The Influence of River Sensitivity and Sediment Connectivity on Geomorphic Response and Effectiveness in the Lockyer Valley, SEQ

Peyton E. Lisenby
B.S. (Geology), M.S. (Geology)

Department of Environmental Sciences, Macquarie University

Thesis submitted for the degree of Doctor of Philosophy, April 2017

For my wife, Elizabeth...

“How can we possibly have the slightest idea what to expect?”

- *Dr. Alan Grant*

Table of Contents

ABSTRACT

The sensitivity of river channels to geomorphic adjustment and the dynamics of sediment connectivity along channel networks are key controls on the ability of a geomorphic system to respond to flood events. In turn, the cumulative impact of geomorphic responses to successive floods determines the geomorphic effectiveness of any flood event. River sensitivity and sediment connectivity can change significantly over space and time. Correspondingly, the ability of a geomorphic system to respond is also variable so that geomorphic effectiveness is not definitively characterized by a static relationship between event magnitude and geomorphic response, but rather is a dynamic comparison between geomorphic response and an actively changing capacity for geomorphic adjustment. Herein, this thesis presents a characterization of river sensitivity and sediment connectivity for the Lockyer Valley, Queensland, Australia. Sensitivity and connectivity datasets are used to establish expectations of geomorphic channel behavior and are linked to concomitant geomorphic factors (i.e. geomorphic thresholds, self-organization, geomorphic recovery, and geomorphic effectiveness). The data chapters in this thesis detail a history of geomorphic channel adjustment along Lockyer Creek and its tributaries and provides a method for analysing the nature of coarse sediment (dis)connectivity within the catchment. This research shows that the sensitivity to, and capacity for, geomorphic adjustment varies significantly with channel morphology and valley position. Additionally, the nature of bedload sediment connectivity changes with the distribution of geomorphic landforms and channel barriers that can impede sediment transference through the system. In the Lockyer Valley, this variability in river sensitivity and sediment connectivity influences the severity, distribution, and form of geomorphic adjustments that occur in response to sporadic, and sometimes catastrophic, flood events. Therefore, river management philosophies that incorporate concepts of river sensitivity and sediment connectivity are better suited to predict and interpret future channel behavior. Ultimately, the geomorphic effectiveness of flood events in the Lockyer Valley can only be determined by comparing geomorphic responses with the ability of this geomorphic system to respond.

CERTIFICATE

This thesis comprises the original research performed by the author, Peyton E. Lisenby, and has not been submitted for higher degree at any other university or institution.

The Introduction section of this thesis details the individual contributions of fellow authors for the 6 published, or prepared for publication, data chapters. Non-author contributions to this thesis are detailed in the acknowledgements section of each data chapter.

The sources of data used in this thesis are detailed in the methods and acknowledgements sections of each data chapter or as footnotes to data tables provided as supplementary information in the Appendices section.

Peyton Lisenby

ACKNOWLEDGEMENTS

I am immensely grateful to my supervisor, Kirstie Fryirs, for going to bat for an American during the international scholarship rounds and for taking the time to sift through all the 'Peyton speak' in my writing. My development as an Earth scientist progressed a great deal through learning from her in-depth understanding and practical approach to geomorphology. Both my perspective as a geomorphologist and my future academic and professional horizons have expanded through working with Kirstie.

I am very grateful to my adjunct supervisor, Jacky Croke, for welcoming me into the 'Big Flood' project team and for taking the time to include me in the project's development. I am truly proud of the work Jacky, Kirstie, and I put in to revising the concept of geomorphic effectiveness. I am also grateful to the 'Big Flood' project team, especially Chris Thompson and my fellow PhD students, for their support during workshops, conferences, and field work.

I am particularly grateful to my geomorphology cohorts – Rory Williams, Kirsten Cowley, Simon Mould, Zacchary Larkin, and Marek Rouillon. They provided quality (mostly) banter, a forum for complaints, and much needed advice regarding grammatical and strategical approaches to thesis writing.

I would also like to thank my associate supervisor, Tim Ralph, for providing much needed and timely advice throughout my PhD candidature.

Lastly, I am indebted to my wife, Elizabeth, for taking this magical mystery ride down under with me. My PhD candidature also documents our first few years of marriage. Her support, organization, enthusiasm for helping me with field work, and excellent note-taking abilities were instrumental to my success both as a student and a husband.

Chapter 1

Introduction

1. Introduction

Over two-thirds of the Earth's continental surfaces are drained by rivers (Baker, 1986). Rivers are subject to change over space and time, and these changes are visible through the geomorphological adjustment of fluvial landforms – those landforms created and maintained by river processes, for example, river channels, floodplains, terraces, sediment bars and benches. Geomorphic adjustments are ultimately responses to disturbances in, or alterations of, a range of environmental forces (e.g. climate change, tectonic activity, vegetation cover, sediment supply, anthropogenic forces, flood events, earthquakes, and droughts). The manner in which rivers respond reveals the complex interplay between factors that are internal and external to the system and that govern river behavior. The effectiveness of these factors at instigating morphological change is partially dependent on the severity and extent of the disturbance. Recently, the Lockyer Valley of southeastern Queensland, Australia was devastated by catastrophic flooding. In the aftermath of the floods, this thesis project was enacted as part of a broader research initiative to better understand and predict the geomorphic impact of large flood events. The research presented here seeks to characterize river adjustments in the Lockyer Valley and to determine how different geomorphic factors control past, present, and future river channel response.

1.1. Geomorphic Response

Geomorphic responses are physical adjustments instigated by both naturally-occurring and anthropogenically-forced disturbance events that are ultimately structured by self-organized, internal system dynamics (Phillips, 1999, 2009; Phillips and Van Dyke, 2016). They are the principal means by which earth scientists can observe the interaction between internal and external, driving and resisting forces at work in natural environments (Wolman and Miller, 1960). Often, geomorphic responses are categorized as different forms of morphological adjustment (e.g. Brierley and Fryirs, 2005; Fryirs et al., 2009). Additionally, geomorphic responses can be portrayed through the alteration of threshold conditions of adjustment (Schumm, 1973; Beven, 1981); although, threshold changes are more difficult to observe until a morphological response is triggered (e.g. soil moisture increase leading to hillslope failure). More often, threshold responses are retrospectively inferred from morphological adjustments. Evaluations of past geomorphic responses in river channels have traditionally been used to recognize morphological adjustments produced by both modern and historical disturbance events, such as hurricanes, floods, earthquakes, and tsunamis (e.g. Bretz, 1925; Collins and Schalk, 1937; Wolman and Eiler, 1958; Hadley, 1960; Kon'no et al., 1960; Baker, 1973). However, in fluvial environments, it was recognized early on that variation in physiographic region and antecedent environmental conditions strongly influenced the ability of river channels to respond via processes of erosion and deposition and in forming the channel (Gilbert and Murphy, 1914; Anderson and Trobitz, 1949; Leopold and Wolman, 1956; Wolman, 1959; Baker, 1977). Nevertheless, the variable relationship between flood events and geomorphic responses was generalized to create a simple relationship between the magnitude and frequency of floods and the resultant geomorphic work, formulating the initial hypothesis for the concept of geomorphic effectiveness (Wolman and Miller, 1960). The desire to link a particular magnitude of response to a recurring magnitude of disturbance event is related to historical efforts to characterize longer-term 'equilibrium' conditions in all natural landscapes (Gilbert, 1877; Mackin, 1948; Langbein and Leopold, 1964; Howard, 1965). An equilibrium state implies a particular and consistent balance between driving and resisting forces, so that landscape evolution is driven by a linear 'seesawing' between forces of adjustment and forces of stability that approaches equilibrium conditions (e.g. Lane, 1955). However, as this simple approach was used to characterize a broader range of geomorphic processes in different physiographic environments, the recognition of variability in the nature of geomorphic response highlighted the err in assuming equilibrium tendencies at all scales in all landscapes (Trimble, 1977; Phillips, 1992; Renwick, 1992; Thorn and Welford, 1994; Bracken and Wainwright, 2006).

1.2. Characterizing the Variability of Geomorphic Response and Effectiveness

Our understanding of the complex and contingent relationship between geomorphic responses and an array of externally- and internally-derived controls greatly expanded through the development of geomorphic concepts that linked auto- and allogenic influences to variability in geomorphic response, for example, thresholds and complex response (Schumm, 1973, 1979), landscape sensitivity (Brunsden and Thornes, 1979), sediment connectivity (Walling, 1983), geomorphic recovery (Wolman and Gerson, 1978), and self-organization (Bak et al., 1987, 1988). These concepts are fundamentally interdependent, as the nature of one will influence the nature of the others. The evolution of landforms to a critical failure state, defined as thresholds of change by Schumm (1979), is a key control on the ease with which landforms can adjust, defined as sensitivity by Fryirs (2016). Correspondingly, geomorphic adjustments within landscapes can affect the ease with which sediment can be transported from its source to a sink or between landforms and landscape compartments, defined as sediment connectivity by Fryirs (2013) and Bracken et al. (2015). Reciprocally, the availability and transportability of sediment can affect the form, severity, and distribution of geomorphic adjustments and establish further adjustment thresholds (Hooke, 2003; Czuba and Foufoula-Georgiou, 2015). The interplay between landform sensitivity and sediment connectivity after threshold-breaching events (e.g. floods) will then influence the suite of post event landform adjustments, defined as recovery by Phillips and Van Dyke (2016). Over time, the feedbacks initiated by past responses and the propagation of geomorphic effects can instigate internally-evolved threshold states, described as self-organized behavior by Phillips (1999, 2003) that 'set-up' future landform adjustments to occur alongside externally-initiated responses. Ultimately, the interaction of these geomorphic factors not only dictate the nature of geomorphic response to a single disturbance event, but also the variability of response across sequences of events and the recovery of the landscape during interim periods. Therefore, each of these concepts dictate, in part, a landscape's ability to respond and will subsequently control the geomorphic effectiveness of any disturbance event. Moreover, these concepts demonstrate the limitations of simple magnitude-frequency methodologies in predicting geomorphic response (Crozier, 1999; Richards, 1999), and they have since independently developed into frameworks for assessing geomorphic interactions at multiple scales, from landform and channel reach adjustments to landscape evolution (Brunsden, 2001; Werner, 2003; Phillips, 2014; Bracken et al., 2015; Fryirs, 2016; Phillips and Van Dyke, 2016). Crucially, concepts that can explicate the spatiotemporal variability of geomorphic response are inextricably linked through the geomorphic concept designed to evaluate the significance of those responses – the concept of geomorphic effectiveness.

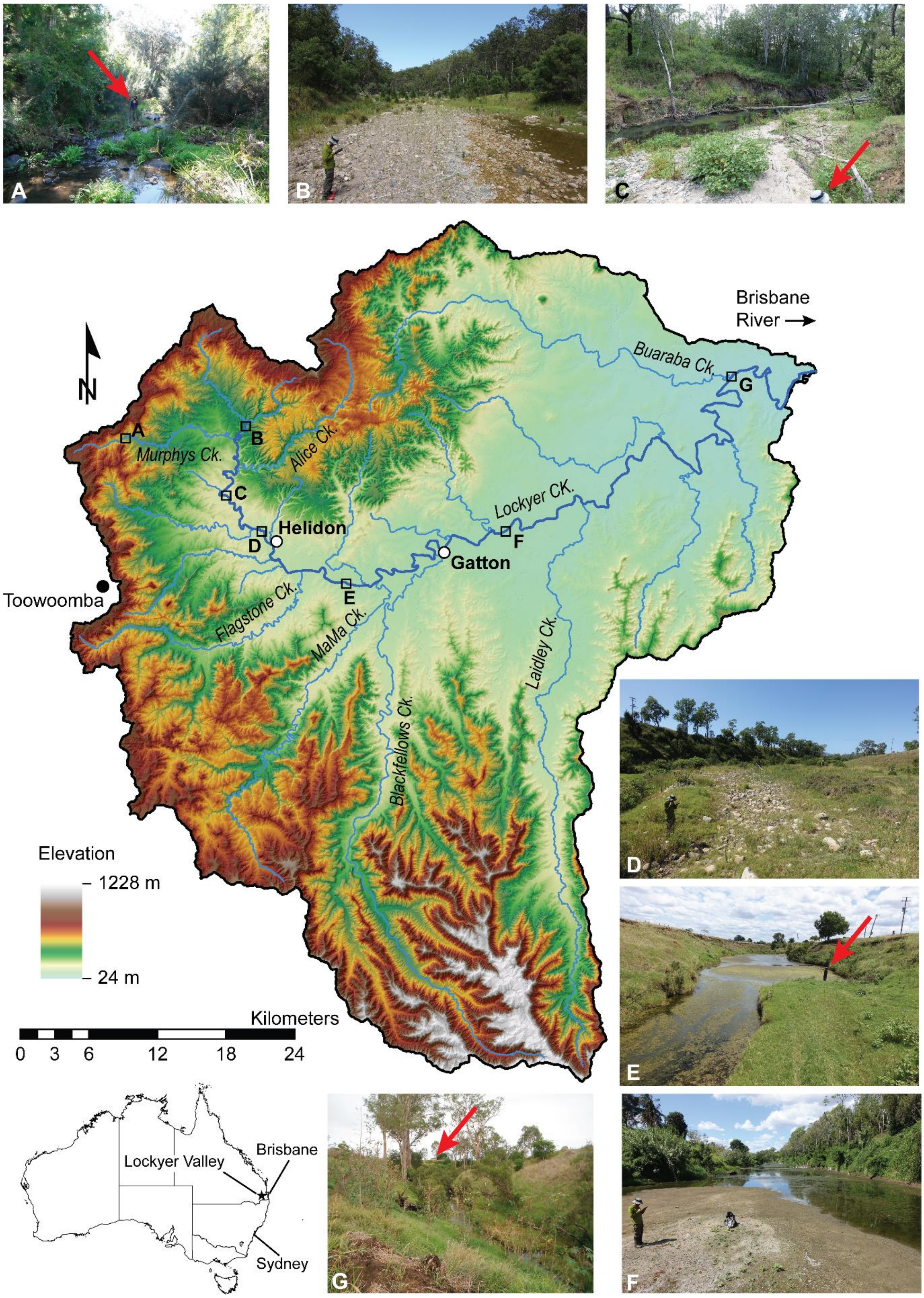
1.3. Linking Geomorphic Response to River Management

Incorporating geomorphic knowledge into holistic river management policies is a recent trend in river management practice (Wohl et al., 2015). Historically, rivers have been managed, restored, or rehabilitated to address very specific aims, such as flood control, fishing, irrigation, sanitation, navigation, water supply, or aesthetics (White, 1998; Thompson and Stull, 2002; Poff et al., 2007; Wohl, 2014; Wohl et al., 2015). These types of management interventions, until recently, rarely utilized a geomorphic understanding of channel behavior to inform decisions. In the past few decades, river management has become more multifaceted, where numerous stakeholders with different motivations may establish multiple river restoration and management goals (White, 1998; Bernhardt et al., 2005; Wohl et al., 2005; Kondolf et al., 2007). Geomorphic knowledge is essential for these types of initiatives because it can help determine what types of outcomes are possible and how different management goals may interact in a particular channel reach (Brierley and Fryirs, 2005; Wohl et al., 2005; Fryirs, 2015; Wohl et al., 2015). Unfortunately, geomorphic insights are often only incorporated with management strategies at the scale of individual channel reaches. This ignores a broader contextual understanding that can help characterize how well sediment is connected upstream to downstream, and what catchment-scale factors may influence morphological adjustments within a particular reach (Kondolf et al., 2006; Fryirs and Brierley, 2009; Raven et al., 2010; Fuller et al., 2011a; 2014). The ability of those tasked with river management to characterize and understand the controls on geomorphic response (e.g. river sensitivity and sediment connectivity) in their catchment will determine their subsequent ability to effectively manage, restore, or rehabilitate river channels (Bernhardt et al., 2007; Fuller et al., 2011b).

1.4. The Lockyer Valley

The Lockyer Valley is a ~ 3000 km^2 tributary catchment of the Brisbane River located in subtropical, southeastern Queensland (SEQ), about 80 km west of Brisbane (Figure 1). This region receives seasonally variable rainfall ranging from 900 to 1800 mm (Rustomji et al., 2009), and mean monthly temperatures range between 21 and 29° C (Croke et al., 2013a). The trunk stream, Lockyer Creek, confluences with 20 major tributaries, and river types vary from bedrock-confined or partly confined to occasionally wandering or gravel-boulder bed, to single thread, sand bed macrochannels with cohesive banks (Figures 1 A-G, 2 A-F). The upper portions of the catchment on the western and southern boundaries are steep, forested, and orographically influence rainfall (Jordan, 2011; SEQWater, 2013). The valley widens downstream and develops extensive floodplains shared with several of the largest tributaries of Lockyer Creek.

Figure 1. Location of the Lockyer Valley in SEQ. A) Gravel-boulder bed channel with pool-riffle sequences in upper Murphys Creek. B) Gravel-bedrock bed channel near the beginning of Lockyer Creek. C) Sand-gravel channel in the first expansion zone (see Chapter 1 for definitions and locations of expansion and contraction zones). D) Near beginning of macrochannel form of Lockyer Creek. E) Lockyer Creek macrochannel open to grazing. F) Lower Lockyer Creek macrochannel with large sand bars. G) Lockyer Creek macrochannel near Buaraba Creek and the Brisbane River Confluence. Red arrows indicate scale.


A
B
C
Brisbane
River
Buaraba Ck.
G
N
A
B
Murphys Ck.
Alice Ck.
C
Lockyer CK.
Helidon
D
F
Gatton
Toowoomba
E
Flagstone Ck.
MaMa Ck.
Laidley Ck.
Blackfellows Ck.
Elevation
1228 m
24 m
Kilometers
0
3
6
12
18
24
Lockyer Valley
Brisbane
Sydney
D
E
G
F

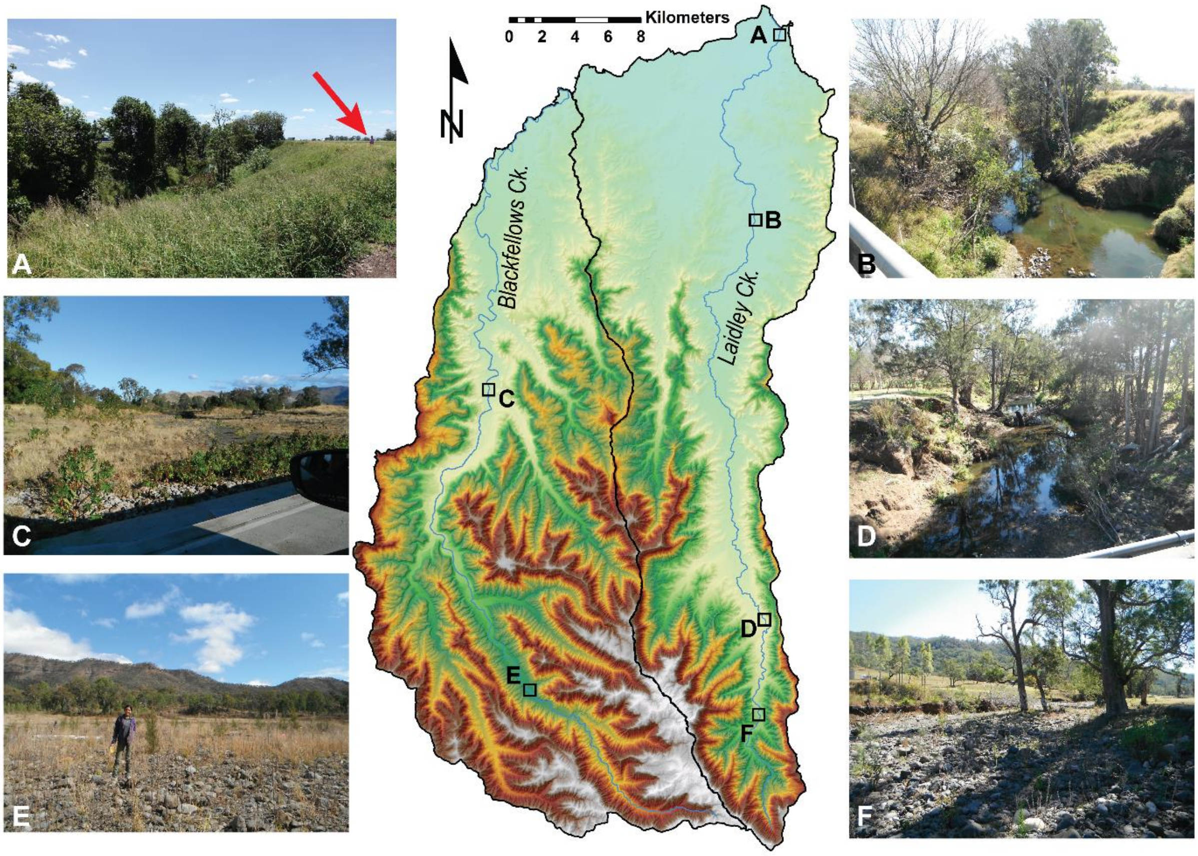


Figure 2. Changing channel morphology along the Blackfellows (*left*) and Laidley Creek (*right*) tributaries. A) Laidley Creek macrochannel near confluence with Lockyer Creek. B) Gradual decrease in channel size upstream along Laidley Creek. C) Channel widening, shallowing, and coarsening along Blackfellows Creek. D) Sand-gravel channel in the upper Laidley catchment. E) Wide, shallow, gravel-bed channel in the upper Blackfellows catchment. F) Wide, shallow, gravel-bed channel in the upper Laidley catchment.

Prior to European settlement and exploration in 1823, the Lockyer Valley was characterized by early explorers as having mixed forests with variable density along with abundant grassland plains and pastures (Steele, 1983; Kemp et al., 2015). Agricultural development in this region began in the early-mid 1800s with widespread farmland irrigation and weir construction developing through the early and mid-1900s (Tew, 1979; Lockyer Catchment Centre, 2000). Since European settlement, two-thirds of native vegetation has been cleared for agricultural purposes (Apan et al., 2002).

This thesis project originates from a broader Australian Research Council (ARC) Linkage Grant (LP120200093) awarded in 2012 to a multi-institution and state agency team. This grant was motivated by a catastrophic flood that occurred in the Lockyer Valley, SEQ in January 2011. This flood claimed the lives of 17 people in the Lockyer Valley and caused considerable damage to property and infrastructure in SEQ (ICA Hydrology Panel, 2011; van den Honert and McAneney, 2011; Rogencamp and Barton, 2012). The severity of the 2011 flood brought into focus the hydroclimatic setting of the Lockyer Valley, where extended dry periods are punctuated by intense rainfall events (Rustomji et al., 2009; Taschetto and England, 2009; Cai et al., 2010; Cai and van Rensch, 2012). The 2011 flood is credited with 'breaking' the Millennial Drought, the most severe drought on record (van Dijk et al., 2013). These periodic floods result in high flood variability for SEQ which is related to the El Nino-Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO). Major floods have occurred over 10 times within the past 200 years (Croke et al., 2013b; Fryirs et al., 2015), with recent large floods occurring in 2011 and 2013. The largest floods on record occurred in 1841 and 1893 (van den Honert and McAneney, 2011). Correspondingly, this thesis work stems from 'Stage 3' of the ARC Linkage Grant, titled 'Geomorphic Assessment of River Response to Floods and Droughts.' Research in this stage compliments three other stages that investigate the quaternary evolution of the Lockyer Valley, the regional paleoflood record of SEQ, the immediate geomorphic effects of the 2011 flood, and modelling river response and the geomorphic evolution of channels in the Lockyer Valley (Croke et al., 2012; Thompson et al., 2012; Croke et al., 2013a; Croke et al., 2013b; Grove et al., 2013; Thompson and Croke, 2013; Thompson et al., 2013; Croke et al., 2014; Thompson et al., 2014; Croke et al., 2016a; Croke et al., 2016b; Lam et al., 2016; Thompson et al., 2016a; Thompson et al., 2016b; Daley et al., 2017). The final report of this ARC Linkage Project and a synthesis of the research conducted, including portions of this thesis, is provided at http://www.thebigflood.com.au/.

1.5. Thesis Aims and Structure

The overarching objective of this thesis is to characterize the controls on, and the variability of, river responses to sequences of floods and droughts in the Lockyer Valley, SEQ. To accomplish this objective, this thesis will utilize the geomorphic concepts of river sensitivity and sediment connectivity to describe how geomorphic responses, and the ability of landscapes to respond, can vary in space and time. The controls of river sensitivity and sediment connectivity will be related using the concept of geomorphic effectiveness to characterize how channel sensitivity/resilience and sediment (dis)connectivity can influence channel adjustment and the evolution of rivers in a catchment. Characterizing the array of controls on geomorphic response is a key step in establishing sound catchment management strategies that consider the variability of geomorphic behavior across the Lockyer Valley.

This thesis has five aims:

Aim 1. Relate geomorphic controls on river response to the variability of geomorphic effectiveness for disturbance events.

Aim 2. Characterize the variability of river sensitivity in the Lockyer Valley.

Aim 3. Characterize the variability of sediment (dis)connectivity in the Lockyer Valley.

Aim 4. Evaluate catchment- to reach-scale controls on geomorphic response in river channels.

Aim 5. Utilize river sensitivity and sediment connectivity datasets to assess future river response in the Lockyer Valley.

These aims are addressed through six data chapters (Chapters 2 through 7) that are published in, or prepared for submission to, international journals. A discussion section (Chapter 8) integrates the findings from the data chapters into a cohesive assessment of geomorphic responses and effectiveness. Supporting information for the data chapters is provided in an appendices section. The data chapters are sequenced according to the thesis aims. Below, the purpose of each chapter is briefly summarized and the contributions of each individual author (Peyton Lisenby – PL; Kirstie Fryirs – KF; Jacky Croke – JC) are provided.

Chapter 2 –Geomorphic Effectiveness

Lisenby, P., Croke, J., Fryirs, K., 2016. Geomorphic effectiveness: A linear concept in a non-linear world. Earth Surface Processes and Landforms, doi: 10.1002/esp.4096.

This chapter, titled 'Geomorphic Effectiveness: A linear concept in a non-linear world,' is published as a 'State of Science' article in the journal 'Earth Surface Processes and Landforms.' This chapter establishes the conceptual framework for analyzing geomorphic response in the subsequent data chapters. Here, the historical development of the concept of geomorphic effectiveness is reviewed and some important and troubling legacies of that history are explained. The paper goes on to critique the metrics used to quantify the causes and effects of natural disturbance events, emphasizing that metrics of cause and effect must be distinguishable (not the same), comparable (apply at similar spatiotemporal scales), and flexible (apply in a variety of geomorphic environments) in order to determine the geomorphic effectiveness of a single or multiple disturbance events. Lastly, this paper sets the ‘effectiveness’ concept in a non-linear context. In order for the geomorphic effectiveness concept to remain useful in the future, it must fit into a framework that explains the variability of geomorphic response over time, incorporating concepts of geomorphic sensitivity and sediment connectivity. Where ‘geomorphic effectiveness’ is used to determine if a disturbance event was effective, non-linear concepts like sensitivity and connectivity help to answer why or why not.

Manuscript preparation – PL (75 %), JC (15 %), KF (10 %). PL contributed the majority of manuscript writing and produced all of the figures; JC contributed to the manuscript organization and writing revisions; KF contributed writing on specific geomorphic concepts and helped to revise and edit the manuscript.

Intellectual Contribution – PL (60 %), JC (25 %), KF (15 %). PL provided the majority of the intellectual contribution. JC contributed the initial idea and to the direction of this manuscript. KF provided guidance on specific geomorphic concepts.

Chapter 3 – The Resilience of Lockyer Creek

Fryirs, K., Lisenby, P.E., Croke, J., 2015. Morphological and historical resilience to catastrophic flooding: The case of Lockyer Creek, SE Queensland, Australia. Geomorphology 241, 55-71, doi: 10.1016/j.geomorph.2015.04.008.

This chapter, titled ‘Morphological and historical resilience to catastrophic flooding: The case of Lockyer Creek, SE Queensland, Australia,’ is published in the journal ‘Geomorphology.’ This chapter presents an analysis of river sensitivity for Lockyer Creek in an effort to provide a historical context for the extent of geomorphic channel adjustments that occurred during the 2011 flood. This paper utilizes sequential sets of maps, air photos, and satellite imagery to identify the form, number, and distribution of geomorphic channel adjustments along Lockyer

Creek from the late 1800s to 2011. The form and distribution of channel adjustment are listed in Appendix 1. The results demonstrate that the reach-averaged morphology of Lockyer Creek has remained relatively characteristic over time, and no wholesale forms of adjustment or significant changes in channel width have occurred. The majority of adjustments served to adjust or reorganize the geomorphic units occurring within the macrochannel, and overall, trunk stream channel responses to severe flooding have been minor. These results suggest that the trunk stream system is resilient due to the antecedent 'setting' of the macrochannel morphology which acts as a 1^{st}-order control on channel adjustment. This implies that large events that would often be considered geomorphically effective may not impart the expected severity of geomorphic adjustment.

Data compilation and analysis – Data gathered and initial analysis conducted by KF; data analysis performed by PL.

Manuscript preparation – KF (55 %), PL (40 %), JC (5 %). KF provided the manuscript organization, wrote the 'Introduction' and 'Discussion' sections, provided an initial draft of the results, and revised the 'Regional Setting', 'Methodology', and 'Results' sections. PL produced and organized the results figures, and wrote the 'Regional Setting', 'Methodology', and 'Results' sections. JC revised the manuscript.

Intellectual Contribution – KF (65 %), PL (30 %), JC (5 %). KF contributed the majority of the intellectual contribution, provided the initial idea for the paper, and oversaw the conceptual development of the paper. PL contributed ideas for the analysis and discussion of results. JC provided guidance on specific geomorphic concepts.

Chapter 4 – The Expectation of Geomorphic Adjustment

Lisenby, P.E., Fryirs, K.A., 2016. Catchment- and reach-scale controls on the distribution and expectation of geomorphic channel adjustment. Water Resources Research 52(5), 3408-3427, doi: 10.1002/2015WR017747.

This chapter, titled 'Catchment- and reach-scale controls on the distribution and expectation of geomorphic channel adjustment' is published in the journal 'Water Resources Research.' This chapter extends the Chapter 3 analysis of historical channel adjustments along the three largest tributaries of Lockyer Creek – Buaraba, Laidley, and Blackfellows Creek. Additionally, this chapter seeks to identify the catchment-scale morphometric and reach-scale morphological controls on the frequency of channel adjustments. The results demonstrate that portions of the tributaries are much more sensitive to adjustment than the trunk stream, and that these adjustments significantly impact the channel margins through forms of avulsion, lateral expansion, and bend adjustments. Statistical analyses demonstrate that these three tributaries also behave distinctly different from one another in terms of where channel adjustments are concentrated. The number and forms of adjustment in each tributary and statistical analyses are provided as supporting information for this publication in Appendix 2. This paper ultimately identifies distinct process domains in the Lockyer Valley where channel behavior, the sensitivity or resilience to geomorphic adjustment, varies with channel morphology and catchment location.

Fieldwork – Carried out by PL.

Data compilation and analysis – Data gathered by PL; analysis performed by PL.

Manuscript preparation – PL (90 %), KF (10 %). PL provided the manuscript organization, produced and organized all figures, and wrote the majority of the manuscript. KF provided specific writing contributions in the discussion section and revised the manuscript.

Intellectual Contribution – PL (80 %), KF (20 %). PL contributed the majority of the intellectual contribution, provided the initial idea for the paper, and oversaw the conceptual development of the paper. KF contributed ideas for the discussion of the results data and provided guidance on specific geomorphology concepts.

Chapter 5 – Sedimentologically Significant Tributaries

Lisenby, P.E., Fryirs, K., 2017. Sedimentologically significant tributaries: Catchment-scale controls on sediment (dis)connectivity in the Lockyer Valley, SEQ, Australia. Earth Surface Processes and Landforms, doi: 10.1002/esp.4130.

This chapter, titled ‘Sedimentologically significant tributaries: catchment-scale controls on sediment (dis)connectivity in the Lockyer Valley, SEQ, Australia’ is published in the journal ‘Earth Surface Processes and Landforms.’ This chapter analyzes the nature of coarse sediment connectivity throughout the Lockyer Valley, as sediment connectivity is a key control over geomorphic channel adjustments. This paper utilizes three forms of connectivity data – distributions of sediment buffers and barriers, distributions of effective (potential sediment contributing) catchment areas (ECAs), and patterns of downstream sediment fining (sedimentary links) along Lockyer Creek. A preliminary sediment (dis)connectivity study published in the Proceedings of the 8th Australian Stream Management Conference is provided in Appendix 3. The individual sediment fractions for sediment surveys conducted along Lockyer Creek are provided in Appendix 4. The results demonstrate that the Lockyer Valley is highly disconnected where extensive buffers and numerous weirs inhibit sediment transference to and along Lockyer Creek. The most sedimentologically significant tributaries are those located in the upper (NW) portion of the catchment as these tributary basins contain the fewest buffers. This finding is corroborated by a downstream fining pattern that appears to be interrupted by these uppermost tributary junctions. Downstream, numerous weirs (barriers) and accumulating buffers will inhibit sediment transference and disconnect several of the largest tributaries from Lockyer Creek. Overall, the lower Lockyer region is characterized as a large coarse sediment sink.

Fieldwork – Carried out by PL.

Data compilation and analysis – Data gathered by PL; analysis performed by PL.

Manuscript preparation – PL (90 %), KF (10 %). PL provided the manuscript organization, produced and organized all figures, and wrote the majority of the manuscript. KF provided specific writing contributions in the discussion section and revised the manuscript.

Intellectual Contribution – PL (80 %), KF (20 %). PL contributed the majority of the intellectual contribution, provided the initial idea for the paper, and oversaw the conceptual development of the paper. KF contributed ideas for the discussion of the results data and provided guidance on specific geomorphology concepts.

Chapter 6 – The Utility of Coarse Spatial Datasets

Lisenby, P.E., Fryirs, K., 2017. 'Out with the old?' Why coarse spatial datasets are still useful for catchment-scale investigations of sediment (dis)connectivity. Earth Surface Processes and Landforms, doi: 10.1002/esp.4131.

