bathurst (1987) equations indicated the entrainment of $D_{\text{max}}$ in all settings (Table 10).

5.3.2 Temporal Longprofiles and Cross-sections

In order to determine the nature of morphological response to the 2011 and 2013 floods current field data was compared to longprofiles and channel cross-sections derived from LiDAR flown in 2010 (before the 2011 flood) and 2011 (after the 2011 flood). A visual analysis of these plots reveals a number of key implications about the impact of the 2011 and 2013 floods on the existing channel form and ongoing channel response. The 2010 longprofiles of all three streams show a far greater degree of variability along the entire length of the reach in comparison to the more recent bed-profiles, with channel cross-sections indicating widening of the low flow channel and some channel avulsion due to the 2011 event. A comparison of channel planforms is presented in Figure 27, showing the extent of macrochannel erosion and vegetative removal which occurred during the 2011 flood event across the three study reaches.
Figure 27: Channel planform of: A) Murphys Creek 2009; B) Murphys Creek 2011; C) Fifteen Mile Creek 2009; D) Fifteen Mile Creek 2011; E) Paradise Creek 2009; F) Paradise Creek 2011
Figure 28: Temporal longprofiles of; A) Murphys Creek; B) Fifteen Mile Creek; C) Paradise Creek
Figure 29: Plots of residuals calculated from regression of longprofiles; A) Murphys Creek 2010; B) Murphys Creek 2011; C) Murphys Creek 2013; D) Fifteen Mile Creek 2010; E) Fifteen Mile Creek 2011; F) Fifteen Mile Creek 2013; G) Paradise Creek 2010; H) Paradise Creek 2011; I) Paradise Creek 2013
5.3.2.1 **Murphys Creek**

The Murphys Creek longprofile (Figure 28 A), shows distinct changes between each survey period. The 2010 longprofile exhibits a large degree of variability with steep riffles and deep pools of irregular length throughout the reach. *In situ* photographs of the reach prior to 2010 indicate a large store of alluvium within the macrochannel, with a stable low-flow channel and vegetated adjacent bars (Figure 30; A). The 2011 flood event had the competence to mobilise the entire sediment range and resulted in catastrophic channel stripping, presented in planform in Figure 27, destroying channel units and removing in-channel and riparian vegetation. The channel floor was lowered to bedrock along much of the reach, resulting in a largely featureless longprofile with steps in bedrock forming the only significant vertical variability (Figure 28 A). Residuals of the longprofiles, presented in Figure 29, demonstrate the significant reduction in deviation from a linear regression of the reach profile from 2010 to 2011. The 2013 longprofile shows an increased variability, with accumulations of sediment forming a number of riffles and the excavation of pools at 5 locations along the reach (Figure 23). The 2013 flood event represented a ~7 year flood (see Section 5.1.1), and resulted in considerable sediment distribution throughout the catchment evidenced in the formation of in-channel bars and riffles, seen in the longprofile (Figure 28 A) and nature of residuals for the 2013 profile (Figure 29). Nevertheless, the modern Murphys Creek channel exhibits modest variability with the longprofile remaining largely dependent on the level of bedrock throughout the reach.

Temporal cross-sections at the upstream and downstream sections of the reach (Figure 33 A, B), also exhibit significant erosion of in-channel bars and channel widening as a result of the 2011 flood event. The cross-sectional area of the 2010 channel has increased by an average of 85.7m² (171.6%) throughout the reach (Table 11). In both the upstream and downstream cross-sections, the location of the low-flow channel has migrated within the macro-channel from 2010 to 2013. The existing low-flow channel has been infilled along the reach, creating a wide channel which is almost trapezoidal in shape in 2011. The 2013 cross-sections demonstrate small amounts of sediment accretion adjacent to the low flow channel, which has narrowed modestly to form a more discrete morphology. The downstream cross-section shows that the low-flow channel has avulsed from the middle of the macrochannel towards the eastern boundary (Figure 33 B).

*In-situ* photographs (Figure 30) and satellite imagery (Figure 27) of the Murphys Creek reach show the extent of the removal of vegetation by the 2011 flood. Mature riparian and in-channel vegetation communities are evident in pre-flood imagery, with the stripping of the channel in 2011 resulting in complete excavation of vegetation in the channel. Small casuarina saplings and grasses have colonised sedimentary accumulations including bars and riffles following the flood.
5.3.2.2 Fifteen Mile Creek

The Fifteen Mile Creek reach exhibits a response to the floods of 2011 and 2013 which is consistent in many ways with Murphys Creek. The 2010 longprofile shows a morphology of long alluvial riffles interspersed with pools, with a number of major sedimentary steps (Figure 28 B). The 2011 profile demonstrates a lowered and featureless bed profile, with extensive stretches of uniform gradient. The macrochannel was stripped to bedrock during the 2011 flood, with the only significant variability existing at steps in the lithology in the middle and downstream extent of the reach (Figure 28 B). Residuals of the 2010 longprofile show significant deviations from the regressed gradient occurring throughout the reach (Figure 29) whilst the 2011 residuals highlight the decrease in complexity, with longitudinally clustered residuals of diminished magnitude. A return to a more variable bed profile is evident in the 2013 longprofile, with accumulation of sediment contributing to the formation of ripples and armoured planebed channel units (Figure 24). Shallow pools exist downstream of riffles and bedrock steps, with the only significant pool occurring at the outside margin of a tight bend in the bedrock valley.

Cross-sectional comparisons for the three time periods highlight the removal of alluvial bars throughout the reach and channel widening following the 2011 flood event (Figure 33), with excavation to bedrock creating a wide, flat channel profile at the upstream cross-section. The downstream location indicates infilling of the 2010 low-flow channel to form a largely flat macrochannel. The progression from 2010 to 2011 shows a shift towards a more trapezoidal channel at both cross-section locations, with cross-sectional area increasing by an average of 18.5 m² (42.6%) throughout the reach (Table 11). Channel contraction to a marginally narrower lowflow channel is evident in the 2013 cross-sections, though not to the same degree as Murphys Creek.

Photographs of the pre- and post-flood channel of Fifteen Mile Creek demonstrate the stripping of the channel of existing vegetation communities and the extent of channel widening following the 2011 flood event (Figure 31). The large deposit of fine-grained alluvium evident in 2011...
photography is a product of deposition due to flow convergence at the tributary junction of Fifteen Mile and Paradise Creeks, occurring immediately upstream of the Fifteen Mile study reach (and photo-point) (see Figure 8).

**Figure 31**: Photographs of the nature of the channel of Fifteen Mile Creek in A) 2010; B) 2011; c) 2013. View is downstream.

### 5.3.2.3 Paradise Creek

The 2010 longprofile of Paradise Creek has a morphology of alternating riffles and pools of considerable length (Figure 28 C). Reach scale profile variability is moderate in comparison to the 2010 profiles of Murphys Creek and Fifteen Mile Creek (Figure 29). As in the two downstream reaches, the response to the 2011 flood event is characterised by considerable lowering of the channel bed and a progression to a largely featureless profile, with no significant gradient adjustments along the length of the reach (Figure 28 C). Comparison of pre- and post-flood residuals reveals a similar trend to the upstream reaches, displaying lower variance from the regressed mean gradient along the reach. The 2013 longprofile shows minimal variability, with the accumulation of sediment into short riffles and scouring of shallow pools in the upstream portion of the reach. The majority of the reach exhibits featureless planebed morphology with major vertical profile deviations occurring on the outside of tight channel bends where bedrock steps exist (Figure 25).

The upstream cross section of Paradise Creek (Figure 33 E), follows the trend of the downstream reaches response to flooding, with the erosion of alluvium adjacent to the low-flow channel in 2011 and significant channel widening, increasing the width to depth ratio and creating a flat valley floor. The 2013 upstream cross section demonstrates further removal of alluvium, with a small amount of channel contraction creating a more discrete low-flow channel. The downstream cross-section underwent severe changes following the 2011 flood, with total channel avulsion occurring. The 2010 low-flow channel has been completely infilled, accommodating an in-channel bar in 2011, while significant incision into alluvium has occurred on the opposing side of the macrochannel, creating a low-flow channel in 2011 of similar dimensions. While cross-
sectional area has increased by an average of 9.0 m$^2$ (48.6%) throughout the reach, there was a minor decrease in the downstream cross-sectional area (Table 11). The 2013 cross section does not show significant additional change.

*In situ* pre- and post-flood photographs of Paradise Creek show the extent of channel scour which occurred during the 2011 flood, with removal of vegetation and alluvium (Figure 32). As in the downstream reaches, the 2010 photography provides evidence of extensive riparian vegetation throughout the channel, which is completely destroyed by the 2011 flood event, resulting in a chaotic channel planform accommodating significant debris. Satellite photography shows the reach-scale extent of channel stripping (Figure 27).

![Figure 32: Photographs of the nature of the channel of Paradise Creek near Fifteen Mile Creek in; a) 2010; b) 2011. View is upstream.](image)

Table 11: Changes to cross-sectional area of the pre-flood channel due to the 2011 flood at each cross-section location. Bold values represent reach average values.

<table>
<thead>
<tr>
<th></th>
<th>Cross-sectional Area 2010 (m$^2$)</th>
<th>Cross-sectional Area 2011 (m$^2$)</th>
<th>Change (m$^2$)</th>
<th>Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Murphys Creek</strong></td>
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<td></td>
</tr>
<tr>
<td>Upstream</td>
<td>49.9</td>
<td>135.6</td>
<td>85.7</td>
<td>171.6</td>
</tr>
<tr>
<td>Downstream</td>
<td>54.0</td>
<td>124.4</td>
<td>70.4</td>
<td>130.2</td>
</tr>
<tr>
<td><strong>Fifteen Mile Creek</strong></td>
<td>43.4</td>
<td>61.8</td>
<td>18.5</td>
<td>42.6</td>
</tr>
<tr>
<td>Upstream</td>
<td>28.7</td>
<td>41.9</td>
<td>13.2</td>
<td>45.9</td>
</tr>
<tr>
<td>Downstream</td>
<td>58.0</td>
<td>81.8</td>
<td>23.8</td>
<td>41.0</td>
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<tr>
<td><strong>Paradise Creek</strong></td>
<td>18.4</td>
<td>27.4</td>
<td>9.0</td>
<td>48.6</td>
</tr>
<tr>
<td>Upstream</td>
<td>16.6</td>
<td>36.1</td>
<td>19.5</td>
<td>117.1</td>
</tr>
<tr>
<td>Downstream</td>
<td>20.2</td>
<td>18.6</td>
<td>-1.6</td>
<td>-7.8</td>
</tr>
</tbody>
</table>
Figure 33: Temporal cross sections at; A) Murphys Creek Upstream; B) Murphys Creek downstream; C) Fifteen Mile Creek upstream; D) Fifteen Mile Creek downstream; E) Paradise Creek upstream; F) Paradise Creek downstream. All cross-sections are oriented downstream, dashed blue line represents 2011 flood water surface elevation estimated from flood-markers.
5.3.3 Volumetric changes following the 2011 flood