This chapter, titled 'Out with the old? Why coarse spatial datasets are still useful for catchment-scale investigations of sediment (dis)connectivity' is published as a 'Letters to ESEX' article in the journal 'Earth Surface Processes and Landforms.' This chapter, in the form of a technical note, highlights the utility of lower-resolution DEM datasets for simpler, universal, catchment-scale modelling of sediment (dis)connectivity. A preliminary sediment (dis)connectivity study published in the Proceedings of the 8th Australian Stream Management Conference is provided in Appendix 3. The paper utilizes analyses of ECA for seven, very different tributaries of Lockyer Creek. ECAs were calculated using 1 m, 5 m, and 25 m DEM resolutions using a simple slope-threshold model in ArcGIS. The results demonstrate that the 25 m DEM resolution provided more realistic calculations of ECA for comparing sediment (dis)connectivity between tributary catchments and was better related to the distributions of sediment buffers. However, stream definition can decrease, especially for lower-order streams, as DEM resolution decreases. This chapter finds that lower-resolution datasets can provide a quick and reliable source of geomorphic data that can yield useful results when paired with simple surface process models.

Data compilation and analysis – Data gathered by PL; analysis performed by PL.
Manuscript preparation – PL (90 %), KF (10 %). PL provided the manuscript organization, produced and organized all figures, and wrote the majority of the manuscript. KF provided specific writing contributions in the discussion section and revised the manuscript.
Intellectual Contribution – PL (80 %), KF (20 %). PL contributed the majority of the intellectual contribution, provided the initial idea for the paper, and oversaw the conceptual development of the paper. KF contributed ideas for the discussion and organization of the results data and provided guidance on specific geomorphology concepts.

Chapter 7 – Assessing Future Channel Response

Lisenby, P.E., Fryirs, K.A., *in prep*. River sensitivity and sediment connectivity as tools for assessing future channel response: Examples from the Lockyer Valley, SEQ. Journal of Environmental Management.

This chapter, titled 'River sensitivity and sediment connectivity as tools for assessing future channel response: examples from the Lockyer Valley, SEQ' has been prepared for submission to the 'Journal of Environmental Management.' This chapter utilized the results obtained from Chapters 3, 4, 5, and 6 to help establish expectations of future channel adjustment in the Lockyer Valley. The paper combines analyses of river sensitivity (distribution of historical geomorphic adjustments) and sediment (dis)connectivity (distributions of buffers, barriers, ECAs, and sedimentary links) to identify four channel reaches that display different sensitivity and connectivity characteristics: resilient-disconnected, resilient-connected, sensitive-connected, and sensitive-disconnected. Historical trajectories of adjustment, anthropogenic impacts, and future climate change scenarios are considered for each of these four reaches to synthesize possibilities for future channel response. This paper demonstrates how river sensitivity and sediment connectivity datasets can support a 'reach-in-catchment' perspective, which is necessary for generating more holistic management approaches. Utilizing geomorphic concepts to produce catchment-scale datasets and perspectives encourages river managers to work with, not against, the natural behavior of fluvial environments.

Data compilation and analysis – Data gathered by PL; analysis performed by PL.
Manuscript preparation – PL (70 %), KF (30 %). PL provided the manuscript organization, produced and organized all figures, and wrote the majority of the manuscript. KF provided specific writing contributions in the discussion section, helped to organize the manuscript text and revised the manuscript.
Intellectual Contribution – PL (70 %), KF (30 %). PL contributed the majority of the intellectual contribution, provided the initial idea for the paper, and oversaw the conceptual development of the paper. KF contributed ideas for the discussion and organization of the results data and provided guidance on specific geomorphology and river management concepts.

References

Anderson, H.W., Trobitz, H.K., 1949. Influence of some watershed variables on a major flood. Journal of Forestry 47(5), 347-356.

Apan, A.A., Raine, S.R., Paterson, M.S., 2002. Mapping and analysis of changes in the riparian landscape structure of the Lockyer Valley catchment, Queensland, Australia. Landscape and Urban Planning 59(1), 43-57, doi: http://dx.doi.org/10.1016/S0169-2046(01)00246-8.

Bak, P., Tang, C., Wiesenfeld, K., 1987. Self-organized criticality: An explanation of the 1/f noise. Physical review letters 59(4), 381.

Bak, P., Tang, C., Wiesenfeld, K., 1988. Self-organized criticality. Physical review A 38(1), 364.

Baker, V.R., 1973. Erosional forms and processes for the catastrophic Pleistocene Missoula floods in eastern Washington. In: M. Morisawa (Ed.), Fluvial Geomorphology. Allen & Unwin, London, pp. 123-148.

Baker, V.R., 1977. Stream-channel response to floods, with examples from central Texas. Geological Society of America Bulletin 88(8), 1057-1071, doi: 10.1130/0016-7606(1977)88<1057:srtfwe>2.0.co;2.

Baker, V.R., 1986. Fluvial Landforms. In: N.M. Short, R.W. Blair (Eds.), Geomorphology from space: a global overview of regional landforms. Scientific and Technical Information Branch, National Aeronautics and Space Administration, Greenbelt, Maryland, pp. 255-316.

Bernhardt, E.S., Palmer, M.A., Allan, J.D., Alexander, G., Barnas, K., Brooks, S., Carr, J., Clayton, S., Dahm, C., Follstad-Shah, J., Galat, D., Gloss, S., Goodwin, P., Hart, D., Hassett, B., Jenkinson, R., Katz, S., Kondolf, G.M., Lake, P.S., Lave, R., Meyer, J.L., O'Donnell, T.K., Pagano, L., Powell, B., Sudduth, E., 2005. Synthesizing U.S. river restoration efforts. Science 308(5722), 636-637, doi: 10.1126/science.1109769.

Bernhardt, E.S., Sudduth, E.B., Palmer, M.A., Allan, J.D., Meyer, J.L., Alexander, G., Follastad-Shah, J., Hassett, B., Jenkinson, R., Lave, R., Rumps, J., Pagano, L., 2007. Restoring rivers one reach at a time: Results from a survey of U.S. River restoration practitioners. Restoration Ecology 15(3), 482-493, doi: 10.1111/j.1526-100X.2007.00244.x.

Beven, K., 1981. The effect of ordering on the geomorphic effectiveness of hydrologic events. IAHS Publ 132, 510-526.

Bracken, L.J., Wainwright, J., 2006. Geomorphological equilibrium: Myth and metaphor? Transactions of the Institute of British Geographers 31(2), 167-178, doi: 10.1111/j.1475-5661.2006.00204.x.

Bracken, L.J., Turnbull, L., Wainwright, J., Bogaart, P., 2015. Sediment connectivity: A framework for understanding sediment transfer at multiple scales. Earth Surface Processes and Landforms 40(2), 177-188, doi: 10.1002/esp.3635.

Bretz, J.H., 1925. The Spokane Flood beyond the channeled scablands. The Journal of Geology 33(2), 97-115, http://www.jstor.org/stable/30067418.

Brierley, G., Fryirs, K., 2005. Geomorphology and River Management: Applications of the River Styles Framework. Blackwell Publishing, Victoria, Australia.

Brunsden, D., Thornes, J.B., 1979. Landscape sensitivity and change. Transactions of the Institute of British Geographers 4(4), 463-484, doi: 10.2307/622210.

Brunsden, D., 2001. A critical assessment of the sensitivity concept in geomorphology. CATENA 42(2–4), 99-123, doi: http://dx.doi.org/10.1016/S0341-8162(00)00134-X.

Cai, W., Rensch, P.v., Cowan, T., Sullivan, A., 2010. Asymmetry in ENSO teleconnection with regional rainfall, its multidecadal variability, and impact. Journal of Climate 23(18), 4944-4955, doi: 10.1175/2010jcli3501.1.

Cai, W., van Rensch, P., 2012. The 2011 southeast Queensland extreme summer rainfall: A confirmation of a negative Pacific Decadal Oscillation phase? Geophysical Research Letters 39(8), L08702, doi: 10.1029/2011GL050820.

Collins, R.F., Schalk, M., 1937. Torrential flood erosion in the Connecticut Valley, March 1936. American Journal of Science Series 5 Vol. 34(202), 293-307, doi: 10.2475/ajs.s5-34.202.293.

Croke, J., Watson, F., Thompson, C., Todd, P., 2012. Erosion and deposition during the January 2011 Lockyer Flood, SE Queensland. In: J. Grove, I.D. Rutherford (Eds.), Proceedings of the 6th Australian Stream Management Conference, Managing for Extremes. River Basin Management Society, Canberra, Australia, pp. 1-9.

Croke, J., Fryirs, K., Thompson, C., 2013a. Channel–floodplain connectivity during an extreme flood event: Implications for sediment erosion, deposition, and delivery. Earth Surface Processes and Landforms 38(12), 1444-1456, doi: 10.1002/esp.3430.

Croke, J., Todd, P., Thompson, C., Watson, F., Denham, R., Khanal, G., 2013b. The use of multi temporal LiDAR to assess basin-scale erosion and deposition following the catastrophic January 2011 Lockyer flood, SE Queensland, Australia. Geomorphology 184(0), 111-126, doi: 10.1016/j.geomorph.2012.11.023.

Croke, J., Reinfelds, I., Thompson, C., Roper, E., 2014. Macrochannels and their significance for flood-risk minimisation: Examples from southeast Queensland and New South Wales, Australia. Stoch Environ Res Risk Assess 28(1), 99-112, doi: 10.1007/s00477-013-0722-1.

Croke, J., Fryirs, K., Thompson, C., 2016a. Defining the floodplain in hydrologically-variable settings: Implications for flood risk management. Earth Surface Processes and Landforms 41(14), 2153-2164, doi: 10.1002/esp.4014.

Croke, J., Thompson, C., Denham, R., Haines, H., Sharma, A., Pietsch, T., 2016b. Reconstructing a millennial-scale record of flooding in a single valley setting: The 2011 flood-affected Lockyer Valley, south-east Queensland, Australia. Journal of Quaternary Science 31(8), 936-952, doi: 10.1002/jqs.2919.

Crozier, M., 1999. The frequency and magnitude of geomorphic processes and landform behaviour. Zeitschrift für Geomorphologie Supplement Volumes 115, 35-50.

Czuba, J.A., Foufoula-Georgiou, E., 2015. Dynamic connectivity in a fluvial network for identifying hotspots of geomorphic change. Water Resources Research 51(3), 1401-1421, doi: 10.1002/2014WR016139.

Daley, J., Croke, J., Thompson, C., Cohen, T., Macklin, M., Sharma, A., 2017. Late Quaternary channel and floodplain formation in a partly confined subtropical river, eastern Australia. Journal of Quaternary Science, doi: 10.1002/jqs.2930.

Fryirs, K., Brierley, G.J., 2009. Naturalness and place in river rehabilitation. Ecology and Society 14(1), http://www.ecologyandsociety.org/vol14/iss1/art20/.

Fryirs, K., Spink, A., Brierley, G., 2009. Post-European settlement response gradients of river sensitivity and recovery across the upper Hunter catchment, Australia. Earth Surface Processes and Landforms 34(7), 897-918, doi: 10.1002/esp.1771.

Fryirs, K., 2013. (Dis)Connectivity in catchment sediment cascades: A fresh look at the sediment delivery problem. Earth Surface Processes and Landforms 38(1), 30-46, doi: 10.1002/esp.3242.

Fryirs, K., 2015. Developing and using geomorphic condition assessments for river rehabilitation planning, implementation and monitoring. Wiley Interdisciplinary Reviews: Water, 649-667, doi: 10.1002/wat2.1100.

Fryirs, K., Lisenby, P.E., Croke, J., 2015. Morphological and historical resilience to catastrophic flooding: The case of Lockyer Creek, SE Queensland, Australia. Geomorphology 241, 55-71, doi: 10.1016/j.geomorph.2015.04.008.

Fryirs, K., 2016. River sensitivity: A lost foundation concept in fluvial geomorphology. Earth Surface Processes and Landforms 42(1), 55-70, doi: 10.1002/esp.3940.

Fuller, I.C., Basher, L., Marden, M., Massey, C., 2011a. Using morphological adjustments to appraise sediment flux. Journal of Hydrology 50(1), 59.

Fuller, I.C., Richardson, J.M., Basher, L., Dykes, R.C., Vale, S.S., 2011b. Responses to river management? Geomorphic change over decadal and annual timescales in two gravel-bed rivers in New Zealand. In: D.A. Molina (Ed.), River channels: types, dynamics and changes. Earth Sciences in the 21st Century. Nova Press, New York, pp. 137-164.

Fuller, I.C., Basher, L.R., Hicks, D.M., 2014. Towards understanding river sediment dynamics as a basis for improved catchment, channel, and coastal management: The case of the Motueka catchment, Nelson, New Zealand. International Journal of River Basin Management 12(3), 175-192, doi: 10.1080/15715124.2014.885437.

Gilbert, G.K., 1877. Report on the geology of the Henry mountains, U.S. Government Printing Office, Washington D.C. .

Gilbert, G.K., Murphy, E.C., 1914. The transportation of débris by running water. U.S. Government Printing Office, Washington D.C.

Grove, J.R., Croke, J., Thompson, C., 2013. Quantifying different riverbank erosion processes during an extreme flood event. Earth Surface Processes and Landforms 38(12), 1393-1406, doi: 10.1002/esp.3386.

Hadley, J.B., 1960. The Madison Landslide. In: Billings Geological Society (Ed.), 11th Annual Field Conference: West Yellowstone-Earthquake Area. USGS, Billings, MT.

Hooke, J.M., 2003. Coarse sediment connectivity in river channel systems: A conceptual framework and methodology. Geomorphology 56(1–2), 79-94, doi: http://dx.doi.org/10.1016/S0169-555X(03)00047-3.

Howard, A.D., 1965. Geomorphological systems; equilibrium and dynamics. American Journal of Science 263(4), 302-312, doi: 10.2475/ajs.263.4.302.

ICA Hydrology Panel, 2011. Flooding in the Lockyer Valley Regional Council LGA, Brisbane.

Jordan, P.W., 2011. Hydrological Advice to Commission of Inquiry Regarding 2010/11 Queensland Floods, Queensland Floods Commission of Inquiry.

Kemp, J., Olley, J.M., Ellison, T., McMahon, J., 2015. River response to European settlement in the subtropical Brisbane River, Australia. Anthropocene 11, 48-60, doi: http://dx.doi.org/10.1016/j.ancene.2015.11.006.

Kon'no, E., Kitamura, N., Kotaka, T., Kataoka, J., 1960. Erosion and deposition due to the tsunami caused by the Chile Earthquake on May, 24, 1960. Annals of the Tohoku Geographical Association 12(4), 120-127, doi: 10.5190/tga1948.12.120.

Kondolf, G.M., Boulton, A.J., O'Daniel, S., Poole, G.C., Rahel, F.J., Stanley, E.H., Wohl, E., Bång, A., Carlstrom, J., Cristoni, C., 2006. Process-based ecological river restoration: Visualizing three-dimensional connectivity and dynamic vectors to recover lost linkages. Ecology and Society 11(2), http://www.ecologyandsociety.org/vol11/iss2/art5/.

Kondolf, G.M., Anderson, S., Lave, R., Pagano, L., Merenlender, A., Bernhardt, E.S., 2007. Two decades of river restoration in California: What can we learn? Restoration Ecology 15(3), 516-523, doi: 10.1111/j.1526-100X.2007.00247.x.

Lam, D., Thompson, C., Croke, J., 2016. Improving at-site flood frequency analysis with additional spatial information: A probabilistic regional envelope curve approach. Stoch Environ Res Risk Assess, 1-21, doi: 10.1007/s00477-016-1303-x.

Lane, E.W., 1955. Importance of fluvial morphology in hydraulic engineering, Proceedings of the American Society of Civil Engineers. American Society of Civil Engineers.

Langbein, W.B., Leopold, L.B., 1964. Quasi-equilibrium states in channel morphology. American Journal of Science 262(6), 782-794, doi: 10.2475/ajs.262.6.782.

Leopold, L.B., Wolman, M.G., 1956. Floods in relation to the river channel, Union Geod. et Geophysics International, Association d'Hydrologie (Symposium in Dijon), Publication, pp. 85-98.

Lockyer Catchment Centre, 2000. Living in the lockyer : A landholders guide to land, water, wildlife and vegetation management in the Lockyer Catchment and surrounds. Lockyer Catchment Centre, Forest Hill, Qld.

Mackin, H.J., 1948. The concept of the graded river. Geological Society of America Bulletin 59(5), 463-512, doi: 10.1130/0016-7606(1948)59[463:cotgr]2.0.co;2.

Phillips, J.D., 1992. The end of equilibrium? Geomorphology 5(3), 195-201, doi: http://dx.doi.org/10.1016/0169-555X(92)90002-6.

Phillips, J.D., 1999. Divergence, convergence, and self-organization in landscapes. Annals of the Association of American Geographers 89(3), 466-488, doi: 10.2307/2564493.

Phillips, J.D., 2003. Sources of nonlinearity and complexity in geomorphic systems. Progress in Physical Geography 27(1), 1-23, doi: 10.1191/0309133303pp340ra.

Phillips, J.D., 2009. Changes, perturbations, and responses in geomorphic systems. Progress in Physical Geography 33(1), 17-30, doi: 10.1177/0309133309103889.

Phillips, J.D., 2014. Thresholds, mode switching, and emergent equilibrium in geomorphic systems. Earth Surface Processes and Landforms 39(1), 71-79, doi: 10.1002/esp.3492.

Phillips, J.D., Van Dyke, C., 2016. Principles of geomorphic disturbance and recovery in response to storms. Earth Surface Processes and Landforms 41(7), 971-979, doi: 10.1002/esp.3912.

Poff, N.L., Olden, J.D., Merritt, D.M., Pepin, D.M., 2007. Homogenization of regional river dynamics by dams and global biodiversity implications. Proceedings of the National Academy of Sciences 104(14), 5732-5737, doi: 10.1073/pnas.0609812104.

Raven, E.K., Lane, S.N., Bracken, L.J., 2010. Understanding sediment transfer and morphological change for managing upland gravel-bed rivers. Progress in Physical Geography 34(1), 23-45, doi: 10.1177/0309133309355631.

Renwick, W.H., 1992. Equilibrium, disequilibrium, and nonequilibrium landforms in the landscape. Geomorphology 5(3), 265-276, doi: http://dx.doi.org/10.1016/0169-555X(92)90008-C.

Richards, K., 1999. The magnitude-frequency concept in fluvial geomorphology: A component of a degenerating research programme? Zeitschrift für Geomorphologie Supplement Volumes 115, 1-18.

Rogencamp, G., Barton, J., 2012. The Lockyer Creek flood of January 2011: What happened and how should we manage hazard for rare floods, 52nd Annual Floodplain Management Association Conference., pp. 1-14.

Rustomji, P., Bennett, N., Chiew, F., 2009. Flood variability east of Australia's Great Dividing Range. Journal of Hydrology 374(3–4), 196-208, doi: http://dx.doi.org/10.1016/j.jhydrol.2009.06.017.

Schumm, S.A., 1973. Geomorphic thresholds and complex response of drainage systems. Fluvial Geomorphology 6, 69-85.

Schumm, S.A., 1979. Geomorphic thresholds: The concept and its applications. Transactions of the Institute of British Geographers 4(4), 485-515, doi: 10.2307/622211.

SEQWater, 2013. Report on the operation of Somerset Dam and Wivenhoe Dam 2-April-2013, Queensland.

Steele, J.G., 1983. The explorers of the Moreton Bay District, 1770-1830. University of Queensland Press, St. Lucia, Queensland.

Taschetto, A.S., England, M.H., 2009. An analysis of late twentieth century trends in Australian rainfall. International Journal of Climatology 29(6), 791-807, doi: 10.1002/joc.1736.

Tew, A.M., 1979. History of the Gatton Shire in the Lockyer Valley. Gatton Shire Council, Gatton, Australia.

Thompson, C., Croke, J., Pietsch, T., 2012. Geomorphic impact of the January 2011 flood on Murphys Creek, southeast Queensland. In: J. Grove, I.D. Rutherford (Eds.), Proceedings of the 6th Australian Stream Management Conference, Managing for Extremes. River Basin Management Society, Canberra, Australia, pp. 1-9.

Thompson, C., Croke, J., 2013. Geomorphic effects, flood power, and channel competence of a catastrophic flood in confined and unconfined reaches of the upper Lockyer Valley, southeast Queensland, Australia. Geomorphology 197(0), 156-169, doi: 10.1016/j.geomorph.2013.05.006.

Thompson, C., Croke, J., Grove, J., Khanal, G., 2013. Spatio-temporal changes in river bank mass failures in the Lockyer Valley, Queensland, Australia. Geomorphology 191(0), 129-141, doi: 10.1016/j.geomorph.2013.03.010.

Thompson, C., Croke, J., Dent, C., 2014. Potential impacts of levee in construction in the Lockyer Valley, 7th Australian Stream Management Conference, pp. 109-115.

Thompson, C., Croke, J., Fryirs, K., Grove, J.R., 2016a. A channel evolution model for subtropical macrochannel systems. CATENA 139, 199-213, doi: http://dx.doi.org/10.1016/j.catena.2015.12.012.

Thompson, C., Fryirs, K., Croke, J., 2016b. The disconnected sediment conveyor belt: Patterns of longitudinal and lateral erosion and deposition during a catastrophic flood in the Lockyer Valley, southeast Queensland, Australia. River Research and Applications 32, 540-551, doi: 10.1002/rra.2897.

Thompson, D.M., Stull, G.N., 2002. The development and historic use of habitat structures in channel restoration in the United States: The grand experiment in fisheries management. Géographie physique et Quaternaire 56(1), 45-60.

Thorn, C.E., Welford, M.R., 1994. The equilibrium concept in geomorphology. Annals of the Association of American Geographers 84(4), 666-696, doi: 10.1111/j.1467-8306.1994.tb01882.x.

Trimble, S.W., 1977. The fallacy of stream equilibrium in contemporary denudation studies. American Journal of Science 277(7), 876-887, doi: 10.2475/ajs.277.7.876.

van den Honert, R.C., McAneney, J., 2011. The 2011 Brisbane Floods: Causes, impacts and implications. Water 3(4), 1149-1173, http://www.mdpi.com/2073-4441/3/4/1149.

van Dijk, A.I.J.M., Beck, H.E., Crosbie, R.S., de Jeu, R.A.M., Liu, Y.Y., Podger, G.M., Timbal, B., Viney, N.R., 2013. The Millennium Drought in southeast Australia (2001–2009): Natural and human causes and implications for water resources, ecosystems, economy, and society. Water Resources Research 49(2), 1040-1057, doi: 10.1002/wrcr.20123.

Walling, D.E., 1983. The sediment delivery problem. Journal of Hydrology 65(1–3), 209-237, doi: http://dx.doi.org/10.1016/0022-1694(83)90217-2.

Werner, B.T., 2003. Modeling landforms as self-organized, hierarchical dynamical systems. In: P.R. Wilcock, R.M. Iverson (Eds.), Prediction in Geomorphology. American Geophysical Union, Washington D.C., pp. 133-150.

White, G.F., 1998. Reflections on the 50-year international search for integrated water management. Water Policy 1(1), 21-27, doi: http://dx.doi.org/10.1016/S1366-7017(98)00003-8.

Wohl, E., Angermeier, P.L., Bledsoe, B., Kondolf, G.M., MacDonnell, L., Merritt, D.M., Palmer, M.A., Poff, N.L., Tarboton, D., 2005. River restoration. Water Resources Research 41(10), doi: 10.1029/2005WR003985.

Wohl, E., 2014. A legacy of absence wood removal in US rivers. Progress in Physical Geography 38(5), 637-663.

Wohl, E., Lane, S.N., Wilcox, A.C., 2015. The science and practice of river restoration. Water Resources Research 51(8), 5974-5997, doi: 10.1002/2014WR016874.

Wolman, M.G., Eiler, J.P., 1958. Reconnaissance study of erosion and deposition produced by the flood of August 1955 in Connecticut. Eos, Transactions American Geophysical Union 39(1), 1-14, doi: 10.1029/TR039i001p00001.

Wolman, M.G., 1959. Factors influencing erosion of a cohesive river bank. American Journal of Science 257(3), 204-216, doi: 10.2475/ajs.257.3.204.

Wolman, M.G., Miller, J.P., 1960. Magnitude and frequency of forces in geomorphic processes. The Journal of Geology 68(1), 54-74, doi: 10.2307/30058255.

Wolman, M.G., Gerson, R., 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surface Processes 3(2), 189-208, doi: 10.1002/esp.3290030207.

Chapter 2

Geomorphic Effectiveness

Chapter published as:

Lisenby, P., Croke, J., Fryirs, K., 2017. Geomorphic effectiveness: A linear concept in a non-linear world. Earth Surface Processes and Landforms, doi: 10.1002/esp.4096.

Pages 45-61 of this thesis have been removed as they contain published material. Please refer to the following citation for details of the article contained in these pages.

Lisenby, P. E., Croke, J., & Fryirs, K. A. (2018). Geomorphic effectiveness: a linear concept in a non-linear world. *Earth Surface Processes and Landforms*, 43(1), p. 4-20.

DOI: 10.1002/esp.4096

Chapter 3

The Resilience of Lockyer Creek

Chapter published as:

Fryirs, K., Lisenby, P.E., Croke, J., 2015. Morphological and historical resilience to catastrophic flooding: The case of Lockyer Creek, SE Queensland, Australia. Geomorphology 241, 55-71, doi: 10.1016/j.geomorph.2015.04.008

Pages 65-81 of this thesis have been removed as they contain published material. Please refer to the following citation for details of the article contained in these pages.

Fryirs, K., Lisenby, P., & Croke, J. (2015). Morphological and historical resilience to catastrophic flooding: the case of Lockyer Creek, SE Queensland. *Geomorphology*, 241, p. 55-71.

DOI: 10.1016/j.geomorph.2015.04.008

Chapter 4

The Expectation of Geomorphic Adjustment

Chapter published as:

Lisenby, P.E., Fryirs, K.A., 2016. Catchment- and reach-scale controls on the distribution and expectation of geomorphic channel adjustment. Water Resources Research 52(5), 3408-3427, doi: 10.1002/2015WR017747.

Pages 85-104 of this thesis have been removed as they contain published material. Please refer to the following citation for details of the article contained in these pages.

Lisenby, P. E., & Fryirs, K. A. (2016). Catchment- and reach-scale controls on the distribution and expectation of geomorphic channel adjustment. *Water Resource Research*, 52(5), p. 3408-3427.

DOI: 10.1002/2015WR017747

Chapter 5

Sedimentologically Significant Tributaries

Chapter published as:

Lisenby, P.E., Fryirs, K., 2017. Sedimentologically significant tributaries: Catchment-scale controls on sediment (dis)connectivity in the Lockyer Valley, SEQ, Australia. Earth Surface Processes and Landforms, doi: 10.1002/esp.4130.

Pages 107-118 of this thesis have been removed as they contain published material. Please refer to the following citation for details of the article contained in these pages.

Lisenby, P. E., & Fryirs, K. A. (2017). Sedimentologically significant tributaries: catchment-scale controls on sediment (dis)connectivity in the Lockyer Valley, SEQ, Australia. *CEarth Surface Processes and Landforms*, 42(10), p. 1493-1504.

DOI: 10.1002/esp.4130

Chapter 6

The Utility of Coarse Spatial Datasets

Chapter published as:

Lisenby, P.E., Fryirs, K., 2017. 'Out with the old?' Why coarse spatial datasets are still useful for catchment-scale investigations of sediment (dis)connectivity. Earth Surface Processes and Landforms, doi: 10.1002/esp.4131.

Pages 121-129 of this thesis have been removed as they contain published material. Please refer to the following citation for details of the article contained in these pages.

Lisenby, P. E., & Fryirs, K. A. (2017). 'Out with the old?' Why coarse spatial datasets are still useful for catchment-scale investigations of sediment (dis)connectivity. *Earth Surface Processes and Landforms*, 42(10), p. 1588-1596.

DOI: 10.1002/esp.4131

Chapter 7

Assessing Future Channel Response

Chapter prepared for submission as:

Lisenby, P.E., Fryirs, K.A., *in prep*. River sensitivity and sediment connectivity as tools for assessing future channel response: Examples from the Lockyer Valley, SEQ. Journal of Environmental Management.

River Sensitivity and Sediment Connectivity as Tools for Assessing Future Geomorphic Channel Response: Examples from the Lockyer Valley, SEQ

Peyton E. Lisenby[1*] and Kirstie A. Fryirs[1]

[1] Department of Environmental Sciences, Macquarie University, North Ryde, NSW, Australia, 2109.

Email: peyton.lisenby@students.mq.edu.au

Abstract

The science of geomorphology is increasingly used to inform river management efforts; however, the complexity of fluvial systems make predictions of future channel adjustment difficult at best. The geomorphic concepts of landform sensitivity and sediment connectivity are well suited to aid river managers in assessing the probability and variability of future river channel responses. This can be especially helpful in planning for impacts of future climate change, or changes in management activity. River sensitivity and sediment connectivity datasets provide a necessary reach-in-catchment perspective. This places the capacity for adjustment of a channel reach in a catchment-scale context based on its degree of sedimentological connectivity. In this paper, we use river sensitivity and sediment connectivity datasets to describe the historical trajectory and future adjustment possibilities for four channel reaches in the Lockyer Valley, southeast Queensland (SEQ). We use these datasets with three different scenarios of future climate and river management conditions to constrain what forms of geomorphic adjustment are possible for resilient-disconnected, resilient-connected, sensitive-connected, and sensitive-disconnected channels. Forecasting and depicting a range of adjustment scenarios and trajectories can aid river managers by establishing expectations of future channel behavior. This information can then be fed into the decision-making process regarding where to prioritize management actions as part of

catchment action planning that works with, not against, the natural behavior of riverine environments.

Keywords: geomorphic forecasting, climate change, catastrophic flood, river restoration, scenario-building, prioritization

Introduction

Geomorphology in particular, and river science more generally, is experiencing an increasing drive to become as predictive as it is retrodictive (Wilcock and Iverson, 2003). Currently, the precision with which river scientists can simulate, model, and detail the physical adjustments of rivers in response to environmental disturbances is not matched by the ability to forecast what changes may occur in the future. This issue becomes more challenging as geomorphic science is progressively incorporated into river management strategy and policy (Gregory et al., 2008; Biron et al., 2014; Wohl et al., 2015). When river scientists are called upon by public, industry, or government interests to determine what future river adjustments are possible, or if a river can recover, the uncertainty associated with the complex and unpredictable nature of fluvial responses can cause river scientists to fall short of expectations (Schumm, 1973, 1983; Burkham, 1981; Downs, 1995; Clark, 2002; Phillips, 2003; Wohl et al., 2005; Hillman and Brierley, 2008).

Two of the many key controls on the complexity and unpredictability of geomorphic river responses are the interdependent influences of landform sensitivity and sediment connectivity (Brunsden, 2001; Thomas, 2001; Lisenby et al., 2017). Landform sensitivity is a geomorphological concept that describes the propensity of landforms to respond to environmental disturbances (Brunsden and Thornes, 1979). However, the susceptibility of a landform to geomorphic adjustment depends significantly on the availability and transportability (connectivity) of sediment within a landscape (Thomas, 2001; Hooke, 2003a; Bracken et al., 2015). In rivers, sensitivity describes the ease with which fluvial landforms can adjust their morphology over space and time (Brierley and Fryirs, 2005; Fryirs, 2016). Correspondingly, the availability and connectivity of sediment along a river network will control, to some extent, the number, form, and severity of future river channel adjustments (Hooke, 2003a; Czuba and Foufoula-Georgiou, 2015). Ultimately, the spatiotemporal variability of river sensitivity and sediment connectivity exerts significant control on the ability of a river to respond which makes the task of forecasting future river response difficult (Brunsden, 2001; Lisenby et al., 2017). This, however, should not deter fluvial geomorphologists from the task of forecasting, and applying confidence limits to forecasts, particularly in the context of understanding the likely impact of future landuse, human disturbance, and climate change on river forms and processes (Tucker and Slingerland, 1997; Gilvear and Black, 1999; Hooke, 2003b; Wilcock and Iverson, 2003; Wilby et al., 2006; Lane et al., 2008). Limitations of prediction in geomorphology should not detract from the utility of geomorphic guidance regarding the forecasting of possible river futures (Brierley and Fryirs, 2005; Houben et al., 2009; Brierley et al., 2012; Brierley et al., 2013; Brierley and Fryirs, 2016). Instead, such work should form the foundation of planning, prioritization, monitoring, and implementation strategies as part of best river management practice (Pizzuto, 2002; Piégay et al., 2005; Gurnell et al., 2016). It is imperative now that the river science and management communities understand the inherent uncertainties in geomorphic system responses and embrace transparency regarding the challenges of forecasting future behavior (Clark, 2002; Lancaster and Grant, 2003; Boulton et al., 2008; Hillman and Brierley, 2008). The development of geomorphic concepts like river sensitivity and sediment connectivity can provide useful tools for determining the expectation of how rivers have adjusted in the past, how they behave toady, and how they might adjust in the future (Newson, 2002; Grabowski et al., 2014; Czuba and Foufoula-Georgiou, 2015; Fryirs, 2016).

Analyses of river sensitivity should be used to document the history of river channel adjustments across many reach types, thereby establishing historical trajectories of river adjustment and behavior (Montgomery, 2008; Wohl, 2011; Fryirs et al., 2015; Brierley and Fryirs, 2016; Lisenby and Fryirs, 2016). These channel reach adjustments can then be set in a catchment-scale context by analyzing the sediment availability to, and connectivity of, the catchment stream network, thereby establishing expectations of how responses may propagate over space and time (Grabowski et al., 2014; Czuba and Foufoula-Georgiou, 2015; Lane et al., 2017). The application of sensitivity and connectivity analyses at the catchment scale is essential for assessing the ability of different channel reaches to respond to disturbance, and deriving predictions of how reach-scale adjustments may influence further responses along the channel network (Downs and Gregory, 2004; Owens, 2005; Brierley et al., 2006; Brierley and Fryirs, 2009; Fryirs et al., 2009).

In this paper, we use existing river sensitivity and coarse sediment connectivity datasets to outline the historical trajectories of river behavior and possibilities of future channel adjustment for four different channel reaches in the Lockyer Valley, southeast Queensland (SEQ). We consider the impact of current anthropogenic disturbances and utilize climate change forecasts for this region to construct three different future scenarios toward which these channels may adjust. The four reaches represent four different river sensitivity and sediment connectivity conditions (resilient-disconnected, resilient-connected, sensitive-connected, and sensitive-disconnected) and serve as examples to guide management practices in this region.

Regional Setting

The Lockyer Valley is a ~ 3000 km^2 tributary catchment of the Brisbane River located in subtropical SEQ, about 80 km west of Brisbane (Figure 1). This region receives seasonally variable rainfall ranging from 900 to 1800 mm (Rustomji et al., 2009), and mean monthly temperatures range between 21 and 29° C (Croke et al., 2013). The valley widens downstream and develops extensive, cultivated floodplains shared with several of the largest tributaries of the trunk stream – Lockyer Creek. The Lockyer Valley floodplains support an important agricultural industry in the state of Queensland, accounting for over 15% of the state's vegetable produce value (Australian Bureau of Statistics, 2012).

The Lockyer Valley has historically adjusted to large, periodic flood events with interim periods of droughts (Thompson et al., 2016a), and the western and southern catchment boundaries orographically influence rainfall (Jordan, 2011; SEQWater, 2013). For example, the recent 'Millennial Drought' (2001-2009) was the worst drought on record for eastern Australia (van Dijk et al., 2013). Subsequently, the flood of 2011 was brought about by the most intense rainfall event on record in SEQ (Cai and van Rensch, 2012). This high hydrological variability is linked to the El Nino-Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) (Rustomji et al., 2009; Cai and van Rensch, 2012). In SEQ, variable, seasonal flood events drive processes of channel evolution (Fryirs et al., 2015; Thompson et al., 2016a). Major floods have occurred over 10 times within the past 200 years with recent large floods in 2011 and 2013 and the largest floods on record in 1841 and 1893 (van den Honert and McAneney, 2011). Channel types in the Lockyer Valley vary from bedrock-confined or partly confined (Figure 1A) to occasionally wandering or gravel-boulder bed (Figure 1B), to single thread, sand bed macrochannels with cohesive banks (Figure 1C) (Lisenby and Fryirs, 2016).

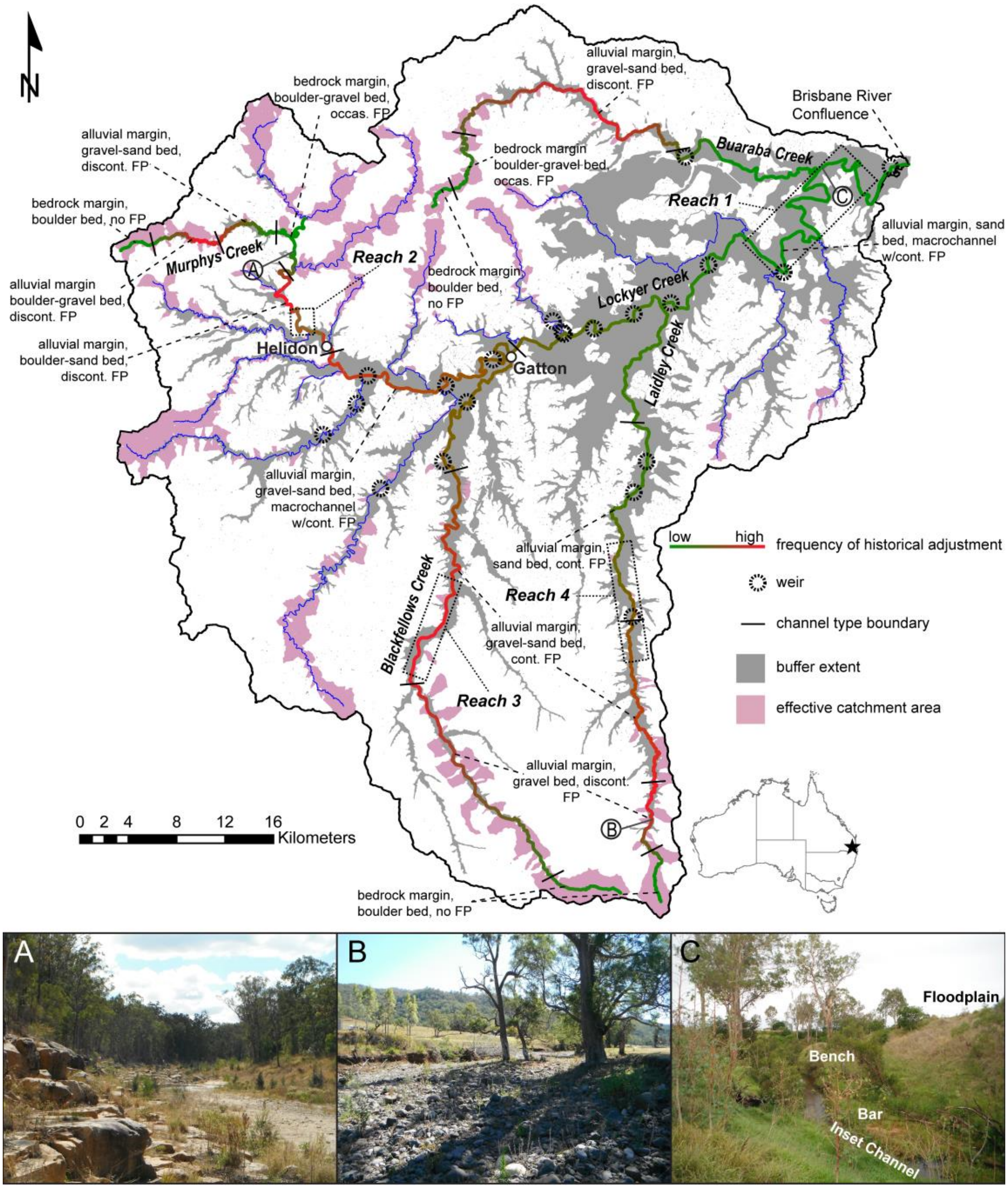


Figure 1. Location of the Lockyer Valley, the four study reaches, and the spatial distributions of sediment buffers, barriers, ECAs (for coarse sediment fractions), and channel types. A) Bedrock channel in upper Lockyer Creek. B) Wide, shallow, gravel-bed reach in upper Laidley Creek. C) Macrochannel along lower Lockyer Creek. Pictures taken by Peyton Lisenby and Kirstie Fryirs. Note that: cont. – continuous, discont. – discontinuous, occas. – occasional, FP – floodplain.

Characterizing River Sensitivity and Sediment Connectivity

The sensitivity and connectivity data presented in this study are from recent research in the Lockyer Valley. River sensitivity was characterized by comparing sequential sets of historical maps, aerial photos, and satellite images of Lockyer Creek (Fryirs et al., 2015) and the three largest tributaries – Buaraba, Laidley, and Blackfellows Creek (Lisenby and Fryirs, 2016). These image comparisons were used to identify the range of historical geomorphic channel adjustments from the late 1800s to 2011/2013. The distribution of these adjustments was then compared to channel geometry/morphology and valley morphometry to identify key controls on the location and form of channel adjustment. Please see Fryirs et al. (2015) and Lisenby and Fryirs (2016) for complete methodological descriptions and for definitions of individual forms of adjustment. In this paper we have summarized this historical information to produce a gradient of adjustment frequency for any given reach (Figure 1) with red representing reaches that have experienced frequent and numerous historical adjustment and green representing reaches that have experienced limited historical adjustment.

Coarse sediment connectivity was characterized through an analysis of sediment (dis)connectivity. This analysis compared catchment-scale spatial distributions of sediment buffers (geomorphic features that impede sediment transfer to channels, e.g. floodplains, terraces, alluvial fans, trapped tributary fills), barriers (features that block sediment transport along channels, e.g. weirs), tributary effective catchment areas (ECAs, i.e. the area of a tributary catchment with a slope steeper than 2° that could contribute coarse, bedload sediment to a channel), and patterns of downstream sediment fining (i.e. sedimentary links) along Lockyer Creek (Lisenby and Fryirs, 2017b, a). The spatial distribution of sediment buffers, barriers, and ECAs are given in Figure 1. Please refer to Lisenby and Fryirs (2017b, 2017a) for the complete methodology and definitions of sediment buffers, barriers, and ECAs (cf. Fryirs et al., 2007).

Climatic and Geomorphic Context of the Lockyer Valley

Historical Context

Alluvial valley bottoms in the SEQ region, and the Lockyer Valley in particular, have experienced several phases of aggradation and incision, resulting in terrace development and river channel avulsions over the past ~ 200,000 years (Daley et al., 2017; Croke et al., under review). In the past 2000 years, the Lockyer Valley has experienced several periods of high flood activity, with major peaks occurring in the mid-1900s, late 1800s, 1730, 1300, and 550 A.D. (Croke et al., 2016; Lam et al., 2016). Ages from preserved bench sediments and the adjacent floodplain along Lockyer Creek indicate that a large event around the 1700s stripped the channel to bedrock (Croke et al, 2016a). Bench sediments have accumulated and been reworked by subsequent floods over decadal to centennial time scales (Thompson et al., 2016a).

Agricultural development in the Lockyer Valley began in the early-mid 1800s with widespread development of farmland irrigation and weir construction occurring through the early and mid-1900s (Tew, 1979; Lockyer Catchment Centre, 2000). Since European settlement, two-thirds of native vegetation has been cleared for agricultural purposes (Apan et al., 2002).

Current Geomorphic Setting – River Sensitivity and Sediment Connectivity

In the upper portion of the Lockyer Valley, near Helidon, the Lockyer Creek trunk stream channel takes on a macrochannel (compound, channel-in-channel) morphology with banks comprised of cohesive, fine-grained alluvium (Croke et al., 2013; Croke et al., 2014; Thompson et al., 2016a). This morphology persists downstream along the lower reaches of

Lockyer Creek and in the lower reaches of the major tributary channels (e.g. Tenthill, Laidley, and Buaraba Creeks) (Figure 1) (Croke et al., 2014; Fryirs et al., 2015). In the far upper reaches of Lockyer Creek and in the middle-upper reaches of the tributaries, the channels have a simpler channel form with a single-channel morphology that ranges from bedrock-boulder, stepped-bed to wide, shallow, gravel-bed to narrower, slot-shaped channels (Figure 1). Overall, the lower Lockyer Creek macrochannel has been relatively resilient to geomorphic adjustment since European colonization (Fryirs et al., 2015). In contrast, portions of the tributary channels, and the upper parts of the trunk stream, have experienced various forms of geomorphic adjustment since European settlement and are considered more geomorphically sensitive than lower Lockyer Creek (Lisenby and Fryirs, 2016). Tributary reaches where geomorphic adjustment has repeatedly occurred over the past ~120 years tend to be located upstream of the influence of the Lockyer Creek fine-grained floodplain buffer, in the middle to upper portions of the tributary catchments (Figure 1). The forms of geomorphic adjustment experienced include reorganization of geomorphic units within the channel, channel expansion, channel avulsion, channel stripping, and bend adjustments (Lisenby and Fryirs, 2016).

Overall, the Lockyer Valley has a high degree of coarse sediment disconnectivity (Lisenby and Fryirs, 2017b, a). Extensive sediment buffers (predominantly floodplains) and numerous weirs (barriers) inhibit coarse sediment transference to, and along, the Lockyer Creek trunk stream (Lisenby and Fryirs, 2017b). This is compounded by the lower Lockyer Valley acting as a significant sediment sink (Thompson et al., 2016b). The bed material texture of Lockyer Creek is controlled by the presence and placement of key sedimentologically significant (connected) tributaries, overbank floodwater expansion or contraction zones, and weirs (Croke et al., 2013; Lisenby and Fryirs, 2017b).

Given this range of geomorphic conditions across the catchment, four representative study reaches have been identified with which to explore the possibilities of future channel adjustment using river sensitivity and sediment connectivity datasets: Reach 1 – lower Lockyer Creek, which is resilient and disconnected; Reach 2 – upper Lockyer Creek, which is resilient and connected; Reach 3 – mid-upper Blackfellows Creek, which is sensitive and connected; and Reach 4 – mid-Laidley Creek, which is sensitive and disconnected (Figure 1).

Adjustments along lower Lockyer Creek (Reach 1) are dominantly characterized by reorganization of the assemblage of instream geomorphic units, particularly sediment bars and benches (Fryirs et al., 2015), with numerous wet bank mass failures (WBMFs) occurring when the banks have high antecedent moisture (Figure 2) (Grove et al., 2013; Thompson et al., 2013). The resilient lower Lockyer channel is sedimentologically disconnected from the upper catchment, with numerous weirs located along the trunk and tributary channels, and is distally located to ECAs (Figure 1).

Upper Lockyer Creek (Reach 2) also has a resilient channel margin, but is located more proximally to ECAs and has experienced more numerous in-channel adjustments than the lower Lockyer. These adjustments primarily consist of periods of sediment erosion, vegetation stripping, and re-aggradation corresponding with the timing of large flood events (Thompson and Croke, 2013; Fryirs et al., 2015) (Figures 1, 2).

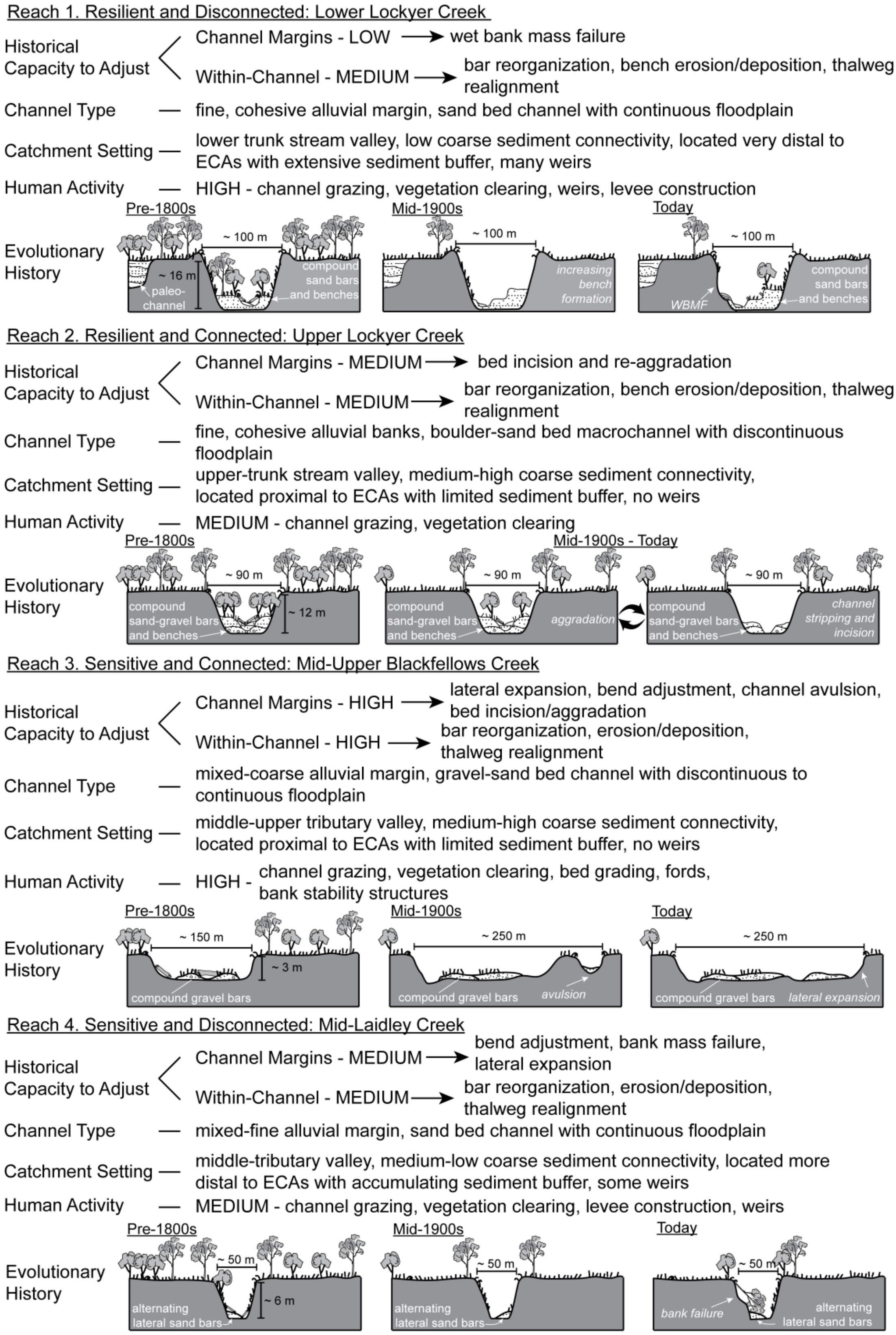


Figure 2. River sensitivity, sediment connectivity, and evolutionary history characteristics for the four study reaches.

The mid-upper portions of several tributaries (e.g. Buaraba, Laidley, and Blackfellows Creek) in the Lockyer Valley have experienced numerous, but localized, geomorphic adjustments since European colonization (Fryirs et al., 2015; Lisenby and Fryirs, 2016) (Figures 1, 2). In mid-upper Blackfellows Creek (Reach 3), these geomorphic adjustments are primarily lateral expansion, thalweg shifts, bend adjustments, and channel avulsions (Olley et al., 2010; Lisenby and Fryirs, 2016) (Figures 1, 2). These sensitive channel reaches typically have high width-to-depth ratios, coarser-grained (gravel) bed material, and are proximally located to ECAs (Figures 1, 3).

Downstream, many of the tributary channels display decreasing sediment connectivity in their middle reaches, as sediment buffers and barriers accumulate (Lisenby and Fryirs, 2017b). These reach locations (e.g. mid-Laidley Creek, Reach 4) have displayed fewer historical geomorphic channel adjustments than the mid-upper tributary reaches, but more than the lower tributary and lower Lockyer reaches. These mid-tributary reaches are still sensitive to future channel adjustment given their mixed, fine alluvial margins and somewhat proximal location to ECAs (Figures 1, 2, 3).

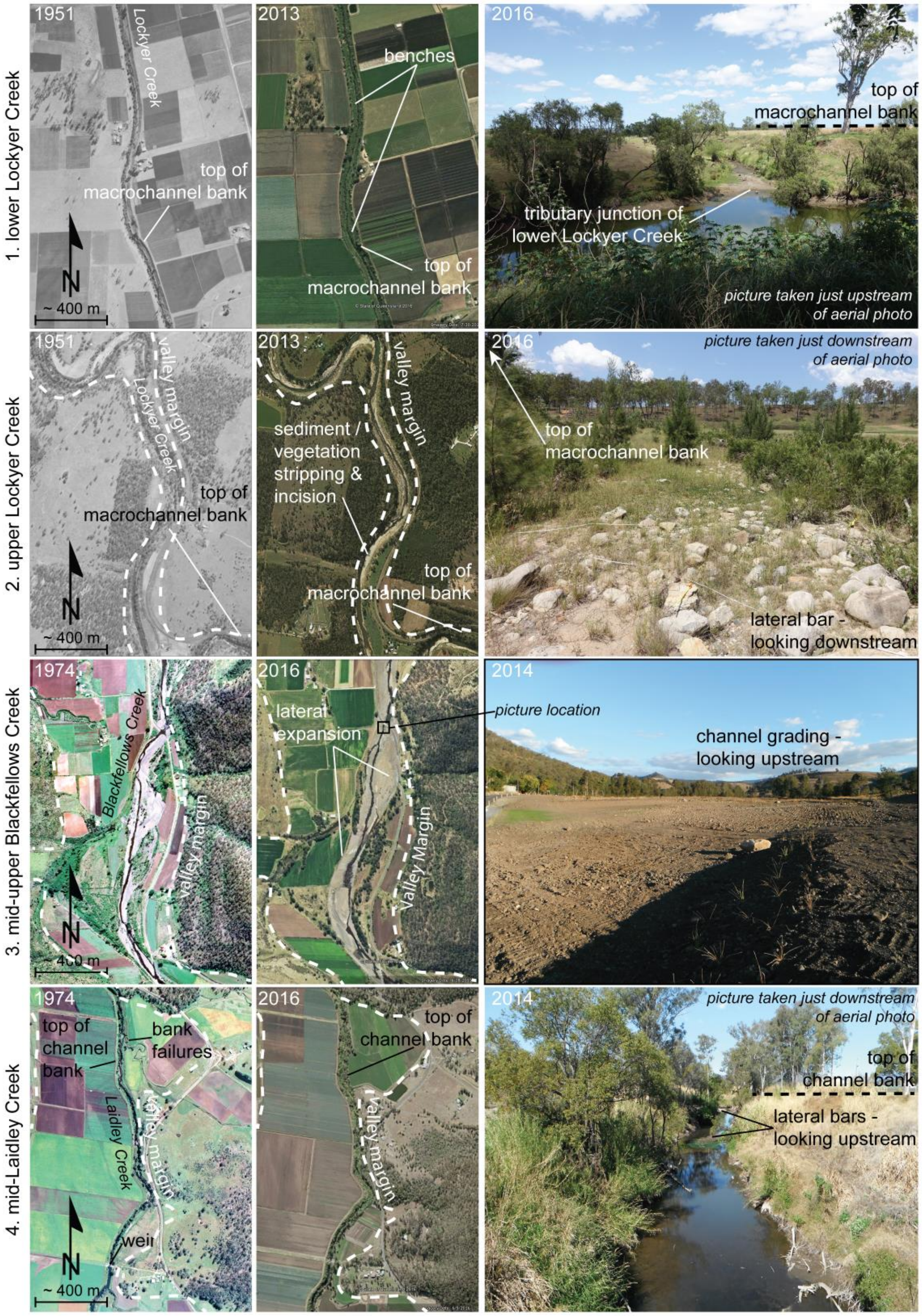


Figure 3. Aerial and in-channel pictures depicting geomorphic units and channel adjustments for each study reach. Aerial and satellite imagery gathered from DNRM and the Queensland Globe plugin for Google Earth, Queensland State Government. In-channel pictures taken by Peyton Lisenby.

Forecasting Future Geomorphic River Response

Future Climate Projections

Rainfall has decreased in SEQ over the past 50 years (Nicholls, 2006; Taschetto and England, 2009; Timbal et al., 2010), and a decreasing rainfall trend is projected to continue in the future (Reisinger et al., 2014). Future climate models project with near certainty that SEQ will experience a warming trend over the next 50 to 100 years (IPCC, 2014; Reisinger et al., 2014) and suggest that warming will be coupled with longer periods of drought (Hennessy et al., 2008) and more extreme precipitation events (Alexander and Arblaster, 2009). Coupling higher temperatures with longer and/or more severe droughts will generate more intense drying conditions that are projected to reduce rainfall runoff and soil moisture content in SEQ (Cai et al., 2009; Chiew et al., 2009; Chiew et al., 2011). Despite reduced total rainfall projections, intense rainfall extremes are projected to increase so that this region may be subjected to long periods of warmer, drier droughts punctuated by more intense rainfall events (Alexander and Arblaster, 2009; Reisinger et al., 2014). Correspondingly, landuse in rural and agricultural areas is also projected to change in order to adapt to climate changes (Bi and Parton, 2008; Settele et al., 2014). Most notably, a warmer and drier climate that reduces soil moisture will generate an increased demand for irrigation water (Cai et al., 2009). Given that landuse in the Lockyer Valley is dominated by agricultural practices, landuse changes in response to climate change can be expected for this region.

Possibilities for Future Channel Adjustment

Our current characterizations of river sensitivity and sediment connectivity are a good starting point for forecasting future possibilities of channel adjustment under different management and climate scenarios in the next 50 to 100 years. We have depicted three scenarios to demonstrate how we expect the geomorphic structure of our study reaches to adjust in the future given a mix of flooding scenarios and management conditions. Scenario 1 is depicted for a future catastrophic flood and status quo management. Scenario 2 is depicted for future catastrophic flooding and expanded riparian vegetation management practice, and Scenario 3 is depicted for interim periods of only small-moderate floods and status quo management (Figure 4). These scenarios are sets of depictions for how we expect geomorphic processes and landforms to adjust along different reaches in the catchment, given what we know about the past trajectory of adjustment, the impacts of recent flooding, and the position of each reach in the catchment. These scenarios represent a baseline set of expectations that could be tested with geomorphic and hydrological modeling to both assess the applicability and likelihood of modelled results and to generate more specific quantitative outcomes, as part of risk assessment and planning in river management practice (Church, 2003; Wilcock et al., 2003).

For the resilient and disconnected lower Lockyer reach (Reach 1), the erosion/deposition and reorganization of instream sediment bars and benches is expected to continue (Figure 4, Reach 1). If no new management strategies are implemented (Scenario 1), future extreme flooding may induce more severe bench sediment stripping, similar to what has been documented upstream along Lockyer Creek (Croke et al., 2013) and has occurred recurrently in the past (Croke et al., 2016). This may be accompanied by sediment transfer through this reach to the junction with the Brisbane River. WBMFs are expected to continue provided that periodic rainfall events create very wet antecedent conditions prior to flooding (Grove et al., 2013).

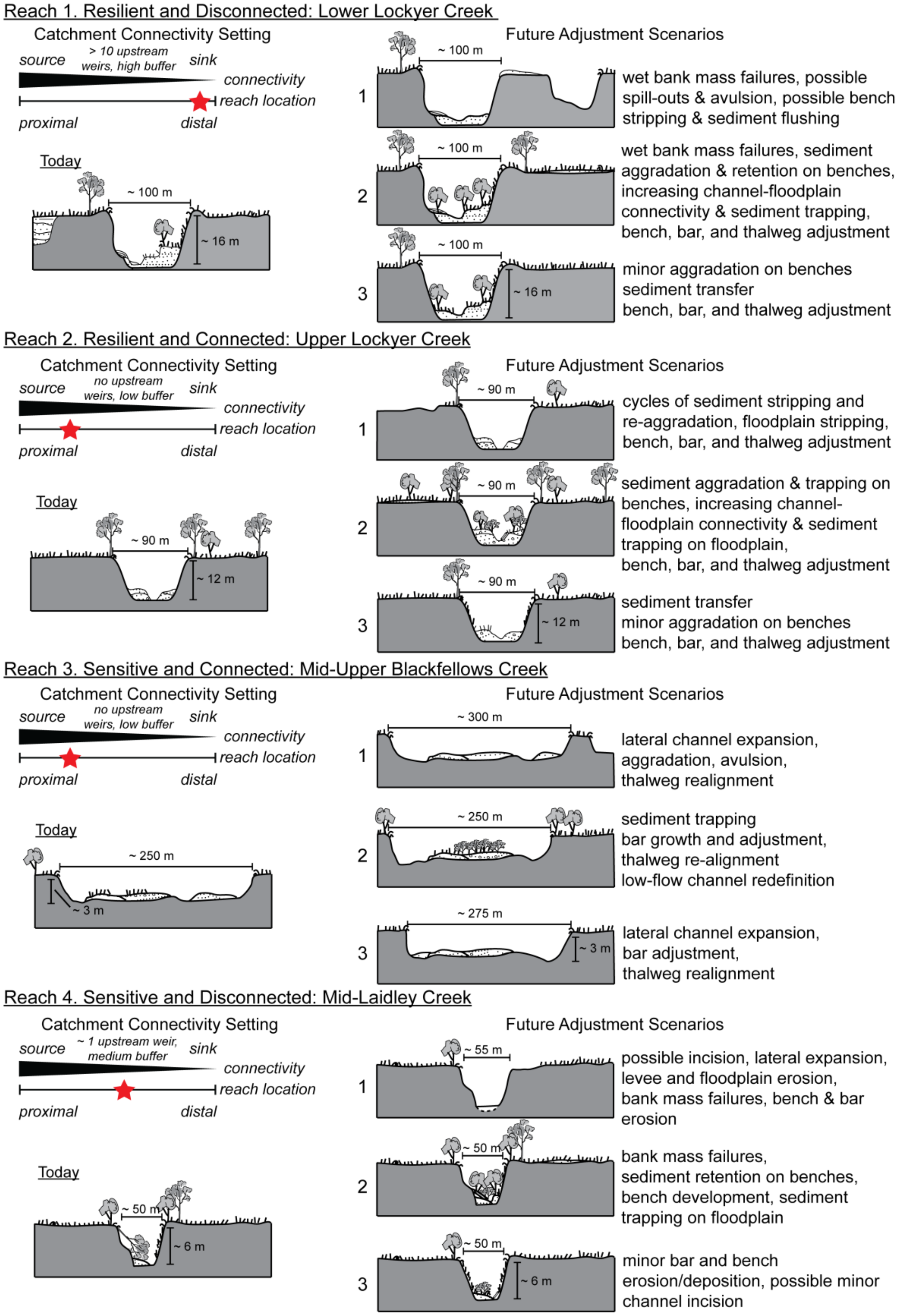


Figure 4. Future adjustment possibilities and catchment connectivity setting for each study reach. Future Adjustment Scenarios are 1 – future catastrophic flooding (equiv. to 2011 flood) and status quo management practices; 2 - future catastrophic flooding and expanded riparian vegetation management practices; 3 – time period with small-moderate flooding and status quo management.

Flood breaches of the natural and anthropogenically modified channel levees will result in future spill-out zones and sediment splays on the floodplain. The height of the levees and the ‘perched’ nature of Lockyer Creek above its floodplain indicate that a channel avulsion is possible during a future severe flood (cf. Thompson et al., 2014). Future riparian management approaches could establish more native vegetation within and along the macrochannel (Croke et al., 2017) (Scenario 2). More densely vegetated channel banks, benches, and levees would reduce the potential for sediment stripping and induce more in-channel sediment aggradation and retention on benches. This may also promote further channel-floodplain connectivity and sediment trapping on the floodplain. WBMFs are still possible. A series of small-moderate flows and a lack of extreme flood events (Scenario 3) could see a slower accumulation of vegetation and sediment on benches. Flows confined within the macrochannel are the most effective at transferring sediment downstream (Thompson et al., 2015). The reorganization of in-stream geomorphic units, such as benches and bars, is likely (Lisenby and Fryirs, 2016).

In the upper Lockyer (Figure 4, Reach 2), the modern cycle of sediment stripping and re-aggradation within the macrochannel, and the corresponding adjustment of the channel thalweg, benches, and bars, will likely continue with future extreme flood events (Scenario 1). More severe flooding may also induce some floodplain erosion along sparsely vegetated alluvial corridors in the partly confined valleys of the upper Lockyer (cf. Nanson, 1986; Warner, 1995; Fryirs et al., 2009; Thompson and Croke, 2013). Again, future riparian management approaches could establish more native vegetation within and along the macrochannel (Scenario 2) (Croke et al., 2017). This would curtail the stripping of sediment during floods and promote sediment aggradation and trapping on benches. Bench and bar development and reorganization may yield a higher degree of floodwater connectivity between the channel and floodplain pockets which may result in future sediment trapping on the floodplain. With small to moderate flooding (Scenario 3) confined within the macrochannel, sediment will likely be transferred through the reach (Thompson et al., 2016a; Thompson et al., 2016b) (Figure 4, Scenario 3). In the absence of catastrophic flooding, native vegetation may become better established, enhancing sediment retention on benches; however, within-channel flows will continue to reorganize channel benches and bars and realign the channel thalweg.

The mid-upper Blackfellows Creek reach (Figure 4, Reach 3) will continue to display a range of channel margin adjustments into the future. Continued anthropogenic channel grading (the smoothing of channel margins using heavy equipment) and vegetation clearing may increase the erodability of channel margins. These practices can promote further lateral channel expansion, bend adjustment, thalweg re-alignment, and channel avulsion during large flood events (Scenario 1). For example, after the 2011 flood this reach was graded, cleared of vegetation, and banks were stabilized near road crossings. Subsequently, a similar flood in 2013 generated large channel avulsions (Ivezich and Hardie, 2014) (Figure 5).

Reach 3 is well-connected and proximally located to potential sediment sources upstream, so channel aggradation is likely if sediment supply increases. Channel bed aggradation may induce further channel avulsions (Jones and Schumm, 1999; Phillips, 2011). Riparian management approaches could promote leaving this reach alone (Scenario 2). Sensitive and well connected reaches have a greater ability to respond to flood events (Downs and Gregory, 2004; Lisenby et al., 2017), and future riparian management will not prevent the occurrence of future channel adjustment. However, leaving the channel alone will promote the establishment of riparian vegetation, sediment bar growth, and sediment trapping which may curtail excessive channel margin erosion and avulsion. Importantly, the anthropogenic stabilization of channel margins will not guarantee reductions in channel adjustment. Sensitive reaches like mid-upper Blackfellows Creek can adjust around in-channel works, similar to the avulsions in this reach in 2013. Without future catastrophic flooding (Scenario

3), this reach may still experience lateral expansion, and bar and thalweg adjustment as a result of in-channel flows.