Analysis of volumetric change conducted within the macrochannel of the study reaches shows clear trends in the degree and location of erosion and deposition due to the 2011 flood event. Figure 34 presents maps of the spatial pattern of erosion and deposition (i.e. volumetric changes). The Murphys Creek reach is a relatively straight reach, which resulted in a uniform pattern of channel stripping concentrated through the centre of the bedrock valley. Deposition occurred along the channel margins in discontinuous pockets. In contrast, erosion of alluvium in the Fifteen Mile Creek is largely determined by meanders in the bedrock-confined macrochannel. Extensive erosion is evident at the outside of channel bends, with sediment being deposited in almost point-bar features on the inside of bends. Significant erosion at the outside of the tightest channel bend was caused by the undercutting of sandstone cliffs, with a large zone of deposition occurring immediately downstream. The map of volumetric change at Paradise Creek shows discrete areas of erosion and deposition, with bedrock-controlled meanders dictating erosion at the outside of channel bends and deposition on the inside of bends. An atypical depositional area exists at the downstream extent of the reach, where depositional bars at two channel bends are continuous, cutting across the valley floor.

<table>
<thead>
<tr>
<th>Catchment Area (km²)</th>
<th>Total Volumetric Change (m³)</th>
<th>Mean Volumetric Change (m³/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murphys Creek</td>
<td>168</td>
<td>-54918.87</td>
</tr>
<tr>
<td>Fifteen Mile Creek</td>
<td>89</td>
<td>-40020.18</td>
</tr>
<tr>
<td>Paradise Creek</td>
<td>26</td>
<td>-13121.19</td>
</tr>
</tbody>
</table>

All three reaches exhibit significant overall net erosion, with the total volume of material eroded increasing with stream order (Table 12). When erosion is considered on a per-unit area basis, the volume of sediment eroded per unit area increases as stream order (and thus drainage area) decreases.
Figure 34: Volumetric changes due to the 2011 flood. Sediment erosion and deposition in m³/m²; A) Murphys Creek; B) Fifteen Mile Creek; C) Paradise Creek. Negative values indicate erosion.
6. DISCUSSION

6.1 CHARACTERISING POST-FLOOD CHANNEL MORPHOLOGY

6.1.1 SEDIMENT SUPPLY AND SEDIMENT TRANSPORT CONSIDERATIONS

In assessing the morphology of the study reaches in the upper Lockyer valley, mathematical surrogates of sediment supply and transport variables were employed. The values calculated for the three study reaches were highly abnormal for reaches of comparable slope and drainage area published elsewhere (Figure 20). The large values calculated for transport capacity and sediment supply are likely the result of depth calculated from flood markers of the 2011 flood. This value was between 4 and 8 metres, which is very large for mountain streams (Vianello & D’Agostino 2007; Wohl & Merritt 2008; Pike et al. 2010). Due to the extent of channel stripping, the study reaches do not currently have clear bankfull morphology. A study by Nanson (1986) highlights the almost random and catastrophic nature of erosion in bedrock-confined channels. Such unpredictable flow regimes and transport mechanisms cause large fluctuations in sediment supply and transport competence, making these values probably impossible to predict. Benda & Dunne (1997) state that sediment influx to low stream order channels is stochastic and rainfall-driven through mass-failures, landslides and debris flows.

The downstream trend of $q_r$ in the three study reaches does not adhere to the general trend observed in other such settings, with the larger drainage areas appearing to be more supply limited than their upstream counterparts. This downstream trend may be a factor of the downstream coarsening of grainsize measured in the study reaches in terms of $D_{50}$ and $D_{84}$ (used in the calculation of $Q_c$ and $Q_s$), which is not consistent with grainsize reduction trends found in the literature. A study by Brummer & Montgomery (2003) across four drainage basins found that downstream coarsening occurs in small catchments with drainage areas less than 10km$^2$, with a subsequent shift to downstream fining as drainage area increases in larger catchments. The drainage areas of the three study reaches are all far greater than this value (Table 2).

Due to the fact that only 3 reaches were analysed in this study, it cannot be determined whether grain-size characteristics found here are indicative of unstable flood-dominated morphology, due to the 2011 flood. A downstream coarsening of grain size is indicative of a basin-wide trend of sediment capacity exceeding supply, with areas exhibiting downstream coarsening being dominated by colluvial, rather than fluvial processes (Vianello & D’Agostino 2007). This may be a function of inputs of very coarse sediment throughout the drainage network due to hillslope failures and landslides during the 2011 event. Increasing valley width downstream would contribute to lower entrainment competence of flows and thus the deposition of coarse material in lower gradient study reaches. A study of sedimentary changes to confined and unconfined reaches
of Murphys Creek by Thompson & Croke (2013) found that the flood caused wholesale erosion of alluvium in confined reaches, with downstream, unconfined reaches being areas of net deposition for much of the eroded material. Limitations of the Wolman (1954) method are well documented in the literature, particularly at sites of high grain size variability (Hey & Thorne 1983; Olsen et al. 2005). It is possible that the grain size characteristics calculated for the reaches is not indicative of true reach-scale trends.