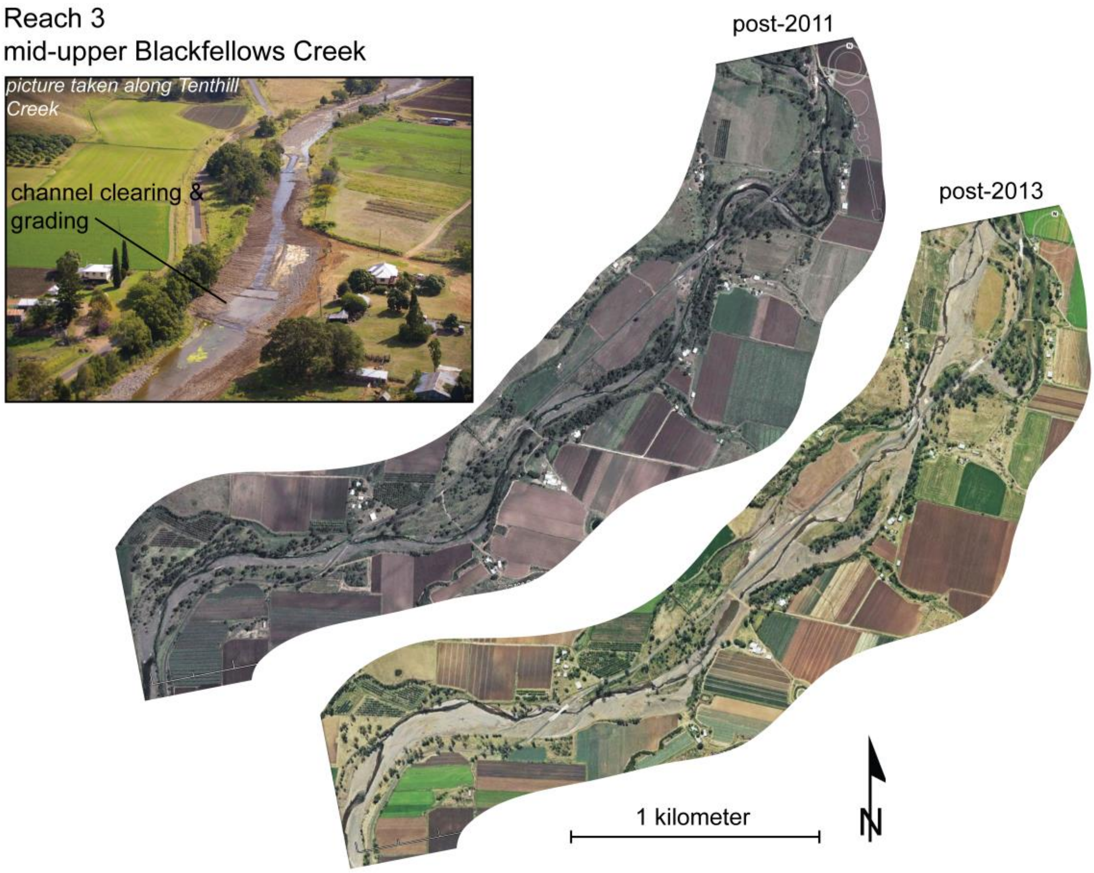


Figure 5. Adjustment of mid-upper Blackfellows Creek following the 2011 and 2013 flood events. Satellite imagery gathered from Queensland Globe plugin for Google Earth, Queensland State Government. Photo of channel grading courtesy of Jon Olley.

The mid-Laidley reach (Figure 4, Reach 4) is sensitive and sedimentologically disconnected. This puts it at risk of channel incision and expansion during future catastrophic flooding (Scenario 1), given its mixed alluvial margins and disconnection from upstream sediment. Bank mass failures may continue in this reach, and anthropogenic levee construction may trigger levee breaches during large flood events, inducing localized bank and floodplain gullying (Walker et al., 2014). Future riparian management could establish more riparian vegetation (Scenario 2) (Walker et al., 2014). This would promote bench and bar development, maximizing sediment retention within this reach. Channel aggradation coupled with increased riparian vegetation could promote more overbank floodwater and sediment connectivity between the channel and the floodplain. This may result in sediment trapping on the floodplain. In the absence of future catastrophic flooding (Scenario 3), this reach may experience minor bar and bench aggradation if vegetation is allowed to become established. Future vegetation clearing may result in minor bench stripping and channel incision from within-channel flows.

Discussion

Analyzing River Sensitivity and Sediment Connectivity

Analyses of river sensitivity and sediment connectivity have been used here to develop a range of future geomorphic scenarios for a range of rivers in the Lockyer Valley. The methods we have used to characterize river sensitivity and sediment connectivity are one of many possible approaches to this type of analysis (Fryirs, 2013, 2016). Elsewhere, other researchers have analyzed river sensitivity through quantifying thresholds of change (e.g. sediment entrainment, bank failure) and assessing these for a range of disturbances to determine, for a given magnitude of event on a landscape in a given geomorphic condition, whether geomorphic change or metamorphosis is likely (Schumm, 1969; Thomas and Allison, 1993; Downs and Gregory, 1995). Sensitivity can also be characterized through analyzing the response and recovery time of fluvial landforms post-disturbance (Richards, 2004; Phillips and Van Dyke, 2016). For example, Harvey (2007) documented the post-flood, geomorphic recovery of two river reaches in adjacent catchments to characterize each channel's intrinsic stability and define their sensitivity to environmental disturbance. Importantly, Harvey (2007) found that the sediment coupling between the channels and hillslopes played a dominant role in differentiating the sensitivity of the two reaches.

Approaches to sediment connectivity analysis have been made through formulating sediment budgets, sedimentary link analyses, sediment delivery ratios and routing models, and sediment tracing/fingerprinting (Meade, 1982; Trimble, 1983; Walling, 1983; Benda and Dunne, 1997; Rice, 1998, 1999; Brown et al., 2009; Wichmann et al., 2009; Fryirs, 2013; Fryirs and Gore, 2013, 2014). Indeed, the use of sediment budget and fingerprinting models have already been incorporated into river management applications (Fryirs and Brierley, 2001; Brierley and Fryirs, 2005; Owens, 2005; Walling and Collins, 2008; Rinaldi et al., 2009; Hoffmann et al., 2010; Mukundan et al., 2012). The identification of sediment source, transfer, and sink zones can also be incorporated into more sophisticated models that characterize sediment connectivity within catchments to identify potential locations of channel change, or the sources of sediment to enhance river recovery (Fryirs and Brierley, 2001; Gasparini et al., 2004; Czuba and Foufoula-Georgiou, 2015; Schmitt et al., 2016).

Management Applications

The concepts of, and approaches to analyzing, river sensitivity and sediment connectivity can be applied to any catchment. Even simple approaches to applying these concepts can provide a first stage consideration of the possibilities and expectations of river adjustment in the future, and where this may (or may not) occur (Houben et al., 2009; Surian et al., 2009; Lisenby and Fryirs, 2017a). This can be used to set scenarios (or moving targets) (Brierley and Fryirs, 2016) for consideration in river management planning and risk assessment. Generating these types of scenarios is a key step in determining if any proactive management strategies are required, what management strategies may be effective and where to prioritize management actions or set goals (Palmer et al., 2008; Kondolf, 2011; Fryirs and Brierley, 2016). For example, knowing that the lower Lockyer Creek macrochannel (Reach 1) is not migrating across its floodplain, but has the potential to produce new spill-out-zones or to avulse (Thompson et al., 2014; Croke et al., 2017), is a key geomorphic insight for consideration in future river management planning and risk assessment. Similarly, knowing that Reaches 2 and 3 along upper Lockyer Creek and Blackfellows Creek respectively are sedimentologically connected reaches and are proximally located to ECAs, allows us to forecast that these reaches may be more likely to aggrade as sediment is sourced from upstream (cf. Ivezich and Hardie, 2014). Conversely, sensitive but disconnected reaches like Reach 4 along Laidley Creek may have a higher risk of channel incision and expansion (cf. Walker et al., 2014).

These analyses demonstrate that scenario-building exercises must be framed within a 'reach-in-catchment' perspective. Such a perspective considers the capacity of the river to adjust and its position in the catchment (Brierley and Fryirs, 2005; Owens, 2005; Wohl et al., 2005; Kondolf et al., 2006; Brierley and Fryirs, 2009). We have used sediment (dis)connectivity analyses (characterization of sediment buffers, barriers, and ECAs) to place reaches with different levels of geomorphic sensitivity (Figure 2) in a catchment-scale context (Figures 1, 2, 4). A reach-in-catchment perspective can be more broadly used to identify the possible reach impacts that may result from upstream disturbances and what downstream impacts may propagate from reach adjustments. This type of information is critical for river managers to identify potential impacts of hillslope and channel disturbances (e.g. landuse change, hard-engineering channel interventions) and to prioritize river management actions based on a geomorphic assessment of those risks (e.g. Hart et al., 2002; Chin and Gregory, 2005; Alcantara and Goudie, 2010). Additionally, catchment-scale characterizations of river sensitivity and sediment connectivity can aid river managers in identifying the natural variability of river channels and designing treatments that work with the natural range of channel behavior (Gilvear, 1999; Brierley and Fryirs, 2005; Fryirs and Brierley, 2009; Brierley et al., 2012; Grabowski et al., 2014; Brierley and Fryirs, 2016). In this way, river management strategies are better equipped to give the river channel the necessary 'freedom space' with which to adjust (e.g. spill-out-zones in Reach 1; lateral expansion and avulsion in

Reach 3) (Piégay et al., 2005; Wohl et al., 2005; Brierley and Fryirs, 2009; Biron et al., 2014; Buffin-Bélanger et al., 2015). This 'freedom space' is set by the expected capacity for channel adjustment of various channels and is highly variable for any given river type at any given position in a catchment (Brierley and Fryirs, 2005; Piégay et al., 2005; Wohl et al., 2005; Brierley and Fryirs, 2009; Biron et al., 2014; Buffin-Bélanger et al., 2015).

Likewise, river sensitivity and sediment connectivity datasets can help determine the potential for future river recovery or restoration in different channel reaches (Fryirs and Brierley, 2000; Brierley and Fryirs, 2005; Fryirs, 2015; Fryirs and Brierley, 2016). In many cases, rivers that become degraded (i.e. are in a state of poor geomorphic, hydrologic, and ecological condition due to anthropogenic disturbance) suffer from either a lack or overabundance of sediment (Fryirs and Brierley, 2001; Bernhardt and Palmer, 2007; Fryirs et al., 2009). Understanding the sediment connectivity for any given reach position within a catchment is crucial to determining how, or if, a river is capable of recovery (Fryirs and Brierley, 2016). Additionally, rehabilitation goals that seek to stabilize channel margins or reconfigure morphology cannot be realistically evaluated without considering the inherent and expected adjustment capability (sensitivity) of different morphologic units (e.g. banks, bed, benches, bars) (Wohl et al., 2005; Brierley and Fryirs, 2009; Fryirs and Brierley, 2009; Bernhardt and Palmer, 2011; Wohl et al., 2015).

Although the forecasted scenarios of future channel adjustment presented here are not computationally modelled outputs, the river sensitivity and sediment connectivity datasets used to generate our forecasts can provide a baseline set of expectations for comparing with modelled outputs that predict landform sensitivity, connectivity, and change. Landform sensitivity and connectivity describe the intrinsic boundary conditions of processes operating within landscapes (Brunsden, 1993; Fryirs, 2013). Geomorphic characterizations of sensitivity and connectivity not only constrain what types of landforms changes are possible, but also establish how the sensitivity and connectivity of the landscape itself may change in the future as extrinsic boundary conditions change (e.g. climate change). The integration of forecasting scenarios that are based on field or remotely-sensed data with those that are generated from computational models is critical to both initializing and evaluating model predictions (Hoey et al., 2003). Computational models that seek to predict landform change require geomorphic datasets as inputs, to set initial and boundary conditions, and to provide comparisons with model outputs (Kelsey et al., 1987; Church, 2003).

Impacts of Future Climate Change on Geomorphic River Adjustment

River channels in the Lockyer Valley have historically adjusted to a hydrologically variable climate characterized by spasmodic floods events and interim drought periods (Thompson et al., 2016a). Additionally, the Lockyer Valley is a highly disconnected catchment and exhibits resilient channel types set into highly buffered valley settings (Thompson et al., 2016b; Lisenby and Fryirs, 2017b). Channel reaches that are sensitive are relatively localized in the catchment and already exhibit a wide range of geomorphic responses that are expected to continue into the future (Lisenby and Fryirs, 2016). Importantly, the future prediction of drier conditions may have significant implications for riparian ecosystems, particularly groundwater and surface water (e.g. pool) dependent ecosystems (Arthington et al., 2000; Palmer et al., 2008; Whitehead et al., 2009; Sheldon et al., 2010; Death et al., 2015).

In other world regions, future climate models project climatic conditions that may have more substantial impacts on fluvial systems (Aldous et al., 2011; IPCC, 2014; Death et al., 2015). The extent to which climate change alters the broader boundary conditions of river sensitivity and sediment connectivity in any catchment, including the Lockyer Valley, will exert significant control on the possibilities for future channel responses to disturbance events (Brunsden and Thornes, 1979; Gregory, 2006; Lane et al., 2008). Changing climate patterns can influence the degree of sediment connectivity along channel networks by altering the residence time of sediment storage features (e.g. buffers) through changing vegetation coverage, extreme flooding events, and breaching thresholds of slope-channel coupling (Lane et al., 2008; Fryirs, 2013; Hoffmann, 2015). Correspondingly, reach sensitivity to adjustment may change in response to varying sediment loads, runoff characteristics, and changing thresholds of erosion/deposition for fluvial landforms (Tucker and Slingerland, 1997; Death et al., 2015; Fryirs, 2016). As climate patterns change, it will be crucial to monitor variations in river sensitivity and sediment connectivity and continually build these observations into scenarios of channel adjustment so that geomorphic risk assessments can be undertaken and proactive river management plans developed and implemented (Wilby et al., 2006; Hoffmann et al., 2010; Wohl et al., 2015).

Conclusions

As scientific and management interests progressively intersect (Wohl et al., 2015), it is critical that the utility of geomorphic concepts is not constrained to scientific pursuits (Newson, 2002). The geomorphic concepts of river sensitivity and sediment connectivity can be used as conceptual tools by managers to identify and understand past river behavior and to constrain forecasts of future channel response (Fryirs, 2016). This type of work is just beginning in the Lockyer Valley. The river sensitivity and connectivity interpretations presented here can be used as a first step towards providing the contextual geomorphic understanding necessary to establish expectations of geomorphic adjustment, formulate catchment-scale management strategies, prioritize management interventions, and model future channel behavior. Catchment-scale geomorphic characterizations of river sensitivity and sediment connectivity facilitate the development of catchment action planning that works with, not against, the natural behavior of riverine environments.

Acknowledgements

Funding was provided by an Australian Research Council Linkage grant (LP120200093). Peyton Lisenby is supported by a Macquarie University International Postgraduate Research Scholarship (MQIPRS) and Higher Degree Research fund. Historical aerial imagery is available for purchase from the Department of Natural Resources and Mines (DNRM), Queensland State Government. Queensland Globe plugin for Google Earth is available at https://data.qld.gov.au/dataset/queensland-globe.

References

Alcantara, I., Goudie, A.S., 2010. Geomorphological Hazards and Disaster Prevention. Cambridge University Press, Cambridge.

Aldous, A., Fitzsimons, J., Richter, B., Bach, L., 2011. Droughts, floods and freshwater ecosystems: evaluating climate change impacts and developing adaptation strategies. Marine and Freshwater Research 62, 223-231, doi: https://doi.org/10.1071/MF09285.

Alexander, L.V., Arblaster, J.M., 2009. Assessing trends in observed and modelled climate extremes over Australia in relation to future projections. International Journal of Climatology 29, 417-435, doi: 10.1002/joc.1730.

Apan, A.A., Raine, S.R., Paterson, M.S., 2002. Mapping and analysis of changes in the riparian landscape structure of the Lockyer Valley catchment, Queensland, Australia. Landscape and Urban Planning 59, 43-57, doi: http://dx.doi.org/10.1016/S0169-2046(01)00246-8.

Arthington, A., Kennard, M.J., Mackay, S.J., Zalucki, J., Brizga, S., Choy, S., McCosker, R., Ruffini, J., 2000. Environmental flow requirements of the Brisbane River downstream from Wivenhoe Dam. Southeast Queensland Water Coorporation Ltd Center for Catchment and In-stream Research Brisbane, Queensland.

Australian Bureau of Statistics, 2012. Value of Agricultural Commodities Produced, Australia, 2010-2011. http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/7503.02010-11?OpenDocument#Publications.

Benda, L., Dunne, T., 1997. Stochastic forcing of sediment routing and storage in channel networks. Water Resources Research 33, 2865-2880.

Bernhardt, E.S., Palmer, M.A., 2007. Restoring streams in an urbanizing world. Freshwater Biology 52, 738-751, doi: 10.1111/j.1365-2427.2006.01718.x.

Bernhardt, E.S., Palmer, M.A., 2011. River restoration: The fuzzy logic of repairing reaches to reverse catchment scale degradation. Ecological Applications 21, 1926-1931, doi: 10.1890/10-1574.1.

Bi, P., Parton, K.A., 2008. Effect of climate change on Australian rural and remote regions: What do we know and what do we need to know? Australian Journal of Rural Health 16, 2-4, doi: 10.1111/j.1440-1584.2007.00945.x.

Biron, P.M., Buffin-Bélanger, T., Larocque, M., Choné, G., Cloutier, C.-A., Ouellet, M.-A., Demers, S., Olsen, T., Desjarlais, C., Eyquem, J., 2014. Freedom space for rivers: A sustainable management approach to enhance river resilience. Environmental Management 54, 1056-1073, doi: 10.1007/s00267-014-0366-z.

Boulton, A., Piégay, H., Sanders, M.D., 2008. Turbulence and train wrecks: Using knowledge strategies to enhance the application of integrative river science in effective river management, in: Brierley, G.J., Fryirs, K. (Eds.), River futures: an integrative scientific approach to river repair. Island Press, Washington D.C., pp. 28-39.

Bracken, L.J., Turnbull, L., Wainwright, J., Bogaart, P., 2015. Sediment connectivity: A framework for understanding sediment transfer at multiple scales. Earth Surface Processes and Landforms 40, 177-188, doi: 10.1002/esp.3635.

Brierley, G., Fryirs, K., 2005. Geomorphology and River Management: Applications of the River Styles Framework. Blackwell Publishing, Victoria, Australia.

Brierley, G., Fryirs, K., Jain, V., 2006. Landscape connectivity: The geographic basis of geomorphic applications. Area 38, 165-174, doi: 10.1111/j.1475-4762.2006.00671.x.

Brierley, G., Fryirs, K., 2009. Don't fight the site: Three geomorphic considerations in catchment-scale river rehabilitation planning. Environmental Management 43, 1201-1218, doi: 10.1007/s00267-008-9266-4.

Brierley, G., Fryirs, K., Cullum, C., Tadaki, M., Huang, H.Q., Blue, B., 2013. Reading the landscape: Integrating the theory and practice of geomorphology to develop place-based understandings of river systems. Progress in Physical Geography 37, 601-621, doi: 10.1177/0309133313490007.

Brierley, G., Fryirs, K., 2016. The use of evolutionary trajectories to guide 'moving targets' in the management of river futures. River Research and Applications 32, 823-835, doi: 10.1002/rra.2930.

Brierley, G.J., Fryirs, K.A., Hobbs, R.J., 2012. River Futures: An Integrative Scientific Approach to River Repair. Island Press, Washington D.C.

Brown, A.G., Carey, C., Erkens, G., Fuchs, M., Hoffmann, T., Macaire, J.-J., Moldenhauer, K.-M., Walling, D.E., 2009. From sedimentary records to sediment budgets: Multiple approaches to catchment sediment flux. Geomorphology 108, 35-47, doi: http://dx.doi.org/10.1016/j.geomorph.2008.01.021.

Brunsden, D., Thornes, J.B., 1979. Landscape sensitivity and change. Transactions of the Institute of British Geographers 4, 463-484, doi: 10.2307/622210.

Brunsden, D., 1993. Barriers to geomorphological change, in: Thomas, D.S.G., Allison, R. (Eds.), Landscape Sensitivity. John Wiley & Sons, New York, pp. 7-29.

Brunsden, D., 2001. A critical assessment of the sensitivity concept in geomorphology. CATENA 42, 99-123, doi: http://dx.doi.org/10.1016/S0341-8162(00)00134-X.

Buffin-Bélanger, T., Biron, P.M., Larocque, M., Demers, S., Olsen, T., Choné, G., Ouellet, M.-A., Cloutier, C.-A., Desjarlais, C., Eyquem, J., 2015. Freedom space for rivers: An economically viable river management concept in a changing climate. Geomorphology 251, 137-148, doi: http://dx.doi.org/10.1016/j.geomorph.2015.05.013.

Burkham, D.E., 1981. Uncertainties resulting from changes in river form. Journal of the Hydraulics Division 107, 593-610.

Cai, W., Cowan, T., Briggs, P., Raupach, M., 2009. Rising temperature depletes soil moisture and exacerbates severe drought conditions across southeast Australia. Geophysical Research Letters 36, L21709, doi: 10.1029/2009GL040334.

Cai, W., van Rensch, P., 2012. The 2011 southeast Queensland extreme summer rainfall: A confirmation of a negative Pacific Decadal Oscillation phase? Geophysical Research Letters 39, L08702, doi: 10.1029/2011GL050820.

Chiew, F.H.S., Teng, J., Vaze, J., Post, D.A., Perraud, J.M., Kirono, D.G.C., Viney, N.R., 2009. Estimating climate change impact on runoff across southeast Australia: Method, results, and implications of the modeling method. Water Resources Research 45, W10414, doi: 10.1029/2008WR007338.

Chiew, F.H.S., Young, W.J., Cai, W., Teng, J., 2011. Current drought and future hydroclimate projections in southeast Australia and implications for water resources management. Stoch Environ Res Risk Assess 25, 601-612, doi: 10.1007/s00477-010-0424-x.

Chin, A., Gregory, K.J., 2005. Managing urban river channel adjustments. Geomorphology 69, 28-45, doi: http://dx.doi.org/10.1016/j.geomorph.2004.10.009.

Church, M., 2003. What is a Geomorphological Prediction?, in: Wilcock, P.R., Iverson, R.M. (Eds.), Prediction in Geomorphology. American Geophysical Union, Washington, DC, pp. 183-194.

Clark, M.J., 2002. Dealing with uncertainty: Adaptive approaches to sustainable river management. Aquatic Conservation: Marine and Freshwater Ecosystems 12, 347-363, doi: 10.1002/aqc.531.

Croke, J., Fryirs, K., Thompson, C., 2013. Channel–floodplain connectivity during an extreme flood event: Implications for sediment erosion, deposition, and delivery. Earth Surface Processes and Landforms 38, 1444-1456, doi: 10.1002/esp.3430.

Croke, J., Reinfelds, I., Thompson, C., Roper, E., 2014. Macrochannels and their significance for flood-risk minimisation: Examples from southeast Queensland and New South Wales, Australia. Stoch Environ Res Risk Assess 28, 99-112, doi: 10.1007/s00477-013-0722-1.

Croke, J., Thompson, C., Denham, R., Haines, H., Sharma, A., Pietsch, T., 2016. Reconstructing a millennial-scale record of flooding in a single valley setting: The 2011 flood-affected Lockyer Valley, south-east Queensland, Australia. Journal of Quaternary Science 31, 936-952, doi: 10.1002/jqs.2919.

Croke, J., Thompson, C., Fryirs, K., 2017. Prioritising the placement of riparian vegetation to reduce flood risk and end-of-catchment sediment yields: Important considerations in hydrologically-variable regions. Journal of Environmental Management 190, 9-19, doi: http://dx.doi.org/10.1016/j.jenvman.2016.12.046.

Croke, J., Thompson, C., Larsen, A., Sharma, A., under review. The nature and timing of fluvial response to changing base-level and climate over the last glacial-interglacial cycle in sub-tropical Australia. Quaternary Science Reviews.

Czuba, J.A., Foufoula-Georgiou, E., 2015. Dynamic connectivity in a fluvial network for identifying hotspots of geomorphic change. Water Resources Research 51, 1401-1421, doi: 10.1002/2014WR016139.

Daley, J., Croke, J., Thompson, C., Cohen, T., Macklin, M., Sharma, A., 2017. Late Quaternary channel and floodplain formation in a partly confined subtropical river, eastern Australia. Journal of Quaternary Science, doi: 10.1002/jqs.2930.

Death, R.G., Fuller, I.C., Macklin, M.G., 2015. Resetting the river template: The potential for climate-related extreme floods to transform river geomorphology and ecology. Freshwater Biology 60, 2477-2496, doi: 10.1111/fwb.12639.

Downs, P.W., 1995. Estimating the probability of river channel adjustment. Earth Surface Processes and Landforms 20, 687-705, doi: 10.1002/esp.3290200710.

Downs, P.W., Gregory, K.J., 1995. Approaches to river channel sensitivity. The Professional Geographer 47, 168-175, doi: 10.1111/j.0033-0124.1995.168_v.x.

Downs, P.W., Gregory, K., 2004. River Channel Management: Towards Sustainable Catchment Hydrosystems. Oxford University Press, New York.

Fryirs, K., Brierley, G., 2000. A geomorphic approach to the identification of river recovery potential. Physical Geography 21, 244-277, doi: 10.1080/02723646.2000.10642708.

Fryirs, K., Brierley, G.J., 2001. Variability in sediment delivery and storage along river courses in Bega catchment, NSW, Australia: implications for geomorphic river recovery. Geomorphology 38, 237-265, doi: http://dx.doi.org/10.1016/S0169-555X(00)00093-3.

Fryirs, K., Brierley, G.J., Preston, N.J., Kasai, M., 2007. Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. CATENA 70, 49-67, doi: http://dx.doi.org/10.1016/j.catena.2006.07.007.

Fryirs, K., Brierley, G.J., 2009. Naturalness and place in river rehabilitation. Ecology and Society 14, http://www.ecologyandsociety.org/vol14/iss1/art20/.

Fryirs, K., Spink, A., Brierley, G., 2009. Post-European settlement response gradients of river sensitivity and recovery across the upper Hunter catchment, Australia. Earth Surface Processes and Landforms 34, 897-918, doi: 10.1002/esp.1771.

Fryirs, K., 2013. (Dis)Connectivity in catchment sediment cascades: A fresh look at the sediment delivery problem. Earth Surface Processes and Landforms 38, 30-46, doi: 10.1002/esp.3242.

Fryirs, K., Gore, D.B., 2013. Sediment tracing in the upper Hunter catchment using elemental and mineralogical compositions: Implications for catchment-scale suspended sediment (dis)connectivity and management. Geomorphology 193, 112-121, doi: http://dx.doi.org/10.1016/j.geomorph.2013.04.010.

Fryirs, K., Gore, D.B., 2014. Geochemical insights to the formation of "sedimentary buffers": Considering the role of tributary–trunk stream interactions on catchment-scale sediment flux and drainage network dynamics. Geomorphology 219, 1-9, doi: http://dx.doi.org/10.1016/j.geomorph.2014.04.035.

Fryirs, K., 2015. Developing and using geomorphic condition assessments for river rehabilitation planning, implementation and monitoring. Wiley Interdisciplinary Reviews: Water, 649-667, doi: 10.1002/wat2.1100.

Fryirs, K., Lisenby, P.E., Croke, J., 2015. Morphological and historical resilience to catastrophic flooding: The case of Lockyer Creek, SE Queensland, Australia. Geomorphology 241, 55-71, doi: 10.1016/j.geomorph.2015.04.008.

Fryirs, K., 2016. River sensitivity: A lost foundation concept in fluvial geomorphology. Earth Surface Processes and Landforms 42, 55-70, doi: 10.1002/esp.3940.

Fryirs, K.A., Brierley, G.J., 2016. Assessing the geomorphic recovery potential of rivers: Forecasting future trajectories of adjustment for use in management. Wiley Interdisciplinary Reviews: Water 3, 727-748, doi: 10.1002/wat2.1158.

Gasparini, N.M., Tucker, G.E., Bras, R.L., 2004. Network-scale dynamics of grain-size sorting: Implications for downstream fining, stream-profile concavity, and drainage basin morphology. Earth Surface Processes and Landforms 29, 401-421, doi: 10.1002/esp.1031.

Gilvear, D., Black, A., 1999. Flood magnitude and embankment failure frequency relationships on the rivers Tay and Earn, Scotland: implications of climate change. Hydrological Sciences Journal 44, 345-362.

Gilvear, D.J., 1999. Fluvial geomorphology and river engineering: Future roles utilizing a fluvial hydrosystems framework. Geomorphology 31, 229-245, doi: http://dx.doi.org/10.1016/S0169-555X(99)00086-0.

Grabowski, R.C., Surian, N., Gurnell, A.M., 2014. Characterizing geomorphological change to support sustainable river restoration and management. Wiley Interdisciplinary Reviews: Water 1, 483-512, doi: 10.1002/wat2.1037.

Gregory, K.J., 2006. The human role in changing river channels. Geomorphology 79, 172-191, doi: http://dx.doi.org/10.1016/j.geomorph.2006.06.018.

Gregory, K.J., Benito, G., Downs, P.W., 2008. Applying fluvial geomorphology to river channel management: Background for progress towards a palaeohydrology protocol. Geomorphology 98, 153-172, doi: http://dx.doi.org/10.1016/j.geomorph.2007.02.031.

Grove, J.R., Croke, J., Thompson, C., 2013. Quantifying different riverbank erosion processes during an extreme flood event. Earth Surface Processes and Landforms 38, 1393-1406, doi: 10.1002/esp.3386.

Gurnell, A.M., Rinaldi, M., Belletti, B., Bizzi, S., Blamauer, B., Braca, G., Buijse, A.D., Bussettini, M., Camenen, B., Comiti, F., Demarchi, L., García de Jalón, D., González del Tánago, M., Grabowski, R.C., Gunn, I.D.M., Habersack, H., Hendriks, D., Henshaw, A.J., Klösch, M., Lastoria, B., Latapie, A., Marcinkowski, P., Martínez-Fernández, V., Mosselman, E., Mountford, J.O., Nardi, L., Okruszko, T., O'Hare, M.T., Palma, M., Percopo, C., Surian, N., van de Bund, W., Weissteiner, C., Ziliani, L., 2016. A multi-scale hierarchical framework for developing understanding of river behaviour to support river management. Aquatic Sciences 78, 1-16, doi: 10.1007/s00027-015-0424-5.

Hart, D.D., Johnson, T.E., Bushaw-Newton, K.L., Horwitz, R.J., Bednarek, A.T., Charles, D.F., Kreeger, D.A., Velinsky, D.J., 2002. Dam removal: Challenges and opportunities for ecological research and river restoration. BioScience 52, 669-682, doi: 10.1641/0006-3568(2002)052[0669:DRCAOF]2.0.CO;2.

Harvey, A.M., 2007. Differential recovery from the effects of a 100-year storm: Significance of long-term hillslope–channel coupling; Howgill Fells, northwest England. Geomorphology 84, 192-208, doi: http://dx.doi.org/10.1016/j.geomorph.2006.03.009.

Hennessy, K., Fawcett, R., Kirono, D., Mpelasoka, F., Jones, D., Bathols, J., Whetton, P., Stafford Smith, M., Howden, M., Mitchell, C., 2008. An assessment of the impact of climate change on the nature and frequency of exceptional climatic events, Canberra: Bureau of Meteorology and CSIRO. Australian Bureau of Meteorology and CSIRO, Melbourne, Vic, p. 33.

Hillman, M., Brierley, G., 2008. Restoring uncertainty: Translating science into management practice, in: Brierley, G.J., Fryirs, K. (Eds.), River futures: An integrative scientific approach to river repair. Island Press, Washington D.C., pp. 257-272.

Hoey, T.B., Bishop, P., Ferguson, R.I., 2003. Testing Numerical Models in Geomorphology: How can we Ensure Critical Use of Model Predictions?, in: Wilcock, P.R., Iverson, R.M. (Eds.), Prediction in Geomorphology. American Geophysical Union, Washington, DC, pp. 241-256.

Hoffmann, T., Thorndycraft, V.R., Brown, A.G., Coulthard, T.J., Damnati, B., Kale, V.S., Middelkoop, H., Notebaert, B., Walling, D.E., 2010. Human impact on fluvial regimes and sediment flux during the Holocene: Review and future research agenda. Global and Planetary Change 72, 87-98, doi: http://dx.doi.org/10.1016/j.gloplacha.2010.04.008.

Hoffmann, T., 2015. Sediment residence time and connectivity in non-equilibrium and transient geomorphic systems. Earth-Science Reviews 150, 609-627, doi: http://dx.doi.org/10.1016/j.earscirev.2015.07.008.

Hooke, J.M., 2003a. Coarse sediment connectivity in river channel systems: A conceptual framework and methodology. Geomorphology 56, 79-94, doi: http://dx.doi.org/10.1016/S0169-555X(03)00047-3.

Hooke, R.L., 2003b. Predictive Modeling in Geomorphology: An Oxymoron?, in: Wilcock, P.R., Iverson, R.M. (Eds.), Prediction in Geomorphology. American Geophysical Union, Washington, DC, pp. 51-61.

Houben, P., Wunderlich, J., Schrott, L., 2009. Climate and long-term human impact on sediment fluxes in watershed systems. Geomorphology 108, 1-7, doi: http://dx.doi.org/10.1016/j.geomorph.2008.08.018.

IPCC, 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 688.

Ivezich, M., Hardie, R., 2014. Repeat channel change in Blackfellows Creek, Lockyer Valley, South East Queensland, in: Vietz, G., Rutherford, I.D., Hughes, R. (Eds.). Proceedings of the 7th Australian Stream Management Conference, Townsville, Queensland, pp. 81-88.

Jones, L.S., Schumm, S.A., 1999. Causes of Avulsion: An overview, in: Smith, N.D., Rogers, J. (Eds.), Fluvial Sedimentology VI. Blackwell Science, United Kingdom, pp. 171-178.

Jordan, P.W., 2011. Hydrological Advice to Commission of Inquiry Regarding 2010/11 Queensland Floods. Queensland Floods Commission of Inquiry, p. 83.

Kelsey, H.M., Lamberson, R., Madej, M.A., 1987. Stochastic model for the long-term transport of stored sediment in a river channel. Water Resources Research 23, 1738-1750, doi: 10.1029/WR023i009p01738.

Kondolf, G.M., Boulton, A.J., O'Daniel, S., Poole, G.C., Rahel, F.J., Stanley, E.H., Wohl, E., Bång, A., Carlstrom, J., Cristoni, C., 2006. Process-based ecological river restoration: Visualizing three-dimensional connectivity and dynamic vectors to recover lost linkages. Ecology and Society 11, http://www.ecologyandsociety.org/vol11/iss2/art5/.

Kondolf, G.M., 2011. Setting Goals in River Restoration: When and Where Can the River "Heal Itself"?, Stream Restoration in Dynamic Fluvial Systems. American Geophysical Union, pp. 29-43.

Lam, D., Thompson, C., Croke, J., 2016. Improving at-site flood frequency analysis with additional spatial information: a probabilistic regional envelope curve approach. Stoch Environ Res Risk Assess, 1-21, doi: 10.1007/s00477-016-1303-x.

Lancaster, S.T., Grant, G.E., 2003. You Want Me to Predict What?, in: Wilcock, P.R., Iverson, R.M. (Eds.), Prediction in Geomorphology. American Geophysical Union, Washington, DC, pp. 41-50.

Lane, S.N., Reid, S.C., Tayefi, V., Yu, D., Hardy, R.J., 2008. Reconceptualising coarse sediment delivery problems in rivers as catchment-scale and diffuse. Geomorphology 98, 227-249, doi: 10.1016/j.geomorph.2006.12.028.

Lane, S.N., Bakker, M., Gabbud, C., Micheletti, N., Saugy, J.-N., 2017. Sediment export, transient landscape response and catchment-scale connectivity following rapid climate warming and Alpine glacier recession. Geomorphology 277, 210-227, doi: http://dx.doi.org/10.1016/j.geomorph.2016.02.015.

Lisenby, P.E., Fryirs, K.A., 2016. Catchment- and reach-scale controls on the distribution and expectation of geomorphic channel adjustment. Water Resources Research 52, 3408-3427, doi: 10.1002/2015WR017747.

Lisenby, P.E., Croke, J., Fryirs, K., 2017. Geomorphic effectiveness: A linear concept in a non-linear world. Earth Surface Processes and Landforms, doi: 10.1002/esp.4096.

Lisenby, P.E., Fryirs, K., 2017a. 'Out with the old?' Why coarse spatial datasets are still useful for catchment-scale investigations of sediment (dis)connectivity. Earth Surface Processes and Landforms, doi: DOI: 10.1002/esp.4131.

Lisenby, P.E., Fryirs, K., 2017b. Sedimentologically significant tributaries: Catchment-scale controls on sediment (dis)connectivity in the Lockyer Valley, SEQ, Australia. Earth Surface Processes and Landforms, doi: 10.1002/esp.4130.

Lockyer Catchment Centre, 2000. Living in the lockyer : A landholders guide to land, water, wildlife and vegetation management in the Lockyer Catchment and surrounds. Lockyer Catchment Centre, Forest Hill, Qld.

Meade, R.H., 1982. Sources, sinks, and storage of river sediment in the Atlantic Drainage of the United States. The Journal of Geology 90, 235-252, http://www.jstor.org/stable/30066396.

Montgomery, D.R., 2008. Dreams of natural streams. Science 319, 291-292, doi: 10.1126/science.1153480.

Mukundan, R., Walling, D.E., Gellis, A.C., Slattery, M.C., Radcliffe, D.E., 2012. Sediment source fingerprinting: Transforming from a research tool to a management tool. JAWRA Journal of the American Water Resources Association 48, 1241-1257, doi: 10.1111/j.1752-1688.2012.00685.x.

Nanson, G.C., 1986. Episodes of vertical accretion and catastrophic stripping: A model of disequilibrium flood-plain development. Geological Society of America Bulletin 97, 1467-1475, doi: 10.1130/0016-7606(1986)97<1467:eovaac>2.0.co;2.

Newson, M.D., 2002. Geomorphological concepts and tools for sustainable river ecosystem management. Aquatic Conservation: Marine and Freshwater Ecosystems 12, 365-379, doi: 10.1002/aqc.532.

Nicholls, N., 2006. Detecting and attributing Australian climate change: A review. Australian Meteorological Magazine 55, 199-211.

Olley, J.M., Ward, D., Pietsch, T., McMahon, J., Laceby, P., Saxton, N.A., Rose, C.A., Pantus, F., Bengtsson, F., 2010. Phase 2c Report : Rehabilitation Priorities Lockyer Focal Area. Australian Rivers Institute, Brisbane, Queensland, p. 62.

Owens, P., 2005. Conceptual models and budgets for sediment management at the river basin scale Journal of Soils and Sediments 5, 201-212, doi: 10.1065/jss2005.05.133.

Palmer, M.A., Reidy Liermann, C.A., Nilsson, C., Flörke, M., Alcamo, J., Lake, P.S., Bond, N., 2008. Climate change and the world's river basins: Anticipating management options. Frontiers in Ecology and the Environment 6, 81-89, doi: 10.1890/060148.

Phillips, J.D., 2003. Sources of nonlinearity and complexity in geomorphic systems. Progress in Physical Geography 27, 1-23, doi: 10.1191/0309133303pp340ra.

Phillips, J.D., 2011. Universal and local controls of avulsions in southeast Texas Rivers. Geomorphology 130, 17-28, doi: 10.1016/j.geomorph.2010.10.001.

Phillips, J.D., Van Dyke, C., 2016. Principles of geomorphic disturbance and recovery in response to storms. Earth Surface Processes and Landforms 41, 971-979, doi: 10.1002/esp.3912.

Piégay, H., Darby, S.E., Mosselman, E., Surian, N., 2005. A review of techniques available for delimiting the erodible river corridor: A sustainable approach to managing bank erosion. River Research and Applications 21, 773-789, doi: 10.1002/rra.881.

Pizzuto, J.I.M., 2002. Effects of dam removal on river form and process. BioScience 52, 683-691, doi: 10.1641/0006-3568(2002)052[0683:EODROR]2.0.CO;2.

Reisinger, A., Kitching, R.L., Chiew, F., Hughes, L., Newton, P.C.D., Schuster, S.S., Tait, A., Whetton, P., 2014. Australasia, in: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1371-1438.

Rice, S., 1998. Which tributaries disrupt downstream fining along gravel-bed rivers? Geomorphology 22, 39-56, doi: http://dx.doi.org/10.1016/S0169-555X(97)00052-4.

Rice, S., 1999. The nature and controls on downstream fining within sedimentary links. Journal of Sedimentary Research 69, 32-39.

Richards, K.S., 2004. Rivers: Form and Process in Alluvial Channels. Blackburn Press.

Rinaldi, M., Simoncini, C., Piégay, H., 2009. Scientific design strategy for promoting sustainable sediment management: the case of the Magra River (Central-Northern Italy). River Research and Applications 25, 607-625, doi: 10.1002/rra.1243.

Rustomji, P., Bennett, N., Chiew, F., 2009. Flood variability east of Australia's Great Dividing Range. Journal of Hydrology 374, 196-208, doi: http://dx.doi.org/10.1016/j.jhydrol.2009.06.017.

Schmitt, R.J.P., Bizzi, S., Castelletti, A., 2016. Tracking multiple sediment cascades at the river network scale identifies controls and emerging patterns of sediment connectivity. Water Resources Research 52, 3941-3965, doi: 10.1002/2015WR018097.

Schumm, S.A., 1969. River metamorphosis, Journal of the hydraulics division, American Society of Civil Engineers, pp. 255-273.

Schumm, S.A., 1973. Geomorphic thresholds and complex response of drainage systems. Fluvial Geomorphology 6, 69-85.

Schumm, S.A., 1983. River morphology and behavior: Problems of extrapolation, in: Elliott, C.M. (Ed.), River Meandering, Proceedings of the Conference Rivers '83. American Society of Civil Engineers, New York, pp. 16-29.

SEQWater, 2013. Report on the operation of Somerset Dam and Wivenhoe Dam 2-April-2013, Queensland, p. 129.

Settele, J., Scholes, R., Betts, R., Bunn, S.E., Leadley, P., Nepstad, D., Overpeck, J.T., Taboada, M.A., 2014. Terrestrial and inland water systems, in: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 271-359.

Sheldon, F., Bunn, S.E., Hughes, J.M., Arthington, A.H., Balcombe, S.R., Fellows, C.S., 2010. Ecological roles and threats to aquatic refugia in arid landscapes: Dryland river waterholes. Marine and Freshwater Research 61, 885-895.

Surian, N., Ziliani, L., Comiti, F., Lenzi, M.A., Mao, L., 2009. Channel adjustments and alteration of sediment fluxes in gravel-bed rivers of North-Eastern Italy: Potentials and limitations for channel recovery. River Research and Applications 25, 551-567, doi: 10.1002/rra.1231.

Taschetto, A.S., England, M.H., 2009. An analysis of late twentieth century trends in Australian rainfall. International Journal of Climatology 29, 791-807, doi: 10.1002/joc.1736.

Tew, A.M., 1979. History of the Gatton Shire in the Lockyer Valley. Gatton Shire Council, Gatton, Australia.

Thomas, D.S.G., Allison, R.J., 1993. Landscape sensitivity. Wiley, Chichester.

Thomas, M.F., 2001. Landscape sensitivity in time and space — an introduction. CATENA 42, 83-98, doi: http://dx.doi.org/10.1016/S0341-8162(00)00133-8.

Thompson, C., Croke, J., 2013. Geomorphic effects, flood power, and channel competence of a catastrophic flood in confined and unconfined reaches of the upper Lockyer Valley, southeast Queensland, Australia. Geomorphology 197, 156-169, doi: 10.1016/j.geomorph.2013.05.006.

Thompson, C., Croke, J., Grove, J., Khanal, G., 2013. Spatio-temporal changes in river bank mass failures in the Lockyer Valley, Queensland, Australia. Geomorphology 191, 129-141, doi: 10.1016/j.geomorph.2013.03.010.

Thompson, C., Croke, J., Dent, C., 2014. Potential impacts of levee in construction in the Lockyer Valley, 7th Australian Stream Management Conference, pp. 109-115.

Thompson, C., Croke, J., Fryirs, K., Grove, J.R., 2016a. A channel evolution model for subtropical macrochannel systems. CATENA 139, 199-213, doi: http://dx.doi.org/10.1016/j.catena.2015.12.012.

Thompson, C., Fryirs, K., Croke, J., 2016b. The disconnected sediment conveyor belt: Patterns of longitudinal and lateral erosion and deposition during a catastrophic flood in the Lockyer Valley, southeast Queensland, Australia. River Research and Applications 32, 540-551, doi: 10.1002/rra.2897.

Timbal, B., Arblaster, J., Braganza, K., Fernandez, E., Hendon, H., Murphy, B., Raupach, M., Rakich, C., Smith, I., Whan, K., 2010. Understanding the anthropogenic nature of the observed rainfall decline across South Eastern Australia. Centre for Australian Weather and Climate Research, Melbourne, Vic, p. 180.

Trimble, S.W., 1983. A sediment budget for Coon Creek basin in the Driftless Area, Wisconsin, 1853-1977. American Journal of Science 283, 454-474.

Tucker, G.E., Slingerland, R., 1997. Drainage basin responses to climate change. Water Resources Research 33, 2031-2047, doi: 10.1029/97WR00409.

van den Honert, R.C., McAneney, J., 2011. The 2011 Brisbane Floods: causes, impacts and implications. Water 3, 1149-1173, http://www.mdpi.com/2073-4441/3/4/1149.

van Dijk, A.I.J.M., Beck, H.E., Crosbie, R.S., de Jeu, R.A.M., Liu, Y.Y., Podger, G.M., Timbal, B., Viney, N.R., 2013. The Millennium Drought in southeast Australia (2001–2009): Natural and human causes and implications for water resources, ecosystems, economy, and society. Water Resources Research 49, 1040-1057, doi: 10.1002/wrcr.20123.

Walker, J., Zavadil, E., Hardie, R., Ghajarnia, H., 2014. Increasing the resilience of horticultural and agricultural systems to future flood events in the highly productive Laidley Creek valley, Floodplain Management Association National Conference, Deniliquin, NSW, pp. 1-19.

Walling, D.E., 1983. The sediment delivery problem. Journal of Hydrology 65, 209-237, doi: http://dx.doi.org/10.1016/0022-1694(83)90217-2.

Walling, D.E., Collins, A.L., 2008. The catchment sediment budget as a management tool. Environmental Science & Policy 11, 136-143, doi: http://dx.doi.org/10.1016/j.envsci.2007.10.004.

Warner, R.F., 1995. Predicting and managing channel change in Southeast Australia. CATENA 25, 403-418, doi: http://dx.doi.org/10.1016/0341-8162(95)00020-S.

Whitehead, P.G., Wilby, R.L., Battarbee, R.W., Kernan, M., Wade, A.J., 2009. A review of the potential impacts of climate change on surface water quality. Hydrological Sciences Journal 54, 101-123, doi: 10.1623/hysj.54.1.101.

Wichmann, V., Heckmann, T., Haas, F., Becht, M., 2009. A new modelling approach to delineate the spatial extent of alpine sediment cascades. Geomorphology 111, 70-78, doi: http://dx.doi.org/10.1016/j.geomorph.2008.04.028.

Wilby, R.L., Orr, H.G., Hedger, M., Forrow, D., Blackmore, M., 2006. Risks posed by climate change to the delivery of Water Framework Directive objectives in the UK. Environment International 32, 1043-1055, doi: http://dx.doi.org/10.1016/j.envint.2006.06.017.

Wilcock, P.R., Iverson, R.M., 2003. Prediction in Geomorphology, in: Wilcock, P.R., Iverson, R.M. (Eds.), Prediction in Geomorphology. American Geophysical Union, Washington, DC, pp. 3-11.

Wilcock, P.R., Schmidt, J.C., Wolman, M.G., Dietrich, W.E., Dominick, D., Doyle, M.W., Grant, G.E., Iverson, R.M., Montgomery, D.R., Pierson, T.C., Schilling, S.P., Wilson, R.C., 2003. When Models Meet Managers: Examples from Geomorphology, in: Wilcock, P.R., Iverson, R.M. (Eds.), Prediction in Geomorphology. American Geophysical Union, Washington, DC, pp. 27-40.

Wohl, E., Angermeier, P.L., Bledsoe, B., Kondolf, G.M., MacDonnell, L., Merritt, D.M., Palmer, M.A., Poff, N.L., Tarboton, D., 2005. River restoration. Water Resources Research 41, doi: 10.1029/2005WR003985.

Wohl, E., 2011. What should these rivers look like? Historical range of variability and human impacts in the Colorado Front Range, USA. Earth Surface Processes and Landforms 36, 1378-1390, doi: 10.1002/esp.2180.

Wohl, E., Lane, S.N., Wilcox, A.C., 2015. The science and practice of river restoration. Water Resources Research 51, 5974-5997, doi: 10.1002/2014WR016874.

Chapter 8

Discussion

8. Discussion

8.1. Thesis Synthesis

This thesis has examined controls on the variability of geomorphic response of river channels in the Lockyer Valley, SEQ. To facilitate this contribution, the thesis addresses 5 research aims (Figure 1) that help to isolate, evaluate, and categorize key geomorphic influences on river response. This discussion will first outline the contributions made by each chapter toward each thesis aim. These chapter contributions will then be integrated to expand the applicability of this work towards better conceptual understandings of geomorphic system behavior and the interplay of the individual geomorphic factors that affect geomorphic response in the Lockyer Valley. This thesis represents one component of a multistage research effort focused on the Lockyer Valley and southeastern Queensland. This work is funded by an Australian Research Council (ARC) 'Linkage' grant, with co-funding from state agency partners. As such, a key component of each research stage is to facilitate the conversion of scientific results into meaningful action strategies for river management in the Lockyer Valley. This requires that characterizations of geomorphic responses and controls on their spatial distribution and temporal occurrence are understood and fed directly into river management efforts in the Lockyer Valley. As part of a larger research effort, this discussion will reference the findings of other research stages to formulate a more complete and meaningful contribution to the geomorphic understanding of the Lockyer Valley.

Thesis Aims	Research Approach	Associated Chapters
1. Relate geomorphic controls on river response to the variability of geomorphic effectiveness for disturbance events	• Review the concept of 'Geomorphic Effectiveness' • Identify and discuss the influence of parallel geomorphic concepts • Introduce a conceptual model for future use of the 'Effectiveness' concept	Chapter 2
2. Characterize the variability of river sensitivity in the Lockyer Valley	• Analyze historical channel adjustments in tributary and trunk stream channels • Relate distributions of channel adjustment to variability in channel form, basin morphometry, and stream power	Chapters 3 & 4
3. Characterize the variability of sediment (dis)connectivity in the Lockyer Valley	• Analyze the distribution of sediment buffers and effective catchment area in all tributary catchments • Relate sediment (dis)connectivity to distributions of sedimentary links along Lockyer Creek	Chapters 5 & 6
4. Evaluate catchment-to-reach scale controls on geomorphic response in river channels	• Use catchment-scale analyses of controls on river sensitivity and sediment (dis)connectivity to categorize reach-scale river response • Formulate typologies of geomorphic behavior for tributary catchments and channel reaches	Chapters 3, 4, 5, & 7
5. Utilize river sensitivity and sediment connectivity datasets to assess future river response in the Lockyer Valley	• Synthesize basic expectations of river response variability in the Lockyer Valley • Identify possibilities of future channel adjustment • Highlight the utility of river sensitivity and sediment connectivity data as tools for river managers to prioritize management actions	Chapter 7

Figure 1. Relationship between thesis aims, research approach and data chapters

Geomorphic responses represent an observable, physical adjustment within a catchment instigated by environmentally-forced disturbance events but ultimately controlled by a suite of geomorphic factors operating internally to the system. Thesis Aim #1 sought to identify the key geomorphic factors that dictate the variability in geomorphic river response which can be physically characterized in fluvial systems, including the Lockyer Valley. This aim was addressed through a review of the geomorphic effectiveness concept (Chapter 2). By examining the history of investigations that attempted to determine the geomorphic significance of disturbance events, this review identified geomorphic factors that account for substantial variability in geomorphic effectiveness between events. In particular, Chapter 2 emphasizes how the spatiotemporal variability of landform sensitivity (i.e. the ease with which landforms can adjust or change over time) (Brunsden and Thornes, 1979; Brunsden, 2001; Fryirs, 2016) and sediment connectivity (i.e. the ease with which sediment is transferred from a source to a sink and across geomorphic environments) (Walling, 1983; Harvey, 2002; Hooke, 2003; Fryirs, 2013; Bracken et al., 2015) can modulate the geomorphic responses of catchments to sequences of disturbance events over time (cf. Newson, 1980; Kochel, 1988; Jacobson et al., 1989; Emmett and Wolman, 2001; Sloan et al., 2001; Heritage et al., 2004). Correspondingly, landform sensitivity and sediment connectivity also act as key controls on both the ability of a geomorphic system to respond to disturbance events and the recovery of the system post-disturbance. Importantly, both landform sensitivity and sediment connectivity have developed into independent and very broad geomorphic concepts.

This thesis approached Aims #2 and #3 by characterizing river sensitivity and sediment connectivity for rivers in the Lockyer Valley. These concepts can be investigated across entire catchments using a variety of methods (Thomas and Allison, 1993; Fryirs and Brierley, 2001; Fryirs et al., 2007a; Fryirs et al., 2007b). Our characterization of river sensitivity (Aim #2) was undertaken through an analysis of historical geomorphic adjustments spanning more than 100 years along Lockyer Creek (Chapter 3) and in the three largest tributaries of the Lockyer Valley – Blackfellows, Laidley, and Buaraba Creek (Chapter 4). Our characterization of sediment connectivity (Aim #3) was undertaken by analyzing the distribution of sediment disconnecting features (buffers and barriers), effective catchment area (ECA), and patterns of downstream bed sediment fining (sedimentary links) within the Lockyer Valley (Chapters 5 and 6). Although river sensitivity and sediment connectivity are not the sole influences on geomorphic response, they can be related to other influential geomorphic concepts including thresholds (e.g. adjustment or sediment transport thresholds) (Schumm, 1973; Beven, 1981; Brunsden, 2001; Fryirs, 2016), geomorphic recovery (Wolman and Gerson, 1978; Phillips and Van Dyke, 2016) and self-organization (Phillips, 1999) (Chapter 2, Figure 2). Ultimately, all of these geomorphic concepts are related by their impact on geomorphic effectiveness, and more broadly, landscape denudation (Wolman and Miller, 1960; Wolman and Gerson, 1978). Therefore, this thesis fits into a hierarchal framework of geomorphic concepts (Figure 2) and represents a timely contribution to the geomorphology and earth science community, who are currently in the process of updating, expanding, and better defining the geomorphic concepts that describe the evolution of landscapes (e.g. Warke and McKinley, 2011a; Wohl and Rathburn, 2013; Parsons et al., 2015; Temme et al., 2016).

Characterizing river sensitivity and sediment connectivity allowed this investigation of geomorphic response to identify both catchment- and reach-scale controls on geomorphic adjustments and to recognize the influence of both allogenic (external) and autogenic (internal) catchment conditions (Aim # 4). This research provided a crucial set of foundations upon which 1st-order expectations of geomorphic behavior could be established and linked to management philosophies, which can be applied in different geomorphic environments and used to forecast the possibilities of future channel behavior in the Lockyer Valley (Aim #5, Chapter 7).

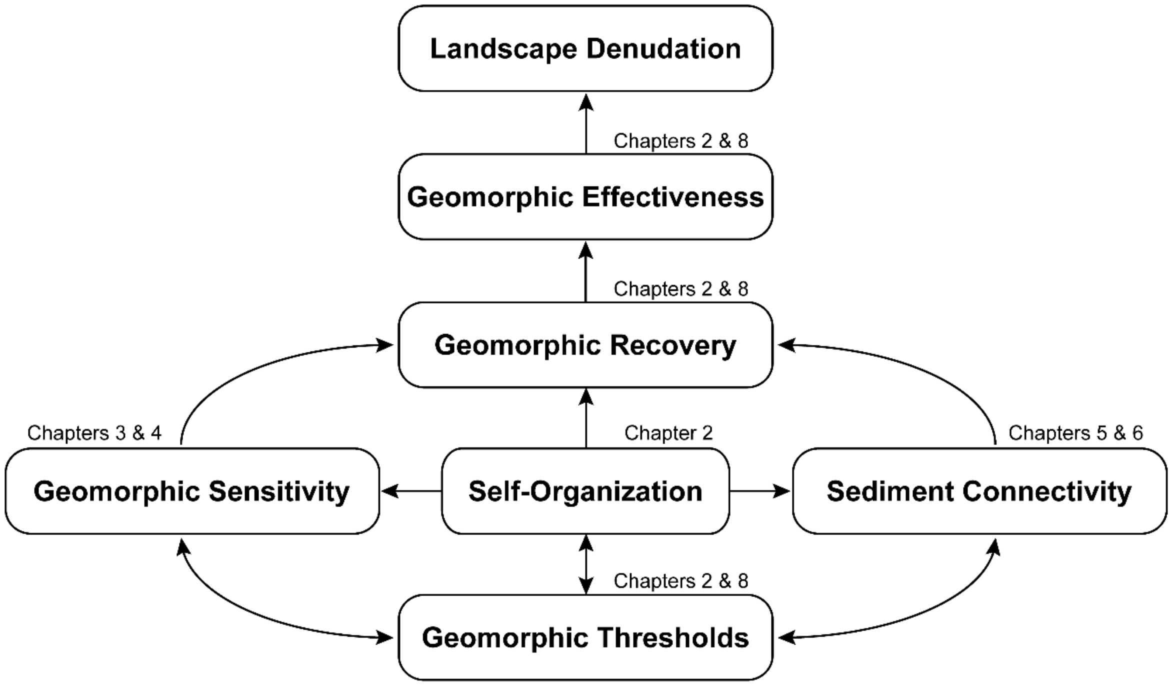


Figure 2. Organization and inter-relationships between geomorphic concepts discussed in this thesis.

8.2. Extrapolating Expectations of Geomorphic Response

Extrapolating results to explain and predict processes operating at both smaller and broader spatiotemporal scales is an important goal of geomorphic research. The extrapolation (prediction) of river behavior was described by Schumm (1983) to include seven key issues (scale, location, convergence, divergence, singularity, sensitivity, and complexity), which complicate forecasts of future river response. These issues can be more broadly organized into two groups. The first group combines the problems associated with applying research to different geomorphic environments with different externally-imposed boundary conditions (scale, location, and singularity). This can be described as the influence of physiographic region and the scale of investigation. The physiographic region of a geomorphic system not only sets the broadest, external controls (e.g. climate, geologic structure, lithology) (Leopold and Wolman, 1956; Tinkler, 1971; Baker, 1977) but can also influence what kind of anthropogenic impacts develop within a catchment (e.g. urban or agricultural development, ground and surface water resource exploitation, deforestation). The role that climatic, geologic, or anthropogenic influences play in driving river evolution at multiple spatiotemporal scales is initially determined by the physiographic region, which initially establishes the uniqueness (individuality) of the system (Baker and Twidale, 1991; Brunsden, 1993; Phillips, 2015). The second group of problems addresses the internally-derived unpredictability of geomorphic systems (complexity, convergence, divergence, and sensitivity). These four issues are encompassed within the influence of self-organization. Self-organized geomorphic responses do not have an obvious 'cause' and are therefore viewed as complex (Werner and Fink, 1993; Phillips, 1999; Werner, 1999; Murray et al., 2009; Murray et al., 2014). For example, self-organized responses can yield different landforms produced by similar processes (divergence) or similar landforms resulting from different processes (convergence, also known as equifinality) (Chorley, 1962; Phillips, 2006, 2014). Even landscape sensitivity, which can be broadly controlled by external factors (e.g. resistant or easily erodible lithologies) can be governed by self-organization, where the sensitivity of individual landscape compartments or landforms change over time as multiple disturbance events alter specific thresholds of adjustment (Brunsden and Thornes, 1979; Fryirs, 2016). Geomorphic systems can autogenically alter the initial or antecedent conditions that yield subsequent control over landform sensitivity (Brunsden and Thornes, 1979; Brunsden, 1993; Phillips, 1999). This can redirect, reduce (filter), or exacerbate (amplify) the impact of system singularities (Schumm, 1983; Phillips, 2010a). Correspondingly, the influence of sediment connectivity must also be considered, as sediment availability and transferability are significant controls over internally-derived geomorphic adjustments and landscape evolution (Brunsden and Thornes, 1979; Hooke, 2003; Phillips, 2003; Coulthard and Van De Wiel, 2007; Baartman et al., 2013).

Analyzing externally-derived and internally-derived influences on a geomorphic system is crucial for making realistic evaluations or predictions of geomorphic response (Downs, 1995; Werner, 2003; Larkin et al., 2016). For example, evaluations of the geomorphic effectiveness of storm events, which are primarily contingent upon the climatic and physiographic setting of a catchment, must be cognisant of the self-organized dynamics operating within the system to explain the variability of geomorphic response across multiple events (Coulthard and Van De Wiel, 2007) (see Chapter 2). Similarly, assessments of the sedimentological significance of tributaries must compare the size, shape, and location of tributary catchments with the internal variability of sediment (dis)connectivity processes operating within each tributary (Faulkner, 2008) (see Chapter 5). Ultimately, the problem of extrapolation is a product of the difficulty in correlating the influences of external and internal controls on system behavior, two of which are river sensitivity and sediment connectivity. The research presented in this thesis accounts for and incorporates these controls to derive robust characterizations (retrodictive) and expectations (predictive) of geomorphic response, and demonstrates how geomorphic responses can be analyzed using the Lockyer Valley as a case study. In doing so, this work has made a purposeful attempt to frame this investigation at the catchment-scale so that reach-scale interpretations of geomorphic response can be made within a context of larger-scaled geomorphic controls.

8.2.1. Geomorphic Response across Multiple Scales

Defining the scales of relevance is a key part of identifying the relationship between geomorphic concepts and the processes of geomorphic adjustment they describe (Brierley et al., 2006; Warke and McKinley, 2011b). The characterization of geomorphic response in the Lockyer Valley was conducted across multiple reaches and subcatchments, thereby establishing a catchment-scale context with which to evaluate individual channel reaches (see

Chapter 6 for specific discussion regarding the utility of catchment-scale perspectives). This perspective is necessary given that the geomorphic processes that determine the nature of river sensitivity and sediment connectivity are not isolated to specific channel reaches, but rather, they may operate at multiple scales throughout a catchment (Brunsden and Thornes, 1979; Brunsden, 2001; Fryirs, 2013; Bracken et al., 2015; Fryirs, 2016). Inherent in this approach is the idea that larger-scaled processes can directly influence geomorphic behavior at smaller scales (e.g. catchment sediment disconnectivity causing reach-scale channel incision) (cf. Murray et al., 2014). This notion may seem obvious; however, the reductionist approach to process geomorphology has emphasized small-scale mechanisms as the drivers of larger-scale processes (Rhoads, 2006; Murray et al., 2014) (e.g. sediment particle transport yielding large and complex dune forms).

A continual challenge for reach-scale studies is the application of small-scale findings to broader spatiotemporal scales and different locations (Schumm, 1983; Baker and Twidale, 1991; Sugden et al., 1997; Werner, 1999; Harrison, 2001). This thesis addresses this issue by using a catchment-scale conceptual framework and using our findings as a geomorphic context in which to couch reach-scale geomorphic responses in specific locations. For example, river sensitivity analyses (see Chapters 3 and 4) performed on trunk and tributary channels of the Lockyer Valley found that the transition from non-macrochannel morphologies to a macrochannel was a major control on the capacity for reach-scale, geomorphic channel adjustment. Macrochannels developed along the trunk stream and lower tributaries within wide floodplains containing thick, cohesive, fine-grained alluvial fill (Thompson et al., 2016a). Upstream, tributary channels become wider and shallower with coarser margin and substrate material. These channel reaches exhibited much more mobile channel thalwegs and margins with numerous adjustments to channel width. The transition from wide and shallow channels to a macrochannel morphology is associated with an overall reduction in the number of historical channel adjustments and a concentration of adjustments that rearranged the geomorphic units contained within the macrochannel (bars, benches, inset channel margins). This change in channel morphology corresponds with a shift in reach-scale threshold conditions of adjustment, where thresholds of channel margin adjustment are higher in macrochannels given the more cohesive substrate material.

Similarly, research on catchment sediment connectivity (see Chapters 5 and 6) reveals the variability in the dichotomic relationship between sediment buffers (geomorphic features that impede sediment conveyance) and ECAs (effective catchment area, i.e. catchment portions that contribute unobstructed sediment to a trunk stream) in tributary catchments. The proportions of sediment buffers and ECAs within tributary basins has profound implications for reach-scale geomorphic response by controlling the nature of catchment sediment connectivity (Hooke, 2003; Czuba and Foufoula-Georgiou, 2015). The results presented in Chapter 5 demonstrate how tributary coarse sediment connectivity can drive patterns of, and interruptions in, downstream sediment fining (sedimentary links) along Lockyer Creek (Rice, 1998, 1999). By controlling the availability and transference of sediment, tributary catchment connectivity plays a significant role in determining the distribution of sediment fractions in a particular trunk stream channel reach. In turn, this will strongly influence the potential geomorphic behavior of that reach (see Chapter 4 for definitions of channel adjustment and behavior) (Surian and Cisotto, 2007; Comiti et al., 2011). These results emphasize that analyses of river sensitivity and sediment connectivity are effective tools to unravel catchment-to-reach scale controls on the form and distribution of reach-scale channel responses.

Catchment-scale analyses of geomorphic response must now be a critical part of applying the concept of geomorphic effectiveness. Chapter 2 emphasizes that the future of the geomorphic effectiveness concept is dependent on using flexible (applicable across a variety of geomorphic environments) metrics to equally compare (metrics must have similar spatiotemporal scales) the effects of event(s) to the causes of those events. Using flexible and comparable metrics ensures that geomorphic responses are evaluated more comprehensively, avoiding a focus on discrete, reach-scale geomorphic adjustments. Additionally, it allows the variability in geomorphic responses (variation in the effectiveness of events) over time to be more meaningfully related to the catchment-scale geomorphic factors that non-linearly influence the ‘cause-and-effect’ relationships that define geomorphic effectiveness, e.g. connectivity, sensitivity, recovery, and self-organization. Altogether, the results presented in this thesis (Chapter 3 – 6) emphasize the importance of characterizing large-scale, non-linear processes and demonstrate how understanding the spatial variability in the ability of channel reaches to respond necessitates evaluations of geomorphic processes that operate at the catchment-scale.

8.2.2. The Influence of Physiographic Region

The influence of physiographic region on geomorphic response is represented by the external, imposed boundary conditions of the catchment, e.g. basin lithology, geologic structure, and climate (Tinkler, 1971; Baker, 1977; Brierley and Fryirs, 2016). For the Lockyer Valley, the factors of climate and basin shape play a large role in determining how processes of river sensitivity and sediment connectivity interact to influence geomorphic response. The subtropical climate of southeastern Queensland (SEQ) generates a spasmodic and intense pattern of rainfall resulting in periodic and severe flooding. This produces a flashy hydrological regime for Lockyer Creek that has driven the evolution of the macrochannel (Thompson et al., 2016a). The impact of these climatic factors is two-fold: 1) the presence of the macrochannel has consequently established a suite of geomorphic adjustment thresholds that are fundamentally different to other (tributary) channel locations (see Chapters 3 and 4); and 2) the flashy hydrological regime of Lockyer Creek means that within-macrochannel flows play a dominant role in the longitudinal transfer of bed sediment and overbank floods lead to sediment deposition in floodplain sinks, effectively decreasing end-of-catchment-sediment yields. Croke et al. (2013a) and Thompson et al. (2016b) found that the distribution of overbank flood waters exerts a strong influence over lateral and longitudinal hydrological and sedimentological connectivity. Sediment connectivity analyses presented in Chapter 5 indicate that overbank floods can also influence patterns of downstream sediment fining. The shape and location of the tributary catchments in the Lockyer Valley also influences the nature of coarse sediment connectivity by broadly determining the accommodation space for alluvial sediment storage. Tributary catchments located downstream in the Lockyer Valley contain proportionally more buffered areas, primarily in the form of floodplains. A similar effect is seen for tributaries that widen downstream. In both cases, the available areas for sediment production and transference (ECAs) are limited by the extent of sediment buffers (see Chapters 5 and 6). These factors characterize geomorphic response in the Lockyer Valley as being particularly influenced by antecedent conditions, in the form of valley morphology (confinement vs. accommodation space) and the evolution of a macrochannel (see Chapter 3).