6.1.2 MODERN CHANNEL MORPHOLOGY AND CLASSIFICATION FRAMEWORKS

One of the objectives of this report was to test existing classification frameworks for bedrock reaches and determine the applicability of such schemes to systems that have undergone catastrophic change. Two of the three study reaches investigated in this study exhibit morphologies and physical characteristics which do not adhere to any of the channel classifications of Thompson et al. (2006). The reaches at Murphys Creek and Fifteen Mile Creek each have a chaotic or disorganised morphology as a result of the 2011 flood. This event resulted in channel stripping and the deposition of flood debris that now mantles the valley floor in a discontinuous manner. In addition, the stripping of alluvium down to bedrock has produced regular planated rock surfaces and rock steps along the channel floor. As a result the reach-scale morphology does not adhere to any existing classifications (Thompson et al. 2006) for their respective physical settings. These two reaches have elements of several classes, which typically exist under very different physical parameters according to the existing classification frameworks of Montgomery & Buffington (1997) and Thompson et al. (2006). Golden & Springer (2006) highlight the fact that mobilisation of alluvium during large floods causes mixed alluvial-bedrock reaches to operate as bedrock reaches in the immediate aftermath of mantle removal. The current morphology of all three reaches indicates that the amount of time following the flood for organisation of alluvial deposits within the macrochannel has been insufficient for the morphology to reflect fluvial processes.

As such, the use of process-based classification systems may be inappropriate for reaches which have recently undergone catastrophic erosion. Analysis of reach long profiles and cross-sections derived from multi-temporal LiDAR data shows that following the 2011 (and more recently the 2013) flood, all three reaches are moving towards greater organisation of alluvial material into channel units. These analyses suggest that the reaches are moving away from the current unstable morphology towards a more stable morphology, as described by Nanson & Huang (2008). Given sufficient time without another significant disturbance, the morphologies of these reaches is predicted to more strongly reflect their physical setting and climatic regime, which will likely reflect existing classification frameworks.
The morphological characteristics of bedrock stream networks have a significant influence over the response of channel reaches to a given discharge or sediment-supply perturbation. Many bedrock, step-pool and cascade morphologies are highly insensitive to all but catastrophic disturbances due to highly resistant boundary conditions and large, immobile sediment stores (Montgomery & Buffington 1997). The study reaches of the Lockyer Valley held a pre-flood morphology which corresponds to the pool-riffle domain of classifications by Montgomery & Buffington (1997) and Thompson et al. (2006). Such morphologies are more vulnerable to large discharge events due to smaller grain sizes and reduced channel confinement, constituting less resistant boundaries. The 2011 flood represented a threshold-exceeding disturbance which had the competence to cause extensive channel scour, bed lowering and the creation of transient post-flood morphologies.

6.2 CHANNEL RESPONSE TO FLOODING IN THE LOCKYER VALLEY

6.2.1 ENTRAINMENT THRESHOLD CALCULATIONS

Calculation of entrainment thresholds for the study reaches given grain-size characteristics and estimated flows for the 2011 flood event demonstrated that the entire sediment range of all three reaches was predicted to undergo mobilisation when equations tailored to upland channels were used. However, anecdotal evidence, multi-temporal photography and assumptions based on rendered maps of volumetric change (Figure 34) indicate probable mobilisation of extremely large boulders up to 4820mm in diameter.

During high magnitude events in steep confined valleys, unusually large clasts and comparatively voluminous bed-load deposits have been transported, which may be a function of the non-Newtonian conditions of flow due to high concentrations of debris (Milan 2012). Although the reaches studied in the Lockyer valley are not steep in mountain stream terms, the strong confinement by resistant bedrock along all three reaches and extreme discharges may have contributed to non-Newtonian conditions and thus entrainment of boulders like those shown in Figure 26.

This analysis shows that the use of sediment entrainment thresholds can be useful in predicting bedload transport during different flood discharges. The equations of Komar & Carling (1991) and Bathurst (1987), which are tailored to bedrock streams, proved to provide better predictions of flow competence in such settings compared with the Shields parameter. Thompson & Croke (2013) found that Costa’s lower envelope for critical unit stream power produced better entrainment predictions than the Shields parameter for similar settings in the Lockyer Valley. The 2011 flood in these streams resulted in the mobilisation of boulders which far exceed the D_{MAX} values from the grain size analysis undertaken in 2013. Entrainment of such particles is indicative
of non-Newtonian flow caused by high concentrations of sediment in the flood discharge. A further consideration in the calculation of entrainment thresholds is the role of multiple flood peaks or paired flood events. Reid et al. (1985) concluded that thresholds of initial motion for consolidated sediment, which has experienced a period without disturbance, are up to 3 times those of final motion for subsequent flood peaks or floods. The flood hydrographs for the 2011 flood (Figure 12 & Figure 13) show a series of flood peaks, which may influence the mechanisms of entrainment thresholds during the duration of the event. Due to the catastrophic erosion caused by the 2011 flood, comparable clasts would also exert less resistive force to entrainment in subsequent floods (the 2013 event), due to the small flood-lag and increased vulnerability of sediment to mobilisation following flood events (Reid et al. 1985; Milan 2012).