An advantage of undertaking catchment-scale characterizations of river sensitivity is the identification of singularities that can impact future channel response. For example, the presence or absence of a macrochannel form has been found to have a strong influence over reach-scale sensitivity to geomorphic adjustment. In the lower Lockyer Valley, where the macrochannel is well established, numerous bedrock exposures occur along the channel bank and abut the outside of meander bends (Thompson et al., 2016a). These isolated bedrock spurs can act as geomorphic singularities (Schumm, 1983, 1985, 1988) by impacting not only the channel's resilience to adjustment, by imposing higher thresholds of erosion, but also the evolution of the macrochannel at the reach scale over time. Although the resilience of the macrochannel can be identified, the timing and extent of specific morphological adjustments will be influenced by this localized feature (Schumm, 1988).

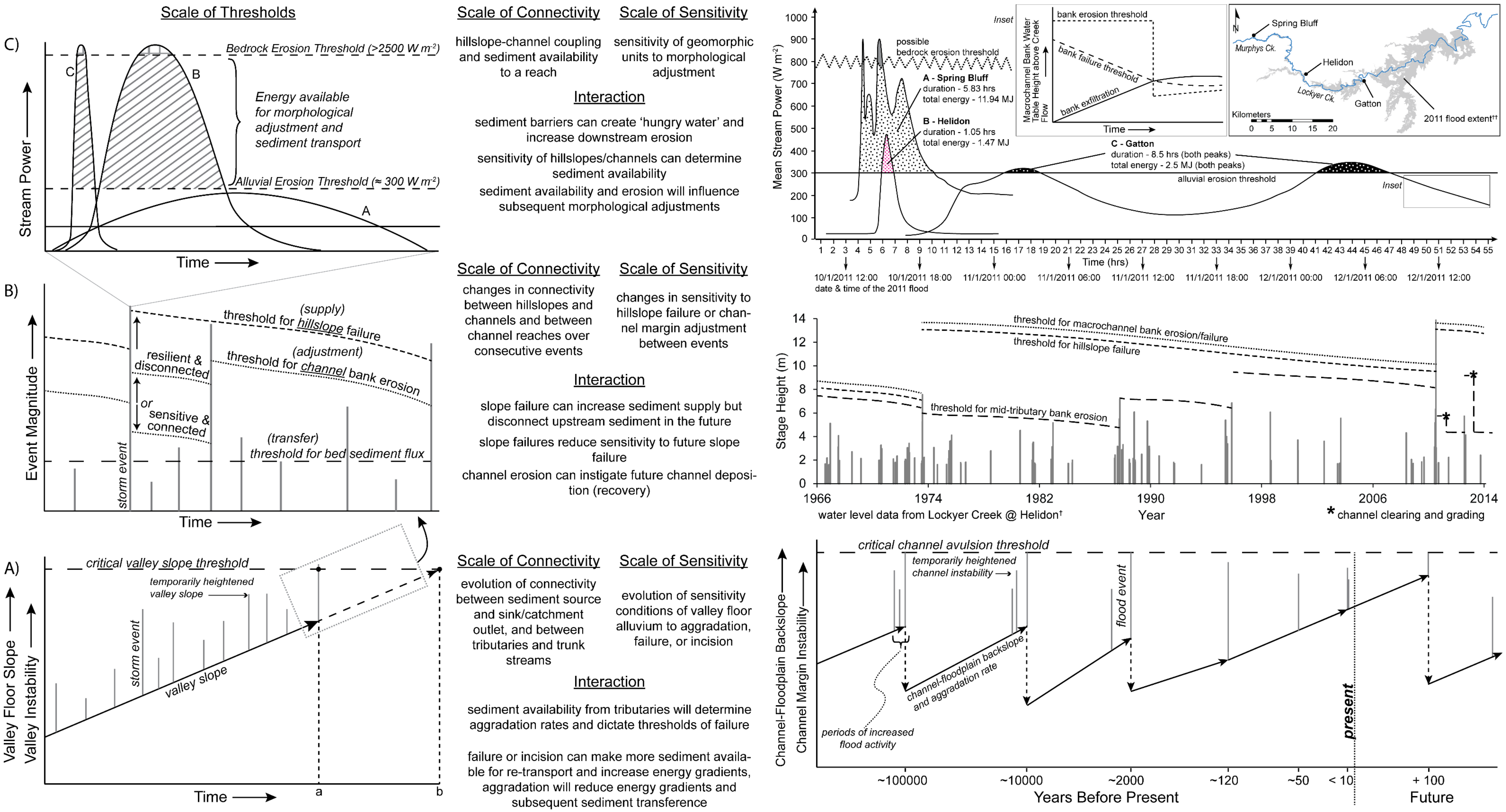
Connectivity analysis has demonstrated how weirs in the Lockyer Valley can control the downstream pattern of sediment fining (sedimentary links) along Lockyer Creek. These weirs can also act as anthropogenic singularities by locally influencing the ability of channels to respond. The preferential retention of coarse bed sediment by weirs (Thoms and Walker, 1993; Rinaldi, 2003) can have repercussive effects on geomorphic adjustment through backwater effects and local channel margin armouring. Therefore, the installation of weirs serves to interrupt the suite of geomorphic processes operating within a particular reach (Montgomery, 1999; Phillips, 2007). Importantly, weirs are temporary manifestations (over geomorphic time scales) of an externally-imposed singularity. Both weir installation or removal may induce a suite of geomorphic responses by changing local base-level, similar to local tectonic impacts on channel beds (e.g. Cook et al., 2013).

8.2.3. Characterizing Internal System Dynamics

The multi-scalar interactions of geomorphic factors internal to earth surface systems have traditionally been described as complex (Schumm, 1973, 1979), resulting in the unpredictability or apparent chaos of geomorphic system response (Phillips, 1999, 2003, 2006). Geomorphic sensitivity and sediment connectivity are a key part of the internal dynamics of catchments. Although this thesis utilized individual sensitivity and connectivity approaches to address questions of geomorphic response, this does not imply that these concepts operate independently of one another (cf. Fuller et al., 2003). Together, they represent the integration of flow regime, sediment availability, vegetation, and anthropogenic impacts as controls on how readily a river channel can adjust and the forms and extent of adjustments possible. Sensitivity and connectivity may be conceptually distinct, but they are certainly geomorphologically interrelated. It should be expected that spatiotemporal adjustments in either river sensitivity or sediment connectivity can denote a corresponding change in the other (Fryirs, 2016).

The interplay between geomorphic sensitivity and sediment connectivity, across a variety of spatiotemporal scales, is facilitated by the presence and variability of threshold conditions of geomorphic adjustment and sediment transport (Figure 3). At the broadest scale, both the sensitivity of and connectivity between landforms will interact to control how system components (e.g. valley floors, entire channels) behave over long periods of time, through their responses to sequences of disturbance events. The sensitivity of individual landforms to adjustment is determined by their proximity to threshold conditions (Schumm, 1973, 1979; Downs and Gregory, 1995) (Figure 3A-left). At large scales, threshold conditions describe the connectivity between sediment sources and sinks or the ease of morphological adjustment of large landforms (Figure 3A-center). For example, over thousands of years in the Lockyer Valley, Lockyer Creek has experienced several large and persistent avulsions (Daley et al., 2017; Croke et al., under review). These adjustments could be responses to changing floodplain and channel aggradation rates, which are linked to the sediment connectivity of the catchment (The Big Flood Project Team, 2016) (Figure 3A-right). The sensitivity of the channel to avulsion increases as the channel aggrades faster than the floodplain and the backslope between the channel levees and floodplain increases (Jones and Schumm, 1999; Slingerland and Smith, 2004). Post adjustment, the system is resilient to further avulsion until the channel and levees re-aggrade. A future avulsion is possible along Lockyer Creek where the channel levees are currently ~ 5 m higher than the floodplain (Chapter 7) (Croke et al., 2013b; Thompson et al., 2014; The Big Flood Project Team, 2016).

Figure 3. Spatial relationships and interactions between geomorphic thresholds, sensitivity and sediment connectivity. A) Catchment-scale thresholds after Schumm (1973). Left – valley evolution where successive flood events move the system closer to a geomorphic threshold of instability (b), where a large storm event breaches a critical threshold (a). Center –sensitivity and connectivity interact at the broadest scale through thresholds of connectivity between sediment sources and sinks and landform sensitivity to large-scale modification. Right – example depiction of historical channel/floodplain aggradation in the lower Lockyer Valley leading to channel avulsions over time, conceptualized from work by Croke et al. (2016b) and Croke et al. (under review), also available at www.thebigflood.com.au. B) Landscape-compartment scale thresholds after Beven (1981) incorporating concepts from Newson (1980). Left – sensitivity and connectivity conditions in a geomorphic environment will influence threshold adjustment between sequences of flood events. Center –sensitivity and connectivity interact at the reach- to multi-reach scale, where adjustments in one reach have immediate impacts downstream. Right – example depiction of threshold adjustments in different geomorphic environments between events over a 48 year flood history of Lockyer Creek, based on data from Chapters 4 and 5. C) Reach-scale thresholds after Costa and O'Connor (1995). Left – scenario depicting time and energy available for short duration/high intensity floods (curve c), high intensity/long duration floods (curve b), and low intensity/long duration floods (curve a), and their respective abilities to breach small-scale erosion thresholds. Erosion thresholds approximated from Miller (1990) and Magilligan (1992). Center – sensitivity and connectivity interact within reaches where local sensitivity will influence both adjustment and sediment transport potential. Right – stream power, total energy, and duration above threshold conditions for the 2011 flood event in the Lockyer Valley, modified from Croke et al. (in prep); *Inset* – threshold conditions of bank failures in the lower Lockyer during the falling limb of the hydrograph.



† Flood stage data available from DNRM, State of Queensland at https://water-monitoring.information.qld.gov.au/host.htm

†† 2011 flood extent data from Croke et al. (2013a). Flood extent data not available for the lowermost portion of Lockyer Creek

When a disturbance event breaches a threshold, the nature of sensitivity and connectivity between landforms or channel reaches can adjust, establishing new threshold conditions which alters the ability of the landscape to respond to future events (Figure 3B-left) (Beven, 1981) (Chapter 2). Here, thresholds describe critical states of individual landform adjustment and of sediment connectivity between landscape compartments, which lie between the sediment source and sink environments (e.g. hillslopes, channel banks) (Figure 3B-center). Over the past 48 years in the Lockyer Valley, a sequence of flood events has instigated adjustments to catchment hillslopes (Thompson and Croke, 2013; Cohen, unpublished dataset; Thompson, unpublished dataset) and channel margins (Chapters 3 and 4) with variable severity (Figure 3B-right). Thresholds of hillslope failure and macrochannel bank erosion/failure are high; although, the largest events (1974 and 2011) were able to breach them. Breaching these thresholds, however, increases the resilience of the landform to further failures (Crozier and Glade, 1999; Thompson et al., 2016a). In more sensitive channel environments, smaller events can trigger adjustments; however, their number and severity will depend in part on the sequencing and adjustment to previous events (Newson, 1980). Importantly, anthropogenic interventions in the channel environment can lower future thresholds of adjustment, particularly when the interventions reduce the stability of the channel margins. For example, the mid-upper portion of Blackfellows Creek is proximally located to ECAs of this tributary catchment (Chapter 6). The potential availability of abundant sediment will likely influence the behavior of this channel reach, particularly, the propensity of this channel to reach an avulsion threshold through bed aggradation (Chapters 4 and 7). Here, the reworking of aggrading bed sediment can create local imbalances between the channel bed slope and bed load (Lane, 1955). This imbalance can generate variations in stream competence and power which can cause in-channel or even complete channel avulsions (Jones and Schumm, 1999; Törnqvist and Bridge, 2002; Slingerland and Smith, 2004; Jerolmack and Mohrig, 2007; Phillips, 2011) like those that occurred in 2013. These avulsions are natural and expected adjustments occurring for this type of river operating within the catchment boundary conditions. Overall, the 2013 flood was a lower magnitude event than the 2011 flood, however, it induced more severe avulsions in this portion of Blackfellows Creek. The 2011 event may have primed this channel reach for avulsion by aggrading the channel bed. Additionally, this channel reach was subjected to vegetation clearing and bed grading by bulldozers (Chapter 7). The degree to which this activity increased the erodability of the channel margins and the stream power of in-channel flows must be considered a partial contributing factor to the 2013 channel avulsions.

Over the course of a single disturbance event, the thresholds of adjustment and sediment transference established through physiographic and antecedent conditions of sensitivity and connectivity will govern how effective that event can be in terms of sediment flux and landform modification (Figure 3C-left). For a single event, cumulative impacts across a variety of geomorphic environments will demonstrate how effective the event was. At the reach scale, the coupling between hillslopes and channel reaches is a key control on sediment availability. During a flood event, the expenditure of energy within individual reaches will control how available sediment is entrained, transported, and re-deposited (Figure 3C-center). The 2011 flood in the Lockyer Valley breached different erosional thresholds in different locations at different times (Figure 3C-right). Significant alluvial adjustment occurred in the upper part of the catchment, from Helidon to Spring Bluff, where energy expenditure was highest. The upper-most portion of the Lockyer Valley is largely bedrock controlled, so erosional thresholds were much higher in many channel reaches (Sargood et al., 2015). Here, the constriction of flood water in contraction zones produced higher stream powers that could breach bedrock erosion thresholds. The duration of the flood was longer in Gatton, but the energy expenditure was considerably lower as floodwaters could spread out across the lower Lockyer expansion zone. Numerous wet bank mass failures (WBMFs) occurred in the lower Lockyer, where the macrochannel form of Lockyer Creek has been modelled to evolve in part by WBMF processes (Thompson et al., 2016a). These WBMFs are not an initial response to flood events, but rather they occur when the storm conditions and flood waters begin to subside during the falling stage of the hydrograph (Grove et al., 2013) (Figure 3C-right, inset). Here, piping or sapping erosion through the exfiltration of water from supersaturated banks with elevated water tables causes bank material to slump into the channel (Hagerty, 1991; Grove et al., 2013; Thompson et al., 2013). These bank failures make fine-grained sediment available for transport in a channel location that otherwise is highly disconnected from upstream sediment sources (see Chapter 5). However, these failures occur within the channel bank so that overall macrochannel width is largely unchanged (Thompson et al., 2016a) (see Chapter 3). The entrained bank sediment is now available to facilitate further geomorphic response through the formation of new depositional geomorphic units downstream or on the floodplain (see Chapter 3). The resilience of the macrochannel is maintained by the preferential deposition of sediment in bank failure scars by subsequent floods, i.e. geomorphic recovery (Thompson et al., 2013; Thompson et al., 2016a).

These conceptual and actual examples illustrate how characterizing the nature and interplay of geomorphic sensitivity and sediment connectivity across an entire catchment is critical for contextualizing individual thresholds of channel adjustment and sediment transference. This context is necessary to describe what the breaching (or not) of thresholds implies in terms of potential geomorphic system behavior across multiple disturbance events and in different geomorphic environments.

8.3. Assessing Geomorphic Effectiveness

The broadest application of the research presented in this thesis is to constrain determinations of geomorphic effectiveness. The geomorphic effectiveness concept is the primary geomorphic tool used to assess the significance of geomorphic responses across entire catchments for a single event or for long-term landscape evolution (Wolman and Miller, 1960; Wolman and Gerson, 1978). Therefore, assessments of geomorphic effectiveness are *de facto* assessments of how environmental and self-organized controls, including river sensitivity and sediment connectivity, interact to influence geomorphic response at different scales (cf. Beven, 1981; Jacobson et al., 1989; Emmett and Wolman, 2001; Eaton et al., 2003; Heritage et al., 2004). The 'effectiveness' concept serves to integrate these influences and describe how much work (sediment flux plus landscape modification) the resultant responses contributed to the denudation, evolution, efficiency, or metamorphosis of the landscape (Wolman and Miller, 1960; Schumm, 1969, 1971; Wolman and Gerson, 1978; Huang et al., 2004; Nanson and Huang, 2008). Catchments are in a perpetual state of response (Phillips, 2009a), and over time, these responses drive the catchment along a trajectory of evolution (Dollar, 2002; Brierley and Fryirs, 2016) (Figure 4A). Disturbance events that instigate 'driving' responses across multiple spatial scales (Figure 4B) are the most effective events, whether those responses contribute to the ongoing adjustment of a system, for example, denudation by moderate events over time (Wolman and Miller, 1960), or the metamorphosis of the system to a new, or more efficient, state (Schumm, 1969, 1971; Erskine, 1986; Jansen and Nanson, 2004; Phillips, 2010b) (Figure 4C).

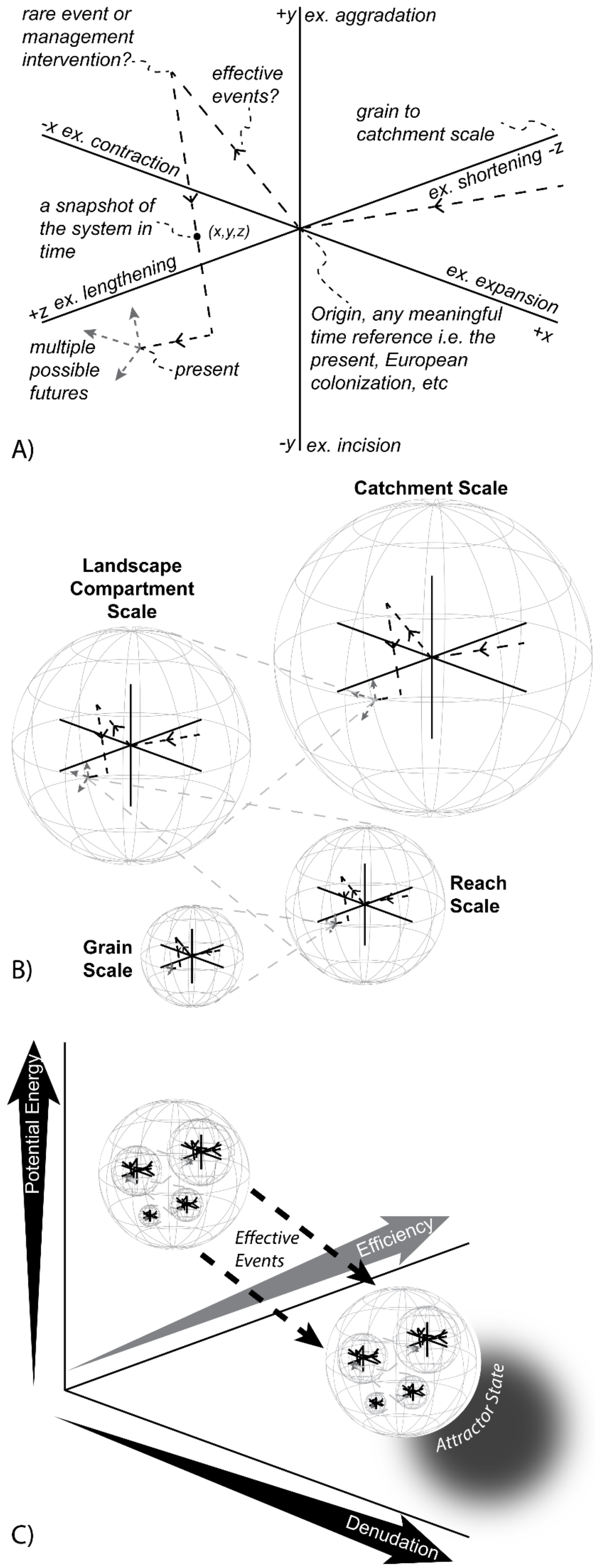


Figure 4. Geomorphic effectiveness conceptualized at multiple scales. A) Geomorphologically effective events facilitate catchment evolution along trajectories. These trajectories can be represented in 3-dimensional space, where the axes can represent forms of geomorphic adjustment. Motion of the system through this 3-D space is facilitated by geomorphic responses. B) Trajectories of system evolution operate at different scales, where the evolution at one scale can influence the trajectory of other larger or smaller scales. C) Over time, effective events evolve the geomorphic system to more denudated states through geomorphic responses that produce more efficient landscape configurations and lower the potential energy for adjustment in the system.

Climate represents a very influential external control over the response and evolution of the Lockyer Valley. In SEQ, geomorphic river responses to anthropogenic impacts have been relatively minor (Kemp et al., 2015). This sets the region apart from catchments in southeast Australia that have continued to respond and recover from landuse changes instigated by European colonization (Rutherfurd, 2000), for example, the Bega catchment (Brooks and Brierley, 1997; Fryirs and Brierley, 1998; Fryirs and Brierley, 1999), the Wollombi catchment (Erskine and Melville, 2008; Fryirs et al., 2012), the Hunter Valley (Hoyle et al., 2008; Fryirs et al., 2009), the Southern Tablelands (Eyles, 1977; Page et al., 2007), the Nepean River (Hubble and Rutherfurd, 2010), the Yarra River (Leahy et al., 2005), the Glenelg River (Erskine, 1994), and the Latrobe River (Reinfelds et al., 1995). The subtropical climate of the Lockyer Valley produces intense rainfall events punctuated by extended dry periods (Rustomji et al., 2009; Taschetto and England, 2009; Cai and van Rensch, 2012). Future climate change models predict this flood and drought pattern will continue and become more exaggerated in the future (Hennessy et al., 2008; Alexander and Arblaster, 2009; Reisinger et al., 2014). This climatic control has generated a geomorphic system where large events drive the morphological evolution of channels (Thompson et al., 2016a), and 'moderate' events (e.g. the 1-2 year flow) are actually low magnitude and geomorphically insignificant (Chapter 3). Over the past 2000 years, major floods have been clustered into periods of high flood activity (Figure 3A-right) (Croke et al., 2016b; The Big Flood Project Team, 2016). In the 20th Century, these floods have been punctuated by severe droughts. For example, the 'Millennial Drought' (2001-2009) was the worst drought on record (van Dijk et al., 2013), and it was punctuated in 2011 by the most intense rainfall event on record in SEQ (Cai and van Rensch, 2012). This drought-flood sequencing creates a pattern where the first, punctuating rainfall event encounters very dry antecedent conditions and can interact with thresholds of adjustment and sediment transport that have not been recently breached. The initial flood may readily breach these thresholds or set up successive floods for more extensive responses. The 2011 flood event triggered numerous landslides (Thompson and Croke, 2013; Cohen, unpublished dataset; Thompson, unpublished dataset), extensively stripped bedrock reaches of alluvium and vegetation (Sargood et al., 2015), deposited thick sand sheets on the lower floodplains (Croke et al., 2013b) (Chapter 3), and generated numerous WBMFs (Grove et al., 2013; Thompson et al., 2013). Subsequently, the 2013 flood infilled some WBMFs along Lockyer Creek (Thompson et al., 2016a), while triggering more numerous adjustments, including large avulsions, in Blackfellows and Laidley Creek (Ivezich and Hardie, 2014) (Chapter 4). The pattern of severe flood-drought sequencing and the variability of sensitivity and connectivity controls make traditional magnitude-frequency analyses inadequate for determining which events will be geomorphically effective in the Lockyer Valley (Crozier, 1999; Richards, 1999). The 'uniqueness' of the Lockyer Valley must be understood before any characterizations of geomorphic effectiveness can be made (Brunsden, 1993). The analyses of river sensitivity and sediment connectivity presented in this thesis ultimately characterizes the individualistic nature of some internal system dynamics. When combined with characterizations of the roles of external (climatic) influences, a more representative model of geomorphic effectiveness for the Lockyer Valley can be developed.

Large events play a more significant role in the Lockyer Valley. However, like the moderate events discussed by Wolman and Miller (1960), large events should not be assumed to always be effective (Chapter 2). The first step in analyzing the significance of flood events should be to determine if the geomorphic responses are part of the system's expected behavior or if they are anomalous (Brierley and Fryirs, 2005) (Chapter 4). Lockyer Creek is largely resilient; however, tributary reaches are more sensitive to adjustment. Tributary reaches should be expected to respond with numerous adjustments to the channel bed and banks; however, channel recovery from these adjustments is easier given the more proximal location of ECAs. Similarly, the numerous WBMFs that occur in the lower Lockyer instigate deposition and recovery by subsequent events (Grove et al., 2013; Thompson et al., 2013; Thompson et al., 2016a). Given the limited extent of sensitive geomorphic environments in the Lockyer Valley, events that respond 'as expected' will not appear to be geomorphologically effective as responses may be localized or recovery may occur quickly. Conversely, events that produce an anomalous response, such as a macrochannel avulsion, would appear more effective because this form of adjustment is more persistent and may shift the behavior of the river to a new state (Brierley and Fryirs, 2005).

Despite the higher level of geomorphic activity in sensitive locations, the bed sediment mobilized during these responses is not transported out of the catchment (Thompson et al., 2016b). The lower Lockyer tributaries become highly disconnected downstream and the largest tributaries contain numerous weirs. The coarse sediment transported by the well-connected upper Lockyer tributaries is blocked by weirs in the lower two-thirds of Lockyer Creek (Chapter 6). Even the 2011 flood event was net depositional in the Lockyer Valley (Croke et al., 2013b; Thompson et al., 2016b) and may have been more significant in terms of suspended sediment transport out of the catchment (Olley et al., 2006; Olley et al., 2013). Therefore, large events serve to redistribute coarse sediment within the catchment, 'filling in' the sediment sink of the lower Lockyer Valley, thereby contributing to the overall denudation and reduction of potential energy of the Lockyer Valley.

Determining geomorphic effectiveness requires the earth scientist to know their catchment (Brierley et al., 2013). The Lockyer Valley is 'badass' (Phillips, 2015), displaying a unique and individualistic pattern of external and internal controls and corresponding geomorphic processes that combine to form a 'perfect' landscape (Phillips, 2007). The resilient and disconnected nature of the Lockyer Valley does not mean that disturbance events cannot be effective. It simply sets a different standard of effectiveness. For example, the extensive benches present in the lower Lockyer are a form of internal organization that stores sediment within compound channels (Erskine and Livingstone, 1999; Croke et al., 2014).

These benches are less transient sediment storage features than sediment bars and are therefore more resilient to adjustment, which is partly reflected in the resilience of the lower Lockyer. Importantly, determinations of geomorphic effectiveness in this macrochannel environment must acknowledge that, despite their resilience, benches are the primary means by which channel width can adjust. Catchments like the Lockyer Valley are adjusted to larger events, and although these events may not evacuate sediment out of the catchment, they do serve to move the catchment along its trajectory of evolution via expected river behavior (Brierley and Fryirs, 2005; Wohl, 2011) (Figure 3A).

Resilient and disconnected catchments present an interesting issue within the geomorphic effectiveness concept. Are effective events those that move the system along the trajectory, however undramatically, or are they those that change the trajectory via anomalous responses, i.e. river metamorphosis (Schumm, 1969) or channel change (Brierley and Fryirs, 2005) (Figure 1A)? The 2011 flood event was exceptionally severe; however, the catchment behaved as expected and sediment was predominantly retained. Was the 2011 flood geomorphologically effective? In terms of individual, observable geomorphic response (adjustments and sediment transport), the answer could be yes or no, depending on your perspective. Over the short term, the 2011 event did not appear to be geomorphologically effective, as the overall magnitude of the responses were less than that of the flood (Chapter 3). However, this should be expected in a resilient, disconnected catchment. Over the long term, the 2011 event did contribute to the denudation and reduction in overall potential energy of the catchment (Figure 4C) (Wolman and Miller, 1960; Caine, 1976; Croke et al., 2013b), regardless of the morphological recovery of individual landform modifications (Wolman and Gerson, 1978). Additionally, it is unknown how the 2011 event has set the system up for a future macrochannel avulsion (Thompson et al., 2014) (Figure 3A-right). Despite the discrete occurrence of disturbance events, geomorphic effectiveness cannot be determined discretely (Chapter 2). This thesis submits that the 2011 event was geomorphologically effective and likely instigated geomorphic responses that have yet to manifest themselves in an observable manner. The impact of these effects may become amplified or filtered depending on whether they are 'in phase' or 'out of phase' with antecedent feedbacks and subsequent responses (Phillips, 2010a).

8.4. Implications for Management and Future Research

Perhaps more important than the geomorphic responses are the management activities and initiatives enacted after 2011. For example, the research undertaken during this thesis work is a form of anthropogenic response to the 2011 flood. Considering the other research stages involved with this project and the government-level revision and expansion of management policy (The Big Flood Project Team, 2016), the 2011 event may become one of the most effective floods in SEQ in terms of government-level and research community response. Anthropogenic and geomorphic responses contemporaneously shape fluvial environments (Wohl, 2013). The way in which waterways are managed, regulated, and exploited can modulate the geomorphic response to, and effectiveness of, flood events (cf. Fuller et al., 2011). As scientific and management interests progressively intersect (Wohl et al., 2015), it is critical that the utility of geomorphic concepts is not constrained to scientific pursuits. River sensitivity and sediment connectivity can be used as conceptual tools by managers to identify and organize catchment management goals and to tailor site-specific management strategies to minimize the effect of flood events on infrastructure and the community (Bracken et al., 2013; Brierley et al., 2013; Fuller et al., 2014; Brierley and Fryirs, 2016). This type of work is just beginning in the Lockyer Valley (Chapter 7) (Croke et al., 2014; Thompson et al., 2014; Croke et al., 2016a; Croke et al., 2017). More research is needed to identify the reach-specific thresholds of erosion, sediment availability, and sediment transport that constrain individual channel adjustments (e.g. Grove et al., 2013).

Additionally, more sophisticated sediment connectivity modelling will aid in understanding reach to reach changes in sediment transference. With additional research continuing in the Lockyer Valley and similar SEQ catchments, the findings of the research presented in this thesis can provide the contextual geomorphic understanding necessary to frame reach-scale geomorphic studies and establish catchment-scale management strategies. As our understanding of geomorphic response in the Lockyer Valley improves, future research can strive to incorporate the influences of biological and/or anthropogenic processes with concepts of river sensitivity, sediment connectivity, thresholds, recovery, and self-organization into more integrated, geo-ecosystem frameworks (Doyle et al., 2000; Doyle et al., 2005; Dollar et al., 2007; Phillips, 2009b).

References

Alexander, L.V., Arblaster, J.M., 2009. Assessing trends in observed and modelled climate extremes over Australia in relation to future projections. International Journal of Climatology 29(3), 417-435, doi: 10.1002/joc.1730.

Baartman, J.E.M., Masselink, R., Keesstra, S.D., Temme, A.J.A.M., 2013. Linking landscape morphological complexity and sediment connectivity. Earth Surface Processes and Landforms 38(12), 1457-1471, doi: 10.1002/esp.3434.

Baker, V.R., 1977. Stream-channel response to floods, with examples from central Texas. Geological Society of America Bulletin 88(8), 1057-1071, doi: 10.1130/0016-7606(1977)88<1057:srtfwe>2.0.co;2.

Baker, V.R., Twidale, C.R., 1991. The reenchantment of geomorphology. Geomorphology 4(2), 73-100, doi: http://dx.doi.org/10.1016/0169-555X(91)90021-2.

Beven, K., 1981. The effect of ordering on the geomorphic effectiveness of hydrologic events. IAHS Publ 132, 510-526.

Bracken, L.J., Wainwright, J., Ali, G.A., Tetzlaff, D., Smith, M.W., Reaney, S.M., Roy, A.G., 2013. Concepts of hydrological connectivity: Research approaches, pathways and future agendas. Earth-Science Reviews 119, 17-34, doi: http://dx.doi.org/10.1016/j.earscirev.2013.02.001.

Bracken, L.J., Turnbull, L., Wainwright, J., Bogaart, P., 2015. Sediment connectivity: A framework for understanding sediment transfer at multiple scales. Earth Surface Processes and Landforms 40(2), 177-188, doi: 10.1002/esp.3635.

Brierley, G., Fryirs, K., 2005. Geomorphology and River Management: Applications of the River Styles Framework. Blackwell Publishing, Victoria, Australia.

Brierley, G., Fryirs, K., Jain, V., 2006. Landscape connectivity: The geographic basis of geomorphic applications. Area 38(2), 165-174, doi: 10.1111/j.1475-4762.2006.00671.x.

Brierley, G., Fryirs, K., Cullum, C., Tadaki, M., Huang, H.Q., Blue, B., 2013. Reading the landscape: Integrating the theory and practice of geomorphology to develop place-based understandings of river systems. Progress in Physical Geography 37(5), 601-621, doi: 10.1177/0309133313490007.

Brierley, G., Fryirs, K., 2016. The use of evolutionary trajectories to guide 'moving targets' in the management of river futures. River Research and Applications 32, 823-835, doi: 10.1002/rra.2930.

Brooks, A.P., Brierley, G.J., 1997. Geomorphic responses of lower Bega River to catchment disturbance, 1851–1926. Geomorphology 18(3–4), 291-304, doi: http://dx.doi.org/10.1016/S0169-555X(96)00033-5.

Brunsden, D., Thornes, J.B., 1979. Landscape sensitivity and change. Transactions of the Institute of British Geographers 4(4), 463-484, doi: 10.2307/622210.

Brunsden, D., 1993. Barriers to geomorphological change. In: D.S.G. Thomas, R. Allison (Eds.), Landscape Sensitivity. John Wiley & Sons, New York, pp. 7-29.

Brunsden, D., 2001. A critical assessment of the sensitivity concept in geomorphology. CATENA 42(2–4), 99-123, doi: http://dx.doi.org/10.1016/S0341-8162(00)00134-X.

Cai, W., van Rensch, P., 2012. The 2011 southeast Queensland extreme summer rainfall: A confirmation of a negative Pacific Decadal Oscillation phase? Geophysical Research Letters 39(8), L08702, doi: 10.1029/2011GL050820.

Caine, N., 1976. A uniform measure of subaerial erosion. Geological Society of America Bulletin 87(1), 137-140, doi: 10.1130/0016-7606(1976)87<137:aumose>2.0.co;2.

Chorley, R.J., 1962. Geomorphology and general systems theory, USGS, Washington D.C.

Cohen, T.J., unpublished dataset. Lockyer Valley Landslide Dataset.

Comiti, F., Da Canal, M., Surian, N., Mao, L., Picco, L., Lenzi, M.A., 2011. Channel adjustments and vegetation cover dynamics in a large gravel bed river over the last 200 years. Geomorphology 125(1), 147-159, doi: http://dx.doi.org/10.1016/j.geomorph.2010.09.011.

Cook, K.L., Turowski, J.M., Hovius, N., 2013. A demonstration of the importance of bedload transport for fluvial bedrock erosion and knickpoint propagation. Earth Surface Processes and Landforms 38(7), 683-695, doi: 10.1002/esp.3313.

Costa, J.E., O'Connor, J.E., 1995. Geomorphically Effective Floods. In: J.E. Costa, A.J. Miller, K.W. Potter, P.R. Wilcock (Eds.), Natural and Anthropogenic Influences in Fluvial Geomorphology. American Geophysical Union, pp. 45-56.

Coulthard, T.J., Van De Wiel, M.J., 2007. Quantifying fluvial non linearity and finding self organized criticality? Insights from simulations of river basin evolution. Geomorphology 91(3–4), 216-235, doi: http://dx.doi.org/10.1016/j.geomorph.2007.04.011.

Croke, J., Fryirs, K., Thompson, C., 2013a. Channel–floodplain connectivity during an extreme flood event: Implications for sediment erosion, deposition, and delivery. Earth Surface Processes and Landforms 38(12), 1444-1456, doi: 10.1002/esp.3430.

Croke, J., Todd, P., Thompson, C., Watson, F., Denham, R., Khanal, G., 2013b. The use of multi temporal LiDAR to assess basin-scale erosion and deposition following the catastrophic January 2011 Lockyer flood, SE Queensland, Australia. Geomorphology 184(0), 111-126, doi: 10.1016/j.geomorph.2012.11.023.

Croke, J., Reinfelds, I., Thompson, C., Roper, E., 2014. Macrochannels and their significance for flood-risk minimisation: Examples from southeast Queensland and New South Wales, Australia. Stoch Environ Res Risk Assess 28(1), 99-112, doi: 10.1007/s00477-013-0722-1.

Croke, J., Fryirs, K., Thompson, C., 2016a. Defining the floodplain in hydrologically-variable settings: Implications for flood risk management. Earth Surface Processes and Landforms 41(14), 2153-2164, doi: 10.1002/esp.4014.

Croke, J., Thompson, C., Denham, R., Haines, H., Sharma, A., Pietsch, T., 2016b. Reconstructing a millennial-scale record of flooding in a single valley setting: The 2011 flood-affected Lockyer Valley, south-east Queensland, Australia. Journal of Quaternary Science 31(8), 936-952, doi: 10.1002/jqs.2919.

Croke, J., Thompson, C., Fryirs, K., 2017. Prioritising the placement of riparian vegetation to reduce flood risk and end-of-catchment sediment yields: Important considerations in hydrologically-variable regions. Journal of Environmental Management 190, 9-19, doi: http://dx.doi.org/10.1016/j.jenvman.2016.12.046.

Croke, J., Thompson, C., Fryirs, K., in prep. Flood power and time over threshold: Their relative contribution to patterns of channel erosion during an extreme flood event. Geomorphology.

Croke, J., Thompson, C., Larsen, A., Sharma, A., under review. The nature and timing of fluvial response to changing base-level and climate over the last glacial-interglacial cycle in sub-tropical Australia. Quaternary Science Reviews.

Crozier, M., 1999. The frequency and magnitude of geomorphic processes and landform behaviour. Zeitschrift für Geomorphologie Supplement Volumes 115, 35-50.

Crozier, M., Glade, T., 1999. Frequency and magnitude of landsliding: fundamental research issues. Zeitschrift für Geomorphologie Supplement Volumes 115, 141-155.

Czuba, J.A., Foufoula-Georgiou, E., 2015. Dynamic connectivity in a fluvial network for identifying hotspots of geomorphic change. Water Resources Research 51(3), 1401-1421, doi: 10.1002/2014WR016139.

Daley, J., Croke, J., Thompson, C., Cohen, T., Macklin, M., Sharma, A., 2017. Late Quaternary channel and floodplain formation in a partly confined subtropical river, eastern Australia. Journal of Quaternary Science, doi: 10.1002/jqs.2930.

Dollar, E.S.J., 2002. Magnitude and frequency controlling fluvial sedimentary systems: issues, contributions and challenges. In: F.J. Dryer, M.C. Thoms, J.M. Olley (Eds.), The Structure, Function and Management Implications of Fluvial Sedimentary Systems. International Assoication of Hydrological Sciences, Oxfordshire, UK, pp. 355-362.

Dollar, E.S.J., James, C.S., Rogers, K.H., Thoms, M.C., 2007. A framework for interdisciplinary understanding of rivers as ecosystems. Geomorphology 89(1–2), 147-162, doi: http://dx.doi.org/10.1016/j.geomorph.2006.07.022.

Downs, P.W., 1995. Estimating the probability of river channel adjustment. Earth Surface Processes and Landforms 20(7), 687-705, doi: 10.1002/esp.3290200710.

Downs, P.W., Gregory, K.J., 1995. Approaches to river channel sensitivity. The Professional Geographer 47(2), 168-175, doi: 10.1111/j.0033-0124.1995.168_v.x.

Doyle, M.W., Harbor, J.M., Rich, C.F., Spacie, A., 2000. Examining the effects of urbanization on streams using indicators of geomorphic stability. Physical Geography 21(2), 155-181, doi: 10.1080/02723646.2000.10642704.

Doyle, M.W., Stanley, E.H., Strayer, D.L., Jacobson, R.B., Schmidt, J.C., 2005. Effective discharge analysis of ecological processes in streams. Water Resources Research 41(11), W11411, doi: 10.1029/2005WR004222.

Eaton, L.S., Morgan, B.A., Kochel, R.C., Howard, A.D., 2003. Role of debris flows in long-term landscape denudation in the central Appalachians of Virginia. Geology 31(4), 339-342, doi: 10.1130/0091-7613(2003)031<0339:rodfil>2.0.co;2.

Emmett, W.W., Wolman, M.G., 2001. Effective discharge and gravel-bed rivers. Earth Surface Processes and Landforms 26(13), 1369-1380, doi: 10.1002/esp.303.

Erskine, W., 1994. River response to accelerated soil erosion in the Glenelg River catchment, Victoria. Australian Journal of Soil and Water Conservation (Australia) 7(2), 39-47.

Erskine, W., Livingstone, E., 1999. In-channel benches: the role of floods in their formation and destruction on bedrock-confined rivers. In: A.J. Miller, A. Gupta (Eds.), Varieties of fluvial form. John Wiley and Sons, New York, pp. 445-475.

Erskine, W.D., 1986. River metamorphosis and environmental change in the Macdonald Valley, New South Wales, since 1949. Australian Geographical Studies 24(1), 88-107, doi: 10.1111/j.1467-8470.1986.tb00513.x.

Erskine, W.D., Melville, M.D., 2008. Geomorphic and stratigraphic complexity: Holocene alluvial history of upper Wollombi Brook, Australia. Geografiska Annaler: Series A, Physical Geography 90(1), 19-35, doi: 10.1111/j.1468-0459.2008.00331.x.

Eyles, R.J., 1977. Changes in drainage networks since 1820, Southern Tablelands, N.S.W. Australian Geographer 13(6), 377-386, doi: 10.1080/00049187708702716.

Faulkner, H., 2008. Connectivity as a crucial determinant of badland morphology and evolution. Geomorphology 100(1–2), 91-103, doi: http://dx.doi.org/10.1016/j.geomorph.2007.04.039.

Fryirs, K., Brierley, G., 1998. The character and age structure of valley fills in upper Wolumla Creek catchment, south coast, New South Wales, Australia. Earth Surface Processes and Landforms 23(3), 271-287, doi: 10.1002/(SICI)1096-9837(199803)23:3<271::AID-ESP867>3.0.CO;2-5.

Fryirs, K., Brierley, G.J., 1999. Slope–channel decoupling in Wolumla catchment, New South Wales, Australia: the changing nature of sediment sources following European settlement. CATENA 35(1), 41-63, doi: http://dx.doi.org/10.1016/S0341-8162(98)00119-2.

Fryirs, K., Brierley, G.J., 2001. Variability in sediment delivery and storage along river courses in Bega catchment, NSW, Australia: implications for geomorphic river recovery. Geomorphology 38(3–4), 237-265, doi: http://dx.doi.org/10.1016/S0169-555X(00)00093-3.

Fryirs, K., Brierley, G.J., Preston, N.J., Kasai, M., 2007a. Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. CATENA 70(1), 49-67, doi: http://dx.doi.org/10.1016/j.catena.2006.07.007.

Fryirs, K., Brierley, G.J., Preston, N.J., Spencer, J., 2007b. Catchment-scale (dis)connectivity in sediment flux in the upper Hunter catchment, New South Wales, Australia. Geomorphology 84(3–4), 297-316, doi: http://dx.doi.org/10.1016/j.geomorph.2006.01.044.

Fryirs, K., Spink, A., Brierley, G., 2009. Post-European settlement response gradients of river sensitivity and recovery across the upper Hunter catchment, Australia. Earth Surface Processes and Landforms 34(7), 897-918, doi: 10.1002/esp.1771.

Fryirs, K., Brierley, G.J., Erskine, W.D., 2012. Use of ergodic reasoning to reconstruct the historical range of variability and evolutionary trajectory of rivers. Earth Surface Processes and Landforms 37(7), 763-773, doi: 10.1002/esp.3210.

Fryirs, K., 2013. (Dis)Connectivity in catchment sediment cascades: A fresh look at the sediment delivery problem. Earth Surface Processes and Landforms 38(1), 30-46, doi: 10.1002/esp.3242.

Fryirs, K., 2016. River sensitivity: A lost foundation concept in fluvial geomorphology. Earth Surface Processes and Landforms 42(1), 55-70, doi: 10.1002/esp.3940.

Fuller, I.C., Large, A.R.G., Milan, D.J., 2003. Quantifying channel development and sediment transfer following chute cutoff in a wandering gravel-bed river. Geomorphology 54(3–4), 307-323, doi: http://dx.doi.org/10.1016/S0169-555X(02)00374-4.

Fuller, I.C., Richardson, J.M., Basher, L., Dykes, R.C., Vale, S.S., 2011. Responses to river management? Geomorphic change over decadal and annual timescales in two gravel-bed rivers in New Zealand. In: D.A. Molina (Ed.), River channels: types, dynamics and changes. Earth Sciences in the 21st Century. Nova Press, New York, pp. 137-164.

Fuller, I.C., Basher, L.R., Hicks, D.M., 2014. Towards understanding river sediment dynamics as a basis for improved catchment, channel, and coastal management: The case of the Motueka catchment, Nelson, New Zealand. International Journal of River Basin Management 12(3), 175-192, doi: 10.1080/15715124.2014.885437.

Grove, J.R., Croke, J., Thompson, C., 2013. Quantifying different riverbank erosion processes during an extreme flood event. Earth Surface Processes and Landforms 38(12), 1393-1406, doi: 10.1002/esp.3386.

Hagerty, D.J., 1991. Piping/Sapping Erosion. I: Basic Considerations. Journal of Hydraulic Engineering 117(8), 991-1008, doi: doi:10.1061/(ASCE)0733-9429(1991)117:8(991).

Harrison, S., 2001. On Reductionism and Emergence in Geomorphology. Transactions of the Institute of British Geographers 26(3), 327-339, doi: 10.2307/3650649.

Harvey, A.M., 2002. Effective timescales of coupling within fluvial systems. Geomorphology 44(3–4), 175-201, doi: http://dx.doi.org/10.1016/S0169-555X(01)00174-X.

Hennessy, K., Fawcett, R., Kirono, D., Mpelasoka, F., Jones, D., Bathols, J., Whetton, P., Stafford Smith, M., Howden, M., Mitchell, C., 2008. An assessment of the impact of climate change on the nature and frequency of exceptional climatic events, Australian Bureau of Meteorology and CSIRO, Melbourne, Vic.

Heritage, G.L., Large, A.R.G., Moon, B.P., Jewitt, G., 2004. Channel hydraulics and geomorphic effects of an extreme flood event on the Sabie River, South Africa. CATENA 58(2), 151-181, doi: http://dx.doi.org/10.1016/j.catena.2004.03.004.

Hooke, J.M., 2003. Coarse sediment connectivity in river channel systems: A conceptual framework and methodology. Geomorphology 56(1–2), 79-94, doi: http://dx.doi.org/10.1016/S0169-555X(03)00047-3.

Hoyle, J., Brooks, A., Brierley, G., Fryirs, K., Lander, J., 2008. Spatial variability in the timing, nature and extent of channel response to typical human disturbance along the Upper Hunter River, New South Wales, Australia. Earth Surface Processes and Landforms 33(6), 868-889, doi: 10.1002/esp.1580.

Huang, H.Q., Chang, H.H., Nanson, G.C., 2004. Minimum energy as the general form of critical flow and maximum flow efficiency and for explaining variations in river channel pattern. Water Resources Research 40(4), W04502, doi: 10.1029/2003WR002539.

Hubble, T.C.T., Rutherfurd, I.D., 2010. Evaluating the relative contributions of vegetation and flooding in controlling channel widening: the case of the Nepean River, southeastern Australia. Australian Journal of Earth Sciences 57(5), 525-541, doi: 10.1080/08120099.2010.492910.

Ivezich, M., Hardie, R., 2014. Repeat channel change in Blackfellows Creek, Lockyer Valley, South East Queensland. In: G. Vietz, I.D. Rutherford, R. Hughes (Eds.). Proceedings of the 7th Australian Stream Management Conference, Townsville, Queensland, pp. 81-88.

Jacobson, R.B., Miller, A.J., Smith, J.A., 1989. The role of catastrophic geomorphic events in central Appalachian landscape evolution. Geomorphology 2(1–3), 257-284, doi: http://dx.doi.org/10.1016/0169-555X(89)90015-9.

Jansen, J.D., Nanson, G.C., 2004. Anabranching and maximum flow efficiency in Magela Creek, northern Australia. Water Resources Research 40(4), W04503, doi: 10.1029/2003WR002408.

Jerolmack, D.J., Mohrig, D., 2007. Conditions for branching in depositional rivers. Geology 35(5), 463-466, doi: 10.1130/g23308a.1.

Jones, L.S., Schumm, S.A., 1999. Causes of Avulsion: An overview. In: N.D. Smith, J. Rogers (Eds.), Fluvial Sedimentology VI. Blackwell Science, United Kingdom, pp. 171-178.

Kemp, J., Olley, J.M., Ellison, T., McMahon, J., 2015. River response to European settlement in the subtropical Brisbane River, Australia. Anthropocene 11, 48-60, doi: http://dx.doi.org/10.1016/j.ancene.2015.11.006.

Kochel, R.C., 1988. Geomorphic impact of large floods: review and new perspectives on magnitude and frequency. In: K. Baker, R.C. Kochel, P.C. Patton (Eds.), Flood Geomorphology. Wiley-Interscience, Toronto, pp. 169-187.

Lane, E.W., 1955. Importance of fluvial morphology in hydraulic engineering, Proceedings of the American Society of Civil Engineers. American Society of Civil Engineers.

Larkin, Z.T., Ralph, T.J., Tooth, S., McCarthy, T.S., 2016. The interplay between extrinsic and intrinsic controls in determining floodplain wetland characteristics in the South African drylands. Earth Surface Processes and Landforms, doi: 10.1002/esp.4075.

Leahy, P.J., Tibby, J., Kershaw, A.P., Heijnis, H., Kershaw, J.S., 2005. The impact of European settlement on Bolin Billabong, a Yarra River floodplain lake, Melbourne, Australia. River Research and Applications 21(2-3), 131-149, doi: 10.1002/rra.837.

Leopold, L.B., Wolman, M.G., 1956. Floods in relation to the river channel, Union Geod. et Geophysics International, Association d'Hydrologie (Symposium in Dijon), Publication, pp. 85-98.

Magilligan, F.J., 1992. Thresholds and the spatial variability of flood power during extreme floods. Geomorphology 5(3–5), 373-390, doi: 10.1016/0169-555X(92)90014-F.

Miller, A.J., 1990. Flood hydrology and geomorphic effectiveness in the central Appalachians. Earth Surface Processes and Landforms 15(2), 119-134.

Montgomery, D.R., 1999. Process domains and the river continuum. JAWRA Journal of the American Water Resources Association 35(2), 397-410, doi: 10.1111/j.1752-1688.1999.tb03598.x.

Murray, A.B., Lazarus, E., Ashton, A., Baas, A., Coco, G., Coulthard, T., Fonstad, M., Haff, P., McNamara, D., Paola, C., Pelletier, J., Reinhardt, L., 2009. Geomorphology, complexity, and the emerging science of the Earth's surface. Geomorphology 103(3), 496-505, doi: http://dx.doi.org/10.1016/j.geomorph.2008.08.013.

Murray, A.B., Coco, G., Goldstein, E.B., 2014. Cause and effect in geomorphic systems: Complex systems perspectives. Geomorphology 214, 1-9, doi: http://dx.doi.org/10.1016/j.geomorph.2014.03.001.

Nanson, G.C., Huang, H.Q., 2008. Least action principle, equilibrium states, iterative adjustment and the stability of alluvial channels. Earth Surface Processes and Landforms 33(6), 923-942.

Newson, M.D., 1980. The geomorphological effectiveness of floods - A contribution stimulated by two recent events in mid-Wales. Earth Surf. Process. 5(1), 1-16.

Olley, J., Wilkinson, S., Caitcheon, G., Read, A., 2006. Protecting Moreton Bay: How can we reduce sediment and nutrient loads by 50%. Proceedings of the 9th International River Symposium, Brisbane, Australia 47, 19.

Olley, J., Burton, J., Smolders, K., Pantus, F., Pietsch, T., 2013. The application of fallout radionuclides to determine the dominant erosion process in water supply catchments of subtropical South-east Queensland, Australia. Hydrological Processes 27(6), 885-895, doi: 10.1002/hyp.9422.

Page, K.J., Frazier, P., Pietsch, T., Dehaan, R., 2007. Channel change following European settlement: Gilmore Creek, southeastern Australia. Earth Surface Processes and Landforms 32(9), 1398-1411, doi: 10.1002/esp.1481.

Parsons, A.J., Bracken, L.J., Poeppl, R.E., Wainwright, J., Keesstra, S.D. (Eds.), 2015. Connectivity in Water and Sediment Dynamics, Virtual Special Issue. Earth Surface Processes and Landforms.

Phillips, J.D., 1999. Divergence, convergence, and self-organization in landscapes. Annals of the Association of American Geographers 89(3), 466-488, doi: 10.2307/2564493.

Phillips, J.D., 2003. Sources of nonlinearity and complexity in geomorphic systems. Progress in Physical Geography 27(1), 1-23, doi: 10.1191/0309133303pp340ra.

Phillips, J.D., 2006. Deterministic chaos and historical geomorphology: A review and look forward. Geomorphology 76(1–2), 109-121, doi: http://dx.doi.org/10.1016/j.geomorph.2005.10.004.

Phillips, J.D., 2007. The perfect landscape. Geomorphology 84(3–4), 159-169, doi: 10.1016/j.geomorph.2006.01.039.

Phillips, J.D., 2009a. Changes, perturbations, and responses in geomorphic systems. Progress in Physical Geography 33(1), 17-30, doi: 10.1177/0309133309103889.

Phillips, J.D., 2009b. Biological energy in landscape evolution. American Journal of Science 309(4), 271-289, doi: 10.2475/04.2009.01.

Phillips, J.D., 2010a. Amplifiers, filters and geomorphic responses to climate change in Kentucky rivers. Climatic Change 103(3), 571-595, doi: 10.1007/s10584-009-9775-z.

Phillips, J.D., 2010b. The job of the river. Earth Surface Processes and Landforms 35(3), 305-313, doi: 10.1002/esp.1915.

Phillips, J.D., 2011. Universal and local controls of avulsions in southeast Texas Rivers. Geomorphology 130(1–2), 17-28, doi: 10.1016/j.geomorph.2010.10.001.

Phillips, J.D., 2014. Thresholds, mode switching, and emergent equilibrium in geomorphic systems. Earth Surface Processes and Landforms 39(1), 71-79, doi: 10.1002/esp.3492.

Phillips, J.D., 2015. Badass geomorphology. Earth Surface Processes and Landforms 40(1), 22-33, doi: 10.1002/esp.3682.

Phillips, J.D., Van Dyke, C., 2016. Principles of geomorphic disturbance and recovery in response to storms. Earth Surface Processes and Landforms 41(7), 971-979, doi: 10.1002/esp.3912.

Reinfelds, I., Rutherfurd, I.A.N., Bishop, P., 1995. History and Effects of Channelisation on the Latrobe River, Victoria. Australian Geographical Studies 33(1), 60-76, doi: 10.1111/j.1467-8470.1995.tb00685.x.

Reisinger, A., Kitching, R.L., Chiew, F., Hughes, L., Newton, P.C.D., Schuster, S.S., Tait, A., Whetton, P., 2014. Australasia. In: V.R. Barros, C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, L.L. White (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1371-1438.

Rhoads, B.L., 2006. The Dynamic Basis of Geomorphology Reenvisioned. Annals of the Association of American Geographers 96(1), 14-30, doi: 10.1111/j.1467-8306.2006.00496.x.

Rice, S., 1998. Which tributaries disrupt downstream fining along gravel-bed rivers? Geomorphology 22(1), 39-56, doi: http://dx.doi.org/10.1016/S0169-555X(97)00052-4.

Rice, S., 1999. The nature and controls on downstream fining within sedimentary links. Journal of Sedimentary Research 69(1), 32-39.

Richards, K., 1999. The magnitude-frequency concept in fluvial geomorphology: A component of a degenerating research programme? Zeitschrift für Geomorphologie Supplement Volumes 115, 1-18.

Rinaldi, M., 2003. Recent channel adjustments in alluvial rivers of Tuscany, central Italy. Earth Surface Processes and Landforms 28(6), 587-608, doi: 10.1002/esp.464.

Rustomji, P., Bennett, N., Chiew, F., 2009. Flood variability east of Australia's Great Dividing Range. Journal of Hydrology 374(3–4), 196-208, doi: http://dx.doi.org/10.1016/j.jhydrol.2009.06.017.

Rutherfurd, I., 2000. Some human impacts on Australian stream channel morphology. In: S.O. Brizga, B.L. Finlayson (Eds.), River Management: The Australasian Experience. John Wiley and Sons, New York, pp. 11-49.

Sargood, M.B., Cohen, T.J., Thompson, C., Croke, J., 2015. Hitting rock bottom: morphological responses of bedrock-confined streams to a catastrophic flood. Earth Surface Dynamics 3(2), 265-279.

Schumm, S.A., 1969. River metamorphosis, Journal of the hydraulics division, American Society of Civil Engineers, pp. 255-273.

Schumm, S.A., 1971. Fluvial geomorphology: Channel adjustment and river metamorphosis. Water Resources Publications, Colorado State University, CO.

Schumm, S.A., 1973. Geomorphic thresholds and complex response of drainage systems. Fluvial Geomorphology 6, 69-85.

Schumm, S.A., 1979. Geomorphic thresholds: The concept and its applications. Transactions of the Institute of British Geographers 4(4), 485-515, doi: 10.2307/622211.

Schumm, S.A., 1983. River morphology and behavior: Problems of extrapolation. In: C.M. Elliott (Ed.), River Meandering, Proceedings of the Conference Rivers '83. American Society of Civil Engineers, New York, pp. 16-29.

Schumm, S.A., 1985. Explanation and extrapolation in geomorphology: seven reasons for geologic uncertainty. Transactions, Japanese Geomorphological Union 6(1), 1-18.

Schumm, S.A., 1988. Geomorphic Hazards: problem of prediction. Zeitschrift für Geomorphologie 67, 17-24.

Slingerland, R., Smith, N.D., 2004. River avulsions and their deposits. Annual Review of Earth and Planetary Sciences 32(1), 257-285, doi: 10.1146/annurev.earth.32.101802.120201.

Sloan, J., Miller, J.R., Lancaster, N., 2001. Response and recovery of the Eel River, California, and its tributaries to floods in 1955, 1964, and 1997. Geomorphology 36(3–4), 129-154, doi: http://dx.doi.org/10.1016/S0169-555X(00)00037-4.

Sugden, D.E., Summerfield, M.A., Burt, T.P., 1997. Editorial: Linking Short-term Geomorphic Processes to Landscape Evolution. Earth Surface Processes and Landforms 22(3), 193-194, doi: 10.1002/(SICI)1096-9837(199703)22:3<193::AID-ESP747>3.0.CO;2-9.

Surian, N., Cisotto, A., 2007. Channel adjustments, bedload transport and sediment sources in a gravel-bed river, Brenta River, Italy. Earth Surface Processes and Landforms 32(11), 1641-1656, doi: 10.1002/esp.1591.

Taschetto, A.S., England, M.H., 2009. An analysis of late twentieth century trends in Australian rainfall. International Journal of Climatology 29(6), 791-807, doi: 10.1002/joc.1736.

Temme, A.J.A.M., Keiler, M., Karssenberg, D., Lang, A. (Eds.), 2016. Complexity and Non-Linearity in Earth Surface Processes, Virtual Special Issue. Earth Surface Processes and Landforms.

The Big Flood Project Team, 2016. The Big Flood: Will it Happen Again?, http://thebigflood.com.au/, Final Report available at http://thebigflood.com.au/resources.html.

Thomas, D.S.G., Allison, R.J., 1993. Landscape sensitivity. Wiley, Chichester.

Thompson, C., Croke, J., 2013. Geomorphic effects, flood power, and channel competence of a catastrophic flood in confined and unconfined reaches of the upper Lockyer Valley, southeast Queensland, Australia. Geomorphology 197(0), 156-169, doi: 10.1016/j.geomorph.2013.05.006.

Thompson, C., Croke, J., Grove, J., Khanal, G., 2013. Spatio-temporal changes in river bank mass failures in the Lockyer Valley, Queensland, Australia. Geomorphology 191(0), 129-141, doi: 10.1016/j.geomorph.2013.03.010.

Thompson, C., Croke, J., Dent, C., 2014. Potential impacts of levee in construction in the Lockyer Valley, 7th Australian Stream Management Conference, pp. 109-115.

Thompson, C., Croke, J., Fryirs, K., Grove, J.R., 2016a. A channel evolution model for subtropical macrochannel systems. CATENA 139, 199-213, doi: http://dx.doi.org/10.1016/j.catena.2015.12.012.

Thompson, C., Fryirs, K., Croke, J., 2016b. The disconnected sediment conveyor belt: Patterns of longitudinal and lateral erosion and deposition during a catastrophic flood in the Lockyer Valley, southeast Queensland, Australia. River Research and Applications 32, 540-551, doi: 10.1002/rra.2897.

Thompson, C., unpublished dataset. Lockyer Valley Landslide Dataset.

Thoms, M.C., Walker, K.F., 1993. Channel changes associated with two adjacent weirs on a regulated lowland alluvial river. Regulated Rivers: Research & Management 8(3), 271-284, doi: 10.1002/rrr.3450080306.

Tinkler, K.J., 1971. Active valley meanders in south-central Texas and their wider implications. Geological Society of America Bulletin 82(7), 1783-1800, doi: 10.1130/0016-7606(1971)82[1783:avmist]2.0.co;2.

Törnqvist, T.E., Bridge, J.S., 2002. Spatial variation of overbank aggradation rate and its influence on avulsion frequency. Sedimentology 49(5), 891-905, doi: 10.1046/j.1365-3091.2002.00478.x.

van Dijk, A.I.J.M., Beck, H.E., Crosbie, R.S., de Jeu, R.A.M., Liu, Y.Y., Podger, G.M., Timbal, B., Viney, N.R., 2013. The Millennium Drought in southeast Australia (2001–2009): Natural and human causes and implications for water resources, ecosystems, economy, and society. Water Resources Research 49(2), 1040-1057, doi: 10.1002/wrcr.20123.

Walling, D.E., 1983. The sediment delivery problem. Journal of Hydrology 65(1–3), 209-237, doi: http://dx.doi.org/10.1016/0022-1694(83)90217-2.

Warke, P.A., McKinley, J. (Eds.), 2011a. Scale issues in geomorphology. Special Issue, 130 (1-2). Geomorphology.

Warke, P.A., McKinley, J.M., 2011b. Scale issues in geomorphology. Geomorphology 130(1–2), 1-4, doi: http://dx.doi.org/10.1016/j.geomorph.2011.04.031.

Werner, B.T., Fink, T.M., 1993. Beach cusps as self-organized patterns. Science 260(5110), 968-971, doi: 10.1126/science.260.5110.968.

Werner, B.T., 1999. Complexity in natural landform patterns. Science 284(5411), 102-104, doi: 10.1126/science.284.5411.102.

Werner, B.T., 2003. Modeling landforms as self-organized, hierarchical dynamical systems. In: P.R. Wilcock, R.M. Iverson (Eds.), Prediction in Geomorphology. American Geophysical Union, Washington D.C., pp. 133-150.

Wohl, E., 2011. What should these rivers look like? Historical range of variability and human impacts in the Colorado Front Range, USA. Earth Surface Processes and Landforms 36(10), 1378-1390, doi: 10.1002/esp.2180.

Wohl, E., 2013. Wilderness is dead: Whither critical zone studies and geomorphology in the Anthropocene? Anthropocene 2(0), 4-15, doi: 10.1016/j.ancene.2013.03.001.

Wohl, E., Rathburn, S. (Eds.), 2013. Historical Range of Variability in a Geomorphic Context, Virtual Special Issue. Earth Surface Processes and Landforms.

Wohl, E., Lane, S.N., Wilcox, A.C., 2015. The science and practice of river restoration. Water Resources Research 51(8), 5974-5997, doi: 10.1002/2014WR016874.

Wolman, M.G., Miller, J.P., 1960. Magnitude and frequency of forces in geomorphic processes. The Journal of Geology 68(1), 54-74, doi: 10.2307/30058255.

Wolman, M.G., Gerson, R., 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surface Processes 3(2), 189-208, doi: 10.1002/esp.3290030207.

Appendices

APPENDIX 1. Supporting information for Chapter 3 – Geomorphic adjustments along Murphys-Lockyer Creek.