6.2.2 MORPHOLOGICAL RESPONSE AND RECOVERY

Each of the three study reaches underwent catastrophic channel stripping during the 2011 flood, with the evacuation of large volumes of sediment, the wholesale removal of vegetation from the macro-channel and a significant reduction in longitudinal and cross-sectional variability. All three study reaches experienced significant net losses to sediment stores. Along considerable sections of the study reaches, the valley floor was lowered to bedrock due to ‘U’ shaped valley scouring typical of low stream order channels (Reinfelds & Nanson 2001). The 2011 flood constitutes the largest flood on record and overcame entrainment thresholds for the entire sediment range. In reference to historical floods, the magnitude of the 2011 flood in the Lockyer Valley is one of the largest on record in Australia in terms of specific peak discharge relative to catchment area (Thompson & Croke 2013). Figure 35 shows the relative discharge of the 2011 flood and other Australian floods in reference to the world maximum flood envelope curve presented by Costa (1987).
In terms of geomorphic effectiveness, this event represents the exceedence of an extrinsic threshold in terms of run-off which was sufficient to overcome intrinsic resistance within the channel (Schumm 1979). The degree of channel stripping, quantified in Section 5.3.3, demonstrates a downstream increase in the geomorphic work carried out by the flood event in net terms, with the overall volume of sediment erosion increasing with drainage area. A general relationship of decreasing stream power downstream is described in literature, although individual watersheds demonstrate significant deviations from this trend due to landscape controls on gradient, confinement and the location of tributary discharge inputs (Knighton 1999; Fonstad 2003; Reinfelds et al. 2004). In the upper Lockyer, the fact that all three reaches are strongly confined by bedrock means that erosive capabilities would continue to increase downstream due to flow constriction and increased discharge with increasing drainage area. Of particular importance to catchment-scale morphological response is the location of the storm-cell which caused the 2011 flood, which was most intense in the upper Lockyer sub-catchments of Fifteen Mile Creek and Alice Creek where the study reaches are located (Rogencamp & Barton 2012).

Wohl (2007) highlights the difficulty of assessing flood impacts in resistant-boundary channels, which often exhibit constantly changing relationships between sediment supply and transport capacity following catastrophic flooding, leading to unstable configurations and morphologies. However, the general assessment of channel response is useful in terms of understanding relationships between morphological processes and their response to disturbance in generating further understanding of the effect of large floods on upland stream networks.
Following the 2011 flood, the study reaches exhibited an unstable flood-dominated morphology with alluvial channel-units exhibiting no spatial arrangement and very poor sorting. Riparian vegetation has proven to be instrumental in preventing braiding and flow separation in steep, coarse bedload channels in upland regions (Smith 2013). The removal of riparian vegetation in the upper Lockyer reaches may have contributed to the chaotic post-flood morphologies. Studies of channel response to catastrophic events suggest that recovery of watersheds to such an event is contingent on a range of factors influencing the nature and rate of change (Costa 1974; Harvey 1991). According to the theory of equilibrium states of fluvial systems, unstable morphologies will move towards the most stable morphology that may exist in the new physical setting (Nanson & Huang 2008). Field survey data collected in 2013, two years after the initial flood, indicate that recovery has occurred to a modest extent across all three reaches, with greater organisation of sedimentary deposits, decreases in reach-scale width-depth ratios and stabilisation of alluvium in the macrochannel by primary colonising vegetation.

The pre-flood conditions and extent of channel stripping due to the 2011 flood draws close parallels to the model of episodic disequilibrium flood-plain development outlined by Nanson (1986) (Figure 7). The study reaches of this report exhibit similarities to those described by Nanson (1986), with a bedrock-confined planform restricting lateral adjustments with morphological evolution being restricted to vertical sediment accretion. The pre-flood morphology of the upper Lockyer study reaches appear to consist of narrow discontinuous pockets of alluvium, with the primary sedimentary store being the in-channel bars. Studies of Australian and international rivers have shown that such channels can switch between narrow deep channels and wide shallow channels in response to extrinsic factors (Nanson & Erskine 1988; Dean & Schmidt 2013). Episodic periods of vertical accretion and catastrophic stripping of alluvium appear to be the vehicle of major morphological development in the study reaches, with large floods dictating long-term morphological evolution through episodic disequilibrium.

Bedrock channel response to flooding through initial widening due to channel stripping and subsequent narrowing as a result of sediment accumulation is well documented and the study reaches appear to follow this model (Toone et al. 2012). The rate of channel recovery to a stable morphology hinges on the nature of sediment and energy inputs to the system, characterised by sediment supply from the catchment and discharge regimes (Harvey 1991). Wolman & Gerson (1978) state that channels widened by floods of high recurrence intervals may regain their original width rapidly on a decadal time scale where temperate climates exist, due to the inherent supply of sediment, hydraulic energy and vegetative stabilisation which characterise such climates. However, the variability of climatic conditions in the Lockyer catchment means that inter-decadal patterns of rainfall will exert a strong control on recovery rates of the study reaches. In the period immediately following the 2011 flood, the catchment has experienced a period of higher-than-
average rainfall and discharge, with a second, low magnitude flood event occurring in 2013 (Figure 10). The existence of casuarina saplings of >2years age colonising sedimentary deposits in the macrochannel of all three reaches suggest that the discharge of this flood was not sufficient for large-scale mobilisation of alluvium. Nanson & Erskine (1988) predict that channels with morphologies dominated by episodic accretion and erosion will eventually return to a pre-flood size, with recovery likely to be dependent on moderate floods supplying coarse debris from upstream. Multi-temporal longprofile and cross-section plots of the study reaches imply that the 2013 flood was a primarily depositional event, with vertical accretion of alluvium occurring within the three macrochannels, perhaps representing the start of a period of accretion towards pre-flood morphology.

The rate of recovery appears to increase with increasing stream order, which constitutes greater sediment supply and discharge. The degree of change from 2011 to 2013 is greatest in the Murphys Creek reach, as the fluvial processes at this location have greater inputs of sediment and energy to mobilise and arrange sediment due to larger drainage area. Further study of a suite of upland channel reaches in the catchment is required to allow generalisation of the mechanisms of channel response outlined in this section and describe catchment-scale trends.

6.2.2.3 ROLE OF VEGETATION

Riparian vegetation has a significant effect on the stability of fluvial systems, increasing the resistance of channel banks and channel-marginal sedimentary units such as bars and benches (Baker 1977; Hoyle et al. 2012). The rate of revegetation following an erosional flood event has been postulated to exert a large control on the time-scale of a fluvial system returning to a stable morphology. Wolman & Gerson (1978) state that if the rate of revegetation is rapid, then regardless of the degree of destruction exerted by a large flood event and assuming sufficient sediment supply to the system, a rapid recovery to prevailing pre-flood conditions will occur.

Prior to the 2011 flood, extensive and well-established vegetation within the bedrock-confined macrochannel stabilised the channels of the upper Lockyer catchment to a large degree creating a narrow, deep low-flow channel and effectively increasing the intrinsic threshold of the system for geomorphically effective floods. This would have contributed to the extent of the lag-period between effective floods in this part of the catchment, in reducing the ability of given discharges to mould in-channel sediment (Wohl 2007). The lag period in the study area can be assumed to be significantly greater than 30 years based on stream gauge records and regional climatic and discharge trends, notably Brisbane River stream gauge flood history, presented in Figure 15. The sub-humid, sub-tropical climate of the Lockyer region promotes itself to rapid growth of vegetation, already visible in the study reaches (Figure 36).
Nevertheless, the destruction wrought by the 2011 flood indicates that the role of riparian vegetation in long-term channel evolution is minor, as large flood events have the capacity to scour channels of all vegetation. A study by Webb et al. (2002) on flood-dominated evolution of bedrock-confined streams found that riparian vegetation is highly important in fluvial processes on decadal time scales, yet in long-term channel evolution, low frequency-high magnitude floods dominate channel and floodplain morphology.

![Figure 36: Photographs of the nature of the channel of Murphys Creek in; a) 2011; B) 2013. Note that most changes since 2011 have occurred through vegetation regrowth on the right bank. View is downstream.](image)

### 6.3 Wiping the Slate Clean: Episodic Landscape Evolution and Climatic Variability

The long-term evolution of the Earth’s landscape is the product of complex relationships between tectonics and climate, which dictate the creation of topography through uplift and mediation of erosional processes which denude and segment landscapes (Whittaker 2012). The Great Dividing Range of Australia, which hosts the upper reaches of the Lockyer catchment, is a post-orogenic landform in a tectonically stable region. Australian rates of denudation are extremely slow, with fluvial erosion being the primary mechanism for weathering and erosion of the continental land surface (Gale 1992). The stable tectonic setting of the study area highlights the importance of climatic factors in determining the rate of landscape evolution as uplift and tectonic processes are negligible. Climatic variation is fundamental to the rates and magnitude of fluvial processes which influence the nature of landscape evolution, controlling run-off and flood variability, temporal erosional thresholds and the role of vegetation in shaping the landscape (Molnar et al. 2006).

Bedrock streams exert a strong control over landscape evolution, dictating the rates and patterns of denudation, with channels determining dissection and relief structure of unglaciated orogens and setting boundary conditions for hillslope erosion (Whipple 2004). Studies by Macklin et al. (1992) and Nott et al. (2002) used dating of flood deposits and local climatic histories to draw links between rates of fluvial activity and long-term trends in precipitation, demonstrating the
clear coupling of high-rainfall regimes with periods of rapid geomorphic change in fluvial systems. Incision of bedrock-confined streams is dependent on a range of intrinsic factors, with flow variability, flood-frequency, alluvial mantling and the character of bedrock lithology determining the mechanisms and rate of incision. A study by Jansen (2006) regarding incision rates in post-orogenic landscapes highlights the role of alluvial bed material in rate-limiting incision in such settings, effectively protecting underlying bedrock from erosional processes. In the context of the Upper Lockyer study reaches; there was a large degree of mantling by alluvium in pre-flood morphologies, with the 2011 event scouring extensive parts of the reaches to bedrock. It is impossible to determine the degree to which bedrock incision occurred as a result of the 2011 flood, although it can be assumed that the alluvial channel units absorbed the brunt of the flood’s erosive force as little evidence of incision exists in cross-sectional channel profiles.

It is logical to predict that for any significant denudation of the valley floor to occur, a flood exceeding erosional thresholds for local bedrock is required at a time when the morphology of the drainage network maintains bedrock exposures (Jansen 2006). Based on models of sediment supply and transport capacity, the three study reaches do not exhibit strong supply-limited regimes, indicating that alluvial cover is likely to regenerate during inter-flood periods. A study by Thompson et al. (2007) found that residence time of sediments in mountain streams was in the order of hundreds of years, lending weight to the argument that the study reaches undergo ongoing vertical sediment accretion which is only scoured by catastrophic events constituting significant recurrence intervals. However, due to dating of in-channel sediments up to 1400 years, it is considered that even where flow competence exceeds entrainment thresholds, scouring is limited by the depth and grain size of sedimentary deposits during flood events (Thompson et al. 2007).

The literature on the long-term landscape evolution of the Great Dividing Range in New South Wales states that due to incompetence of other processes, very slow rates of evolution are dictated by persistence of lithological control on erosion rates within fluvial systems (Bishop et al. 1985; Prosser et al. 1994; Nott et al. 1996). The gradients and drainage patterns of modern channels in this region are largely consistent with those of the Miocene, highlighting the incompetence of fluvial processes to mould the landscape on a timescale of 20 million years.

This holds important implications for the episodic nature of landscape evolution of post-orogenic areas in terms of bedrock-confined channels. The precipitation regime of Eastern Australia is the result of multi-year variability coupled to the strength and persistence of La Nina and El Niño events and decadal trends of above-average and below-average rainfall (FDRs and DDRs) (Erskine & Warner 1998; Kiem et al. 2003). Flood history is difficult to determine in upland channels due to the likelihood of catastrophic stripping of sediment, removing stratigraphic
evidence of previous events (Sandercock 2012). In addition, short stream gauge records and high flow variability in the Lockyer Catchment has led to flood frequency analyses yielding inconsistent results between studies. This report estimates the 2011 flood had an ARI of ~59 years at Spring Bluff and ~45 years at Helidon, while Thompson & Croke (2013) estimated an ARI of ~2000 years at Spring Bluff and ~400 years at Helidon when stream gauge data up to 2010 was used. Palaeoclimate analysis for Queensland derived from sedimentary ridges and oxygen isotope records suggest that over the past 5000 years a severe cyclone occurs on average every 200-300 years (Nott 2009). This allows some assumption of the frequency of major flood events in the Lockyer catchment, as the 2011 flood was caused by an inland-tracking storm cell of moderate severity. According to paleoclimate and stream gauge data, it can be predicted that the 2011 flood represents an event that occurs every ~150-200 years.

Based on literature regarding landscape denudation rates and climatic conditions, it can be assumed that any significant changes to upper Lockyer catchment landscape evolution would require periods of higher-than average rainfall constituting flood-dominated regimes as described by Erskine & Warner (1998). Nevertheless, as described by Bishop et al. (1985), the landscape of the Great Dividing Range has exhibited strong resistance to denudation throughout a range of climatic regimes over the past 20Ma. While climatic regimes would exert strong control on episodic evolution of the upper Lockyer fluvial network due to periods of high-flood frequency (sensu Nanson 1986), this does not necessarily constitute a significant effect on large-scale and long-term landscape change.

6.4 LIMITATIONS

The primary limitation of this study is the scale, in terms of number of reaches studied and the extent of analysis that could be carried out in the allocated time. Golden & Springer (2006) highlight that a large data set is more likely to yield sensible results to empirical analyses in reach scale investigation of morphology. The study of three reaches revealed useful information about the nature of morphology and response to disturbance in different settings, however general trends are difficult to draw from such a small data set. In addition, the processes of channel response to consecutive floods and channel recovery were difficult to gauge due to the short time-scale of fieldwork. Ideally, monitoring of channel response over years or decades would be carried out to best understand the processes and results of morphological channel response.

The field methods used in this analysis placed some limitations on the type of analysis that could be carried out. The Wolman (1954) method of assessing grain size distribution has been proved to be inhibited by substrate heterogeneity, differences in substrate characteristics between locations, substrate variability between streams and the skill or consistency of the technician (Hey & Thorne
1983; Olsen et al. 2005). The substrate of the study reaches was very poorly sorted and variable within reaches, as described in post-flood morphology studies in similar settings (Reinfelds & Nanson 2001). The variability of sediment size limits the usefulness of this technique in providing an accurate representation of grain size characteristics. Nevertheless, the Wolman method remains the primary method for grainsize analysis in literature based on simplicity, replicability and the ability of untrained personnel to undertake field work. It is also important to note that in assessing volumetric change, the spatial analysis method used in this study cannot differentiate the compensating effects of scour and fill as both erosion and deposition occur during flood events (Thompson & Croke 2013).

The lack of stream gauge data for the upper Lockyer Valley and the short record at existing gauges at Spring Bluff and Helidon, placed constraints on the accuracy and usefulness of flood frequency analysis. The calculations used in this report being subject to limitations in the Manning equation for discharge, including selection of the correct roughness co-efficient and the applicability of empirical equations to natural channels (Greenhill & Sellin 1995). Use of hydraulic modelling to describe volume of discharge and patterns of flow within the study reaches would be useful to better understand flood processes and channel responses to the 2011 and 2013 flood events. In addition, literature concerning geomorphic effectiveness of flows promotes the derivation of peaks-above-threshold and time-above-threshold values for flood events to determine the frequency of threshold events and energy available for morphological work during floods (Costa & O'Connor 1995; Lang et al. 1999). Existing studies of the 2011 flood at Murphys Creek and Lockyer Creek highlight the usefulness of flood-modelling in gauging channel response (Thompson & Croke 2013). Calculation of values for time-above-threshold was not possible due to the scarcity of stream gauge data in the upper Lockyer Valley and constraints on time to undertake hydraulic modelling. Flood modelling provides a vehicle for this analysis which would be useful in characterising channel-response to specific flood events in the study area.

6.5 RECOMMENDATIONS

6.5.1 MORPHOLOGICAL CHANNEL RESPONSE

The morphological response of the channel to ongoing climatic influences requires ongoing monitoring in order to assess the nature and timescale of adjustment to the physical setting of the upper Lockyer Valley. Following the 2011 flood, the morphology of the channels is chaotic and does not reflect the combination of factors such as slope, sediment supply and transport relationships and drainage area which have been proven to dictate reach-scale morphology (Montgomery & Buffington 1997; Vianello & D'Agostino 2007; Addy et al. 2011). Ongoing monitoring through field-survey or high-resolution LiDAR, presents an opportunity to assess the
6.5.2 EPISODIC EVOLUTION

This report concludes that the nature of channel evolution in these reaches is dominated by large floods. However, due to the short stream gauge record, the frequency with which these catastrophic events occur is not addressed in detail. Detailed palaeoflood analysis though stratigraphic dating and assessment of boulder deposits throughout the bedrock-confined reaches of the upper Lockyer catchment has the ability to provide a large flood record for the kinds of reaches described in this study.

6.5.3 INCISION RATES AND GEOMORPHIC EFFECTIVENESS

In assessing the geomorphic effectiveness of the 2011 flood, this report did not differentiate between sedimentary and bedrock changes, with erosion assumed to be dominantly alluvial. Particularly in the investigation of landscape evolution and long-term channel morphology, the degree of bedrock incision as a result of major flood is critical. Cosmogenic nuclide analysis could be used to determine the extent of residual signal on bedrock exposures, highlighting exposure times. The zeroing of multiple surfaces would be indicative of 2+ m of bedrock plucking in the 2011 flood, identifying it as an important bedrock eroding event. In addition, quantification of landslides in the upper Lockyer drainage network through remote sensing analysis of pre- and post-flood imagery would provide additional information on the role of colluvial processes as sediment sources during the 2011 flood.

7. CONCLUSION

The results of this report show that the three study reaches in the upper Lockyer valley experienced catastrophic channel stripping during the 2011 event. The flood resulted in destruction of sedimentary channel units and the wholesale removal of in-channel and riparian vegetation to create a highly disorganised channel morphology. Flood frequency analysis shows that the 2011 flood is the largest on record and represents a ~50-yr ARI. The longevity of stream gauge data and assessment of wider regional trends in rainfall and flood occurrence increases the likelihood that the 2011 event represents a greater recurrence interval than that calculated in this study.

Geomorphic change due to the 2011 flood resulted in net loss of sedimentary material in all three study reaches, with the volume of sediment eroded increasing with stream order and thus catchment area. On a unit-area basis, erosion was greatest in the steepest reach with smallest drainage area, indicating the high geomorphic effectiveness of this event in smaller, strongly confined reaches. Multi-temporal longitudinal profiles and channel cross-sections of all three
study reaches show extensive lowering of the channel floor and large increases in the width of the low-flow channel. All study reaches exhibited a significant reduction in morphological variance due to the destruction of channel-units and diminished vertical variability. Channel cross-sections experienced expansions of up to 220% as a result of the 2011 flood, with the degree of dimensional change generally increasing downstream (with drainage area). It is estimated that the 2011 event mobilised the entire grain-size population of the study reaches, from sand- to boulder-sized material (1670mm). Anecdotal evidence of transportation of large clasts (up to 4820mm) suggests that flow conditions during the flood were non-Newtonian and thus had the competence to mobilise large boulders. Studies of erosion and deposition on confined and unconfined reaches of Murphys Creek and Lockyer Creek following the 2011 flood highlight the extensive erosion in bedrock-confined channels, with eroded material being deposited downstream where channel expansions occur (Thompson & Croke 2013).

Modern longitudinal profiles and cross-sections indicate the progression of channel recovery following the 2011 flood, likely the function of a ~6-yr ARI flood in 2013. This is evident in channel narrowing and increased morphological variance due to vertical accretion of alluvium and pool scour. Modern channel morphologies do not reflect existing classification frameworks for mountain stream morphology due to perturbation of sediment supply and transport conditions during the 2011 flood. Ongoing channel recovery is predicted to demonstrate a progression towards ‘stable’ mixed bedrock-alluvial morphology reflecting the physical setting of the reaches. The time-scale of recovery is dependent on subsequent fluvial conditions in terms of discharge regimes, vegetative regrowth and sediment supply.

It is hypothesised that rare, large magnitude floods dominate the stochastic, episodic morphological evolution of such settings, drawing close parallels to the Nanson (1986) model of disequilibrium episodic vertical accretion and stripping.
8. REFERENCES


APPENDIX

SEDIMENT SUPPLY AND TRANSPORT

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ENTRAINMENT THRESHOLDS

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**RESIDUALS OF LONGPROFILES**

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| R Square              | 0.956424842 | 0.94205825 | 0.938889   |
| Adjusted R Square     | 0.956363208 | 0.94198281 | 0.938603   |
| Standard Error        | 0.635257819 | 0.69138045 | 0.810155   |
| Observations          | 709        | 770        | 216        |</p>
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