Form	Distance Downstream (m)[a]	Type	Process	Unit	Year Range	Reach	Reach Length (m)	Channel Length (m)	Reach Proportion
Erosion	15464	geometric	widening	bank	1997-2011	MCR	17411	247	1.42
Erosion	26718	geometric	widening	bank	1997-2011	ULR	8799	538	6.11
Erosion	26717	geometric	incision	bed	1997-2011	ULR	8799	320	3.64
Erosion	26625	geometric	extension	bend	1997-2011	ULR	8799	146	1.65
Erosion	29864	geometric	bank failure	slumped bank	1997-2011	ULR	8799	149	1.70
Erosion	30416	geometric	extension	bend	1997-2011	ULR	8799	211	2.40
Erosion	30200	geometric	incision	bed	1997-2011	ULR	8799	130	1.48
Erosion	25628	geometric	incision	bed	1997-2011	ULR	8799	57	0.65
Erosion	33601	assemblage	chute	chute channel	1997-2011	LSR	2863	460	16.08
Erosion	38588	geometric	incision	bed	1997-2011	PRR	6491	76	1.18
Erosion	40379	geometric	widening	bank	1997-2011	PRR	6491	275	4.23
Erosion	53744	geometric	bank failure	slumped bank	1997-2011	GRR	20264	171	0.85
Erosion	56359	geometric	bank failure	slumped bank	1997-2011	GRR	20264	332	1.64
Erosion	69777	geometric	bank failure	slumped bank	1997-2011	GAR	4057	1077	26.53
Erosion	72666	assemblage	chute	chute channel	1997-2011	GAR	4057	185	4.55
Erosion	32895	assemblage	scour	scour pool	1997-2011	LSR	2863	64	2.25
Erosion	64999	assemblage	scour	scour pool	1997-2011	GRR	20264	122	0.60
Erosion	84540	geometric	widening	bank	1997-2011	LLR	68876	1114	1.62
Erosion	62281	assemblage	chute	chute channel	1997-2011	GRR	20264	91	0.45
Erosion	30654	assemblage	chute	chute channel	1997-2011	ULR	8799	90	1.02
Erosion	74573	assemblage	removal	point bar	1997-2011	GAR	4057	228	5.62
Erosion	71668	geometric	bank failure	slumped bank	1997-2011	GAR	4057	429	10.58
Erosion	82650	geometric	bank failure	slumped bank	1997-2011	LLR	68876	157	0.23
Erosion	47392	geometric	removal	bench/ledge	1997-2011	HTR	4455	76	1.71
Erosion	92560	assemblage	removal	bench/ledge	1997-2011	LLR	68876	59	0.09
Erosion	96309	assemblage	chute	chute channel	1997-2011	LLR	68876	68	0.10
Erosion	97229	assemblage	chute	chute channel	1997-2011	LLR	68876	250	0.36
Erosion	149960	assemblage	removal	lateral bar	1997-2011	LLR	68876	124	0.18
Erosion	48549	geometric	widening	banks	1997-2011	FSR	534	534	100.00
Erosion	88572	assemblage	chute	chute channel	1997-2011	LLR	68876	90	0.13
Erosion	67130	assemblage	chute	chute channel	1997-2011	GRR	20264	666	3.29
Erosion	51310	geometric	bank failure	slumped bank	1997-2011	GRR	20264	84	0.42
Erosion	53321	geometric	bank failure	slumped bank	1997-2011	GRR	20264	55	0.27
Erosion	54605	geometric	bank failure	slumped bank	1997-2011	GRR	20264	155	0.76
Erosion	54971	geometric	bank failure	slumped bank	1997-2011	GRR	20264	55	0.27
Erosion	55632	geometric	bank failure	slumped bank	1997-2011	GRR	20264	65	0.32
Erosion	55767	geometric	bank failure	slumped bank	1997-2011	GRR	20264	53	0.26
Erosion	58030	geometric	bank failure	slumped bank	1997-2011	GRR	20264	82	0.40
Erosion	60197	geometric	bank failure	slumped bank	1997-2011	GRR	20264	99	0.49
Erosion	60301	geometric	bank failure	slumped bank	1997-2011	GRR	20264	68	0.34
Erosion	60422	geometric	bank failure	slumped bank	1997-2011	GRR	20264	106	0.52
Erosion	60610	geometric	bank failure	slumped bank	1997-2011	GRR	20264	67	0.33
Erosion	68779	geometric	bank failure	slumped bank	1997-2011	GRR	20264	21	0.10
Erosion	75707	geometric	bank failure	slumped bank	1997-2011	LLR	68876	169	0.25
Erosion	77179	geometric	bank failure	slumped bank	1997-2011	LLR	68876	32	0.05
Erosion	77557	geometric	bank failure	slumped bank	1997-2011	LLR	68876	16	0.02
Erosion	78031	geometric	bank failure	slumped bank	1997-2011	LLR	68876	64	0.09
Erosion	82520	geometric	bank failure	slumped bank	1997-2011	LLR	68876	82	0.12
Erosion	83081	geometric	bank failure	slumped bank	1997-2011	LLR	68876	116	0.17
Erosion	83815	geometric	scour	scour pool	1997-2011	LLR	68876	166	0.24
Erosion	84092	geometric	bank failure	slumped bank	1997-2011	LLR	68876	77	0.11
Erosion	84250	geometric	bank failure	slumped bank	1997-2011	LLR	68876	43	0.06
Erosion	86620	geometric	bank failure	slumped bank	1997-2011	LLR	68876	62	0.09
Erosion	47131	geometric	bank failure	slumped bank	1997-2011	HTR	4455	69	1.55
Erosion	41776	geometric	bank failure	slumped bank	1997-2011	PRR	6491	96	1.47

Form	Distance Downstream (m)[a]	Type	Process	Unit	Year Range	Reach	Reach Length (m)	Channel Length (m)	Reach Proportion
Erosion	31189	geometric	bank failure	slumped bank	1997-2011	LSR	2863	32	1.13
Erosion	20369	geometric	bank failure	slumped bank	1997-2011	MCR	17411	27	0.15
Erosion	140504	geometric	bank failure	slumped bank	1997-2011	LLR	68876	153	0.22
Erosion	135709	geometric	bank failure	slumped bank	1997-2011	LLR	68876	23	0.03
Erosion	129568	geometric	bank failure	slumped bank	1997-2011	LLR	68876	34	0.05
Erosion	127528	geometric	bank failure	slumped bank	1997-2011	LLR	68876	39	0.06
Erosion	126584	geometric	bank failure	slumped bank	1997-2011	LLR	68876	37	0.05
Erosion	125214	geometric	bank failure	slumped bank	1997-2011	LLR	68876	34	0.05
Erosion	117385	geometric	bank failure	slumped bank	1997-2011	LLR	68876	29	0.04
Erosion	107407	geometric	bank failure	slumped bank	1997-2011	LLR	68876	33	0.05
Erosion	106144	geometric	bank failure	slumped bank	1997-2011	LLR	68876	71	0.10
Erosion	92202	geometric	bank failure	slumped bank	1997-2011	LLR	68876	438	0.64
Erosion	90920	geometric	bank failure	slumped bank	1997-2011	LLR	68876	69	0.10
Erosion	90145	geometric	bank failure	slumped bank	1997-2011	LLR	68876	138	0.20
Erosion	11543	geometric	widening	bank	1997-2011	MCR	17411	204	1.17
Erosion	11841	assemblage	chute	chute channel	1997-2011	MCR	17411	36	0.21
Erosion	12357	geometric	widening	bank	1997-2011	MCR	17411	153	0.88
Erosion	12744	geometric	removal	bench/ledge	1997-2011	MCR	17411	160	0.92
Erosion	13902	geometric	extension	bend	1997-2011	MCR	17411	30	0.17
Erosion	13917	geometric	chute	chute channel	1997-2011	MCR	17411	50	0.29
Erosion	20172	geometric	widening	bank	1997-2011	MCR	17411	71	0.41
Erosion	21232	geometric	bank failure	bank	1997-2011	MCR	17411	38	0.22
Erosion	3023	geometric	widening	bank	1997-2011	MCR	17411	162	0.93
Erosion	3775	geometric	widening	bank	1997-2011	MCR	17411	390	2.24
Erosion	4284	geometric	widening	bank	1997-2011	MCR	17411	88	0.51
Erosion	4646	geometric	widening	bank	1997-2011	MCR	17411	170	0.98
Erosion	5142	geometric	widening	bank	1997-2011	MCR	17411	246	1.41
Erosion	5151	assemblage	chute	chute channel	1997-2011	MCR	17411	160	0.92
Erosion	6158	geometric	widening	bank	1997-2011	MCR	17411	1100	6.32
Erosion	7422	geometric	widening	bank	1997-2011	MCR	17411	240	1.38
Erosion	8577	assemblage	scour	scour pool	1997-2011	MCR	17411	21	0.12
Erosion	8471	geometric	widening	bank	1997-2011	MCR	17411	778	4.47
Erosion	9360	geometric	widening	bank	1997-2011	MCR	17411	275	1.58
Erosion	31414	assemblage	removal	lateral bar	1997-2011	ULR	8799	36	0.41
Deposition	26103	assemblage	accretion	point bar	1997-2011	ULR	8799	134	1.53
Deposition	26258	assemblage	formation	forced bars	1997-2011	ULR	8799	169	1.92
Deposition	29695	assemblage	formation	lateral bar	1997-2011	ULR	8799	56	0.64
Deposition	34690	assemblage	formation	diagonal bar	1997-2011	LSR	2863	111	3.87
Deposition	33405	assemblage	formation	sand sheet	1997-2011	LSR	2863	2042	71.33
Deposition	48918	assemblage	formation	lateral bar	1997-2011	GRR	20264	114	0.56
Deposition	28871	assemblage	formation	longitudinal bar	1997-2011	ULR	8799	23	0.26
Deposition	26366	assemblage	formation	sand sheet	1997-2011	ULR	8799	102	1.16
Deposition	29813	assemblage	formation	diagonal bar	1997-2011	ULR	8799	60	0.68
Deposition	29901	assemblage	formation	lateral bar	1997-2011	ULR	8799	107	1.22
Deposition	102508	assemblage	formation	sand sheet	1997-2011	LLR	68876	276	0.40
Deposition	48682	assemblage	formation	lateral bar	1997-2011	FSR	534	109	20.41
Deposition	11537	assemblage	formation	sand sheet	1997-2011	MCR	17411	204	1.17
Deposition	11827	assemblage	formation	sand sheet	1997-2011	MCR	17411	114	0.65
Deposition	17315	assemblage	formation	sand sheet	1997-2011	MCR	17411	117	0.67
Deposition	19323	assemblage	formation	forced bars	1997-2011	MCR	17411	16	0.09
Deposition	19972	assemblage	accretion	point bar	1997-2011	MCR	17411	33	0.19
Deposition	20461	assemblage	formation	sand sheet	1997-2011	MCR	17411	150	0.86
Deposition	3775	assemblage	formation	sand sheet	1997-2011	MCR	17411	390	2.24
Deposition	5140	assemblage	formation	sand sheet	1997-2011	MCR	17411	246	1.41
Deposition	6158	assemblage	formation	sand sheet	1997-2011	MCR	17411	1100	6.32
Deposition	7409	assemblage	formation	sand sheet	1997-2011	MCR	17411	240	1.38
Deposition	8466	assemblage	formation	sand sheet	1997-2011	MCR	17411	778	4.47
Deposition	9360	assemblage	formation	sand sheet	1997-2011	MCR	17411	275	1.58

Form	Distance Downstream (m)[a]	Type	Process	Unit	Year Range	Reach	Reach Length (m)	Channel Length (m)	Reach Proportion
FPSS		floodplain	Overbank	FP sand sheet	1997-2011	MCR	17411	176	1.01
FPSS		floodplain	Overbank	FP sand sheet	1997-2011	MCR	17411	177	1.02
FPSS		floodplain	Overbank	FP sand sheet	1997-2011	MCR	17411	120	0.69
FPSS		floodplain	Overbank	FP sand sheet	1997-2011	MCR	17411	207	1.19
FPSS		floodplain	Overbank	FP sand sheet	1997-2011	MCR	17411	446	2.56
FPSS		floodplain	Overbank	FP sand sheet	1997-2011	MCR	17411	230	1.32
FPSS		floodplain	Overbank	FP sand sheet	1997-2011	MCR	17411	123	0.71
FPSS		floodplain	Overbank	FP sand sheet	1997-2011	MCR	17411	120	0.69
FPSS		floodplain	Overbank	FP sand sheet	1997-2011	LSR	2863	2590	90.46
FPSS		floodplain	Overbank	FP sand sheet	1997-2011	PRR	6491	290	4.47
FPSS		floodplain	Overbank	FP sand sheet	1997-2011	PRR	6491	565	8.70
FPSS		floodplain	Overbank	FP sand sheet	1997-2011	HTR	4455	2300	51.63
FPSS		floodplain	Overbank	FP sand sheet	1997-2011	HTR	4455	376	8.44
FPSS		floodplain	Overbank	FP sand sheet	1997-2011	GRR	20264	19200	94.75
FPSS		floodplain	Overbank	FP sand sheet	1997-2011	LLR	68876	7000	10.16
FPSS		floodplain	Overbank	FP sand sheet	1997-2011	MCR	17411	80	0.46
FPSS		floodplain	Overbank	FP sand sheet	1997-2011	MCR	17411	80	0.46
Erosion	50570	assemblage	scour	scour pool	1974-1997	GRR	20264	119	0.59
Erosion	84866	geometric	removal	bench/ledge	1974-1997	LLR	68876	113	0.16
Erosion	46199	assemblage	removal	diagonal bar	1974-1997	HTR	4455	108	2.43
Erosion	18196	geometric	removal	bench	1974-1997	MCR	17411	130	0.75
Erosion	149597	geometric	widening	bank	1974-1997	LLR	68876	290	0.42
Deposition	82554	assemblage	accretion	bench/ledge	1974-1997	LLR	68876	84	0.12
Deposition	150026	assemblage	formation	lateral bar	1974-1997	LLR	68876	243	0.35
Deposition	55998	assemblage	accretion	bench	1974-1997	GRR	20264	916	4.52
Reorganization	48040	assemblage	GUA	lateral bars to benches	1974-1997	HTR	4455	594	13.33
Reorganization	48537	assemblage	GUA	lateral bars to benches	1974-1997	FSR	534	534	100.00
Reorganization	49571	assemblage	GUA	lateral bars to benches	1974-1997	GRR	20264	1400	6.91
Reorganization	69904	assemblage	GUA	lateral bars to benches	1974-1997	GRR	20264	554	2.73
Reorganization	47392	assemblage	GUA	lateral bars to benches	1974-1997	HTR	4455	96	2.15
Reorganization	46243	assemblage	GUA	lateral bars to benches	1974-1997	HTR	4455	474	10.65
Reorganization	46207	assemblage	ICR	Inset channel shift	1974-1997	HTR	4455	404	9.07
Reorganization	36069	assemblage	GUA	lateral bars to benches	1974-1997	PRR	6491	53	0.81
Erosion	28784	assemblage	chute	chute channel	1971-1974	ULR	8799	291	3.31
Erosion	92975	geometric	bank failure	slumped bank	1971-1974	LLR	68876	256	0.37
Erosion	82554	geometric	scour	scour pool	1971-1974	LLR	68876	84	0.12
Erosion	92196	geometric	removal	bench/Ledge	1971-1974	LLR	68876	139	0.20
Erosion	139026	assemblage	chute	chute channel	1971-1974	LLR	68876	182	0.26
Erosion	9488	geometric	extension	bend	1971-1974	MCR	17411	44	0.25
Erosion	31412	assemblage	chute	chute channel	1971-1974	ULR	8799	36	0.41
Erosion	46752	geometric	removal	bench	1971-1974	HTR	4455	170	3.82
Erosion	46752	assemblage	chute	chute channel	1971-1974	HTR	4455	70	1.57
Erosion	48462	geometric	bank failure	bank	1971-1974	FSR	534	85	15.92
Erosion	49560	assemblage	removal	lateral bar	1971-1974	GRR	20264	716	3.53
Erosion	49459	geometric	widening	bank	1971-1974	GRR	20264	300	1.48

Form	Distance Downstream (m)[a]	Type	Process	Unit	Year Range	Reach	Reach Length (m)	Channel Length (m)	Reach Proportion
Erosion	51082	assemblage	removal	longitudinal bar	1971-1974	GRR	20264	80	0.39
Erosion	51292	geometric	removal	bench	1971-1974	GRR	20264	217	1.07
Erosion	52086	geometric	widening	bank	1971-1974	GRR	20264	100	0.49
Erosion	56607	geometric	bank failure	bank	1971-1974	GRR	20264	180	0.89
Erosion	57459	geometric	bank failure	bank	1971-1974	GRR	20264	80	0.39
Erosion	62093	geometric	bank failure	bank	1971-1974	GRR	20264	33	0.16
Erosion	63967	geometric	widening	bank	1971-1974	GRR	20264	111	0.55
Erosion	64787	geometric	removal	bench	1971-1974	GRR	20264	213	1.05
Erosion	71851	geometric	removal	bench	1971-1974	GAR	4057	131	3.23
Erosion	74648	geometric	removal	bench	1971-1974	GAR	4057	51	1.26
Erosion	82901	geometric	removal	bench	1971-1974	LLR	68876	163	0.24
Erosion	94827	assemblage	scour	bed	1971-1974	LLR	68876	73	0.11
Deposition	26073	assemblage	accretion	point bar	1971-1974	ULR	8799	122	1.38
Deposition	36103	assemblage	formation	lateral bar	1971-1974	PRR	6491	52	0.80
Deposition	46199	assemblage	formation	diagonal bar	1971-1974	HTR	4455	108	2.43
Deposition	69648	assemblage	formation	lateral bar	1971-1974	GRR	20264	86	0.43
Deposition	30702	assemblage	accretion	lateral bar	1971-1974	ULR	8799	94	1.07
Deposition	32105	assemblage	formation	sand sheet	1971-1974	ULR	8799	275	3.13
Deposition	44452	assemblage	accretion	longitudinal bar	1971-1974	HTR	4455	30	0.67
Deposition	48130	assemblage	formation	sand sheet	1971-1974	HTR	4455	240	5.39
Deposition	50244	assemblage	formation	diagonal bar	1971-1974	GRR	20264	100	0.49
Deposition	52403	assemblage	formation	lateral bar	1971-1974	GRR	20264	64	0.32
Deposition	56199	assemblage	formation	longitudinal bar	1971-1974	GRR	20264	54	0.27
Deposition	57191	assemblage	formation	point bar	1971-1974	GRR	20264	27	0.13
Deposition	79987	assemblage	formation	lateral bar	1971-1974	LLR	68876	60	0.09
Reorganization	54158	assemblage	GUA	lateral bars to benches	1971-1974	GRR	20264	2664	13.15
Reorganization	42506	assemblage	ICR	Inset channel shift	1971-1974	PRR	6491	173	2.67
Reorganization	71592	assemblage	GUA	lateral bars to benches	1971-1974	GAR	4057	421	10.38
Erosion	10180	geometric	extension	bend	1951-1971	MCR	17411	94	0.54
Erosion	11230	geometric	extension	bend	1951-1971	MCR	17411	110	0.63
Erosion	44140	assemblage	chute	chute channel	1951-1971	HTR	4455	69	1.56
Erosion	69812	assemblage	chute	chute channel	1951-1971	GRR	20264	218	1.08
Erosion	101008	assemblage	scour	bed	1951-1971	LLR	68876	44	0.06
Reorganization	61341	assemblage	GUA	lateral bars to benches	1951-1971	GRR	20264	234	1.15
Reorganization	51137	assemblage	GUA	lateral bars to benches	1951-1971	GRR	20264	2005	9.89
Reorganization	46207	assemblage	ICR	Inset channel shift	1951-1971	HTR	4455	404	9.07
Reorganization	45291	assemblage	ICR	Inset channel shift	1951-1971	HTR	4455	311	6.97
Erosion	149315	geometric	bank failure	slumped bank	1933-1951	LLR	68876	158	0.23
Erosion	118672	geometric	extension	bend	1890-1951	LLR	68876	1025	1.49
Erosion	6785	geometric	extension	bend	1933-1951	MCR	17411	47	0.27
Erosion	78484	geometric	removal	bench/Ledge	1933-1951	LLR	68876	929	1.35
Erosion	104947	geometric	extension	bend	1890-1951	LLR	68876	91	0.13
Erosion	47200	geometric	removal	sand sheet	1933-1951	HTR	4455	191	4.30

Form	Distance Downstream (m)[a]	Type	Process	Unit	Year Range	Reach	Reach Length (m)	Channel Length (m)	Reach Proportion
Reorganization	84476	assemblage	GUA	benches to lateral bars	1933-1951	LLR	68876	412	0.60
Reorganization	71587	assemblage	GUA	benches to lateral bars	1933-1951	GAR	4057	420	10.36
Reorganization	71409	assemblage	GUA	bifurcation to single	1933-1951	GAR	4057	101	2.48
Reorganization	109033	assemblage	GUA	benches to lateral bars	1933-1951	LLR	68876	520	0.76
Reorganization	56915	assemblage	GUA	lateral bars to benches	1933-1951	GRR	20264	1725	8.51
Reorganization	2882	assemblage	GUA	lateral bars to benches	1933-1951	MCR	17411	168	0.96
Erosion	64481	geometric	bank failure	slumped bank	1890-1933	GRR	20264	187	0.92
Erosion	6973	geometric	extension	bend	1890-1933	MCR	17411	80	0.46
Erosion	74208	geometric	bank failure	slumped bank	1890-1933	GAR	4057	245	6.04
Erosion	146565	geometric	bank failure	slumped bank	1890-1933	LLR	68876	568	0.82
Reorganization	35867	assemblage	GUA	lateral bars to benches	1890-1933	PRR	6491	122	1.89
Reorganization	43359	assemblage	GUA	lateral bars to benches	1890-1933	HTR	4455	144	3.22
Reorganization	84123	assemblage	GUA	bifurcation to single	1890-1933	LLR	6491	445	6.86
Reorganization	86476	assemblage	GUA	bifurcation to single	1890-1933	LLR	68876	288	0.42
Reorganization	92507	assemblage	GUA	bifurcation to single	1890-1933	LLR	68876	341	0.49

[a] Measured from the top of Murphys Creek

APPENDIX 2. Supporting information for Chapter 4.
Original file available from: http://onlinelibrary.wiley.com/doi/10.1002/2015WR017747/full

Water Resources Research

Supporting Information for

Catchment- and Reach-Scale Controls on the Distribution and Expectation of Geomorphic Channel Adjustment

Peyton E. Lisenby[1] and Kirstie Fryirs[1]

[1] Department of Environmental Sciences, Macquarie University, North Ryde, NSW 2109, Australia

Contents of this file

Tables S1, S2, and S3; Figures S1 to S7
Table S4 added for the purposes of this thesis

Introduction

This supporting information provides the data sources and coverage extends of the aerial imagery used for our analysis (Table S1), the number and form of geomorphic adjustments noted in each catchment (Table S2), characteristic interquartile ranges of width-to-depth ratio, mean stream power, and basin area data for channel portions that experienced no adjustment (Table S3), a graphical representation of the cluster variable analysis in the form of dendrogram figures (Figure S1), and individual box plots produced from one-way ANOVA analyses (Figures S2-S7) that correspond to data presented in Tables 3 and 4, along with Figures 9 and 10.

Table S1. Date, location, and source of maps, photos, and imagery[a]

Year	Coverage	Catchment(s)	Type	Source
1880s-1890s	Partial (Complete)	Bf, La, (Bu)	Parish Maps	QSA
1933	Partial	Bf, La	Aerial Photos	DNRM
1944	Complete	Bu	Aerial Photos	DNRM
1951	Complete	Bf, La, Bu	Aerial Photos	DNRM
1971	Complete	Bf, La, Bu	Aerial Photos	DNRM
1974	Complete	Bf, La,	Aerial Photos	DNRM
1976	Complete	Bf, La, Bu	Aerial Photos	DNRM
1997	Complete (Partial)	Bf, La, (Bu)	Aerial Photos	DNRM
1997/ 2001	Complete	Bu	Aerial Photos	DNRM
2011	Complete	Bf, La, Bu	Satellite Imagery	ESRI ArcGIS
2013/ 2014	Complete	Bf, La, Bu	Aerial Photos/Satellite Imagery	DNRM/Google Earth

[a] Note: Bf – Blackfellows, La – Laidley, and Bu – Buaraba. QSA – Queensland State Archives, DNRM – Queensland State Department of Natural Resources and Mines. Values in parenthesis correspond with one another.

Table S2. Number of geomorphic adjustments noted per catchment and time period

Year/ Tributary	Avulsion	Lateral Expansion	Bend Adjustment	Chute Cutoff	Bank Failure	Inset Channel Realignment	Straightening	Channel Stripping	Formation /Accretion	Removal /Erosion	Lateral Migration	Channel Contraction	Channel Aggradation	Total #	% Tributary	% Grand Total
1890's-1944	4	3	4	2										13	21	4
1944-1951	4	1	3					1						9	15	3
1951-1971	4	2	4								1	1		12	20	4
1971-1976	2	1	2										1	6	10	2
1976-2001	4		1									1		6	10	2
2001-2011	3	1	1					1					1	7	11	2
2011-2013	3	2	1					1		1				8	13	3
Buaraba Total	24	10	16	2				3		1	1	2	2	61	100	20
1890's-1933	1		8											9	10	3
1890-1951			1											1	1	0
1933-1951			1			1								2	2	1
1951-1971	1	3			1	2				1	1			9	10	3
1971-1974	3	5	1	1	7	2	1	5	1					26	28	8
1974-1976	1	5	1			1								8	9	3
1976-1997	3	4	3	2										12	13	4
1997-2011	2	1	2		1	1		1		1				9	10	3
2011-2013	2	11	1			1				2				17	18	5
Laidley Total	13	29	18	3	9	8	1	6	1	4	1			93	100	30
1880's-1933	1													1	1	0
1933-1951										2				2	1	1
1951-1971	8	5	4	4		2				1				24	15	8
1971-1974	7	3	6	3	1	4				1				25	16	8
1971-1976	2	2	1	1		2	1		1					10	6	3
1974-1976	9	5	3		2				1					20	13	6
1976-1997	7	6	6	1				1				1		22	14	7
1997-2011	4	5	3			1	1	1		1		1		17	11	5
2011-2013	9	11		3		4	3		1	5				36	23	12
Blackfellows Total	47	37	23	12	3	13	5	2	3	10		2		157	100	50
Grand Total	84	77	55	17	12	20	6	11	4	12	2	4	2	311		100

Table S3. Interquartile ranges of non-adjustment locations of each tributary[a]

Tributary	Location	Variable	1st Quartile	3rd Quartile
Buaraba	upper *~ 2-6 km* *downstream*	*W:D*	7	9
		ω (W m^{-2})	198	452
		A (%)	2	3
	lower *~ 57-63 km* *downstream*	*W:D*	5	9
		ω (W m^{-2})	66	156
		A (%)	96	100
Laidley	upper *~ 2-6 km* *downstream*	*W:D*	13	35
		ω (W m^{-2})	129	331
		A (%)	1	2
	middle *~ 52-58 km* *downstream*	*W:D*	4	6
		ω (W m^{-2})	0	286
		A (%)	40	40
	lower *~ 66-72 km* *downstream*	*W:D*	6	17
		ω (W m^{-2})	10	243
		A (%)	95	98
Blackfellows	upper *~ 2-9 km* *downstream*	*W:D*	12	30
		ω (W m^{-2})	473	819
		A (%)	2	3
	middle *~ 12-17 km* *downstream*	*W:D*	13	19
		ω (W m^{-2})	198	337
		A (%)	6	6
	lower *~ 70-74 km* *downstream*	*W:D*	6	11
		ω (W m^{-2})	70	181
		A (%)	84	85

[a] Locations correspond to downstream distances presented in Figure 7, where upper – upstream-most box, middle – middle box, lower – downstream-most box.

Table S4. Gauging station information* for Lockyer Valley discharge-area relationship.

	Gauge ID	Record Length (yrs)	Area (km^2)	2yr Q[a]	5yr Q	10yr Q	15yr Q	25yr Q	50yr Q	100yr Q	Description
No Upstream Weirs	143208A	34	85.19	29.00	71.00	103.00	121.42	145.00	177.00	209.00	15 Mile Creek at Dam Site
	143203A,B,C	89	346.07	102.66	432.08	681.27	827.04	1010.69	1259.88	1509.07	Lockyer Creek at Helidon
	143212A	47	445.35	90.00	440.00	704.00	857.99	1052.00	1316.00	1580.00	Tenthill Creek at Tenthill
	143209A,B	47	162.74	85.00	199.00	285.00	335.65	399.00	485.00	571.00	Laidley Creek at Mulgowie
	143220A	26	83.65	7.00	30.00	46.00	55.49	68.00	85.00	101.00	Sandy Creek at Forest Hill
	143219A	36	14.64	9.24	56.42	92.11	112.99	139.29	174.98	210.67	Murphy's Creek at Spring Bluff
Upstream Weirs	143210A	25	2499.82	266.68	874.92	1335.04	1604.19	1943.28	2403.40	2863.52	Lockyer Creek at Lyons Bridge
	143206A	20	2416.24	217.62	541.83	787.09	930.55	1111.30	1356.55	1601.81	Lockyer Creek at Brightview Weir
	143204A	25	1618.42	165.50	389.78	559.44	658.69	783.73	953.39	1123.05	Lockyer Creek at Wilsons Weir
	143229A	25	465.92	90.52	431.30	689.10	839.90	1029.88	1287.68	1545.47	Laidley Creek at Warrego Hwy

[a] Q – discharge (m^3 s^{-1})

*Discharge data are available from the Department of Natural Resources and Mines (DNRM), Queensland State Government.

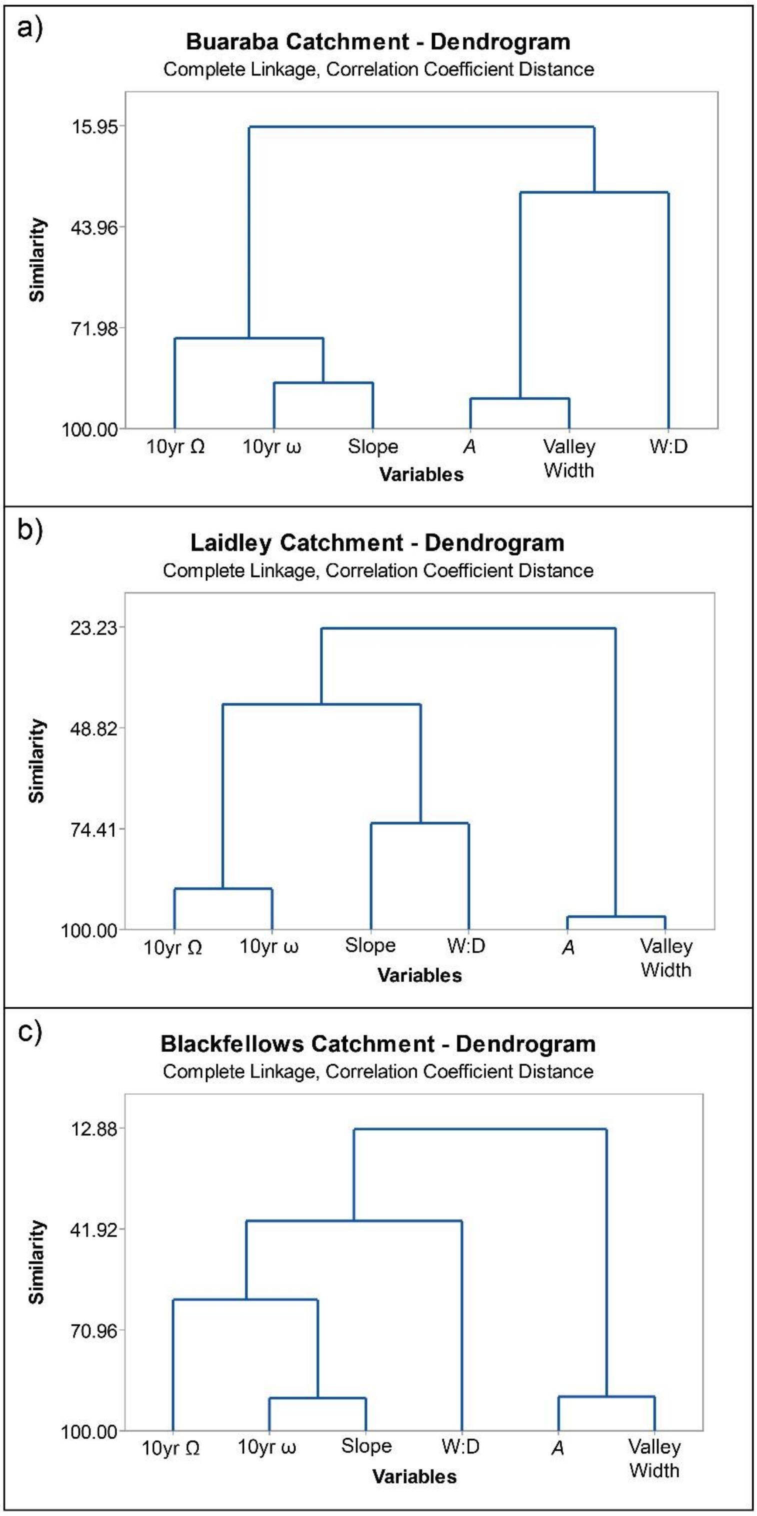


Figure S1. Cluster variable analysis of total stream power (Ω), mean stream power (*ω*) slope, basin area (*A*), valley width, and width-to-depth ratio (*W:D*) associated with adjustments occurring along (a) Buaraba Creek, (b) Laidley Creek, and (c) Blackfellows Creek.

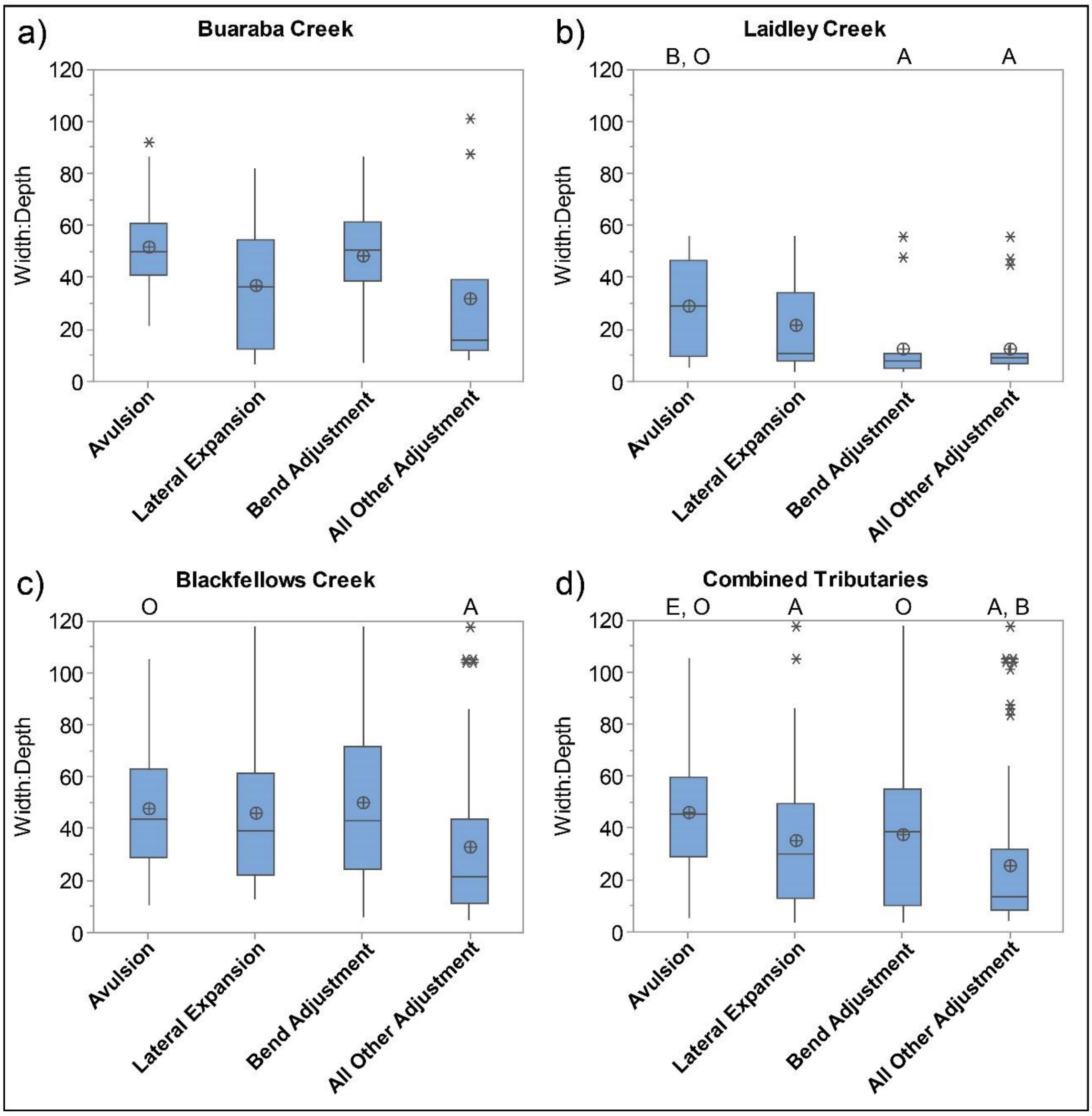


Figure S2. Box-and-whisker plots from one-way ANOVA analysis of width-to-depth ratio data for Buaraba (a), Laidley (b), Blackfellows (c) Creek, and the combined tributaries (d). Note that asterisks represent outlier values (at least 1.5x the interquartile range) and circles represent sample means. Letters above individual box plots indicate a statistical distinction (at a 95% CI) between the individual box plot data and the data plot represented by the letter where: A – avulsion, E – lateral expansion, B – bend adjustment, O – all other adjustment. Noted statistical distinctions correspond to Table 3. Interquartile ranges correspond to Figure 9.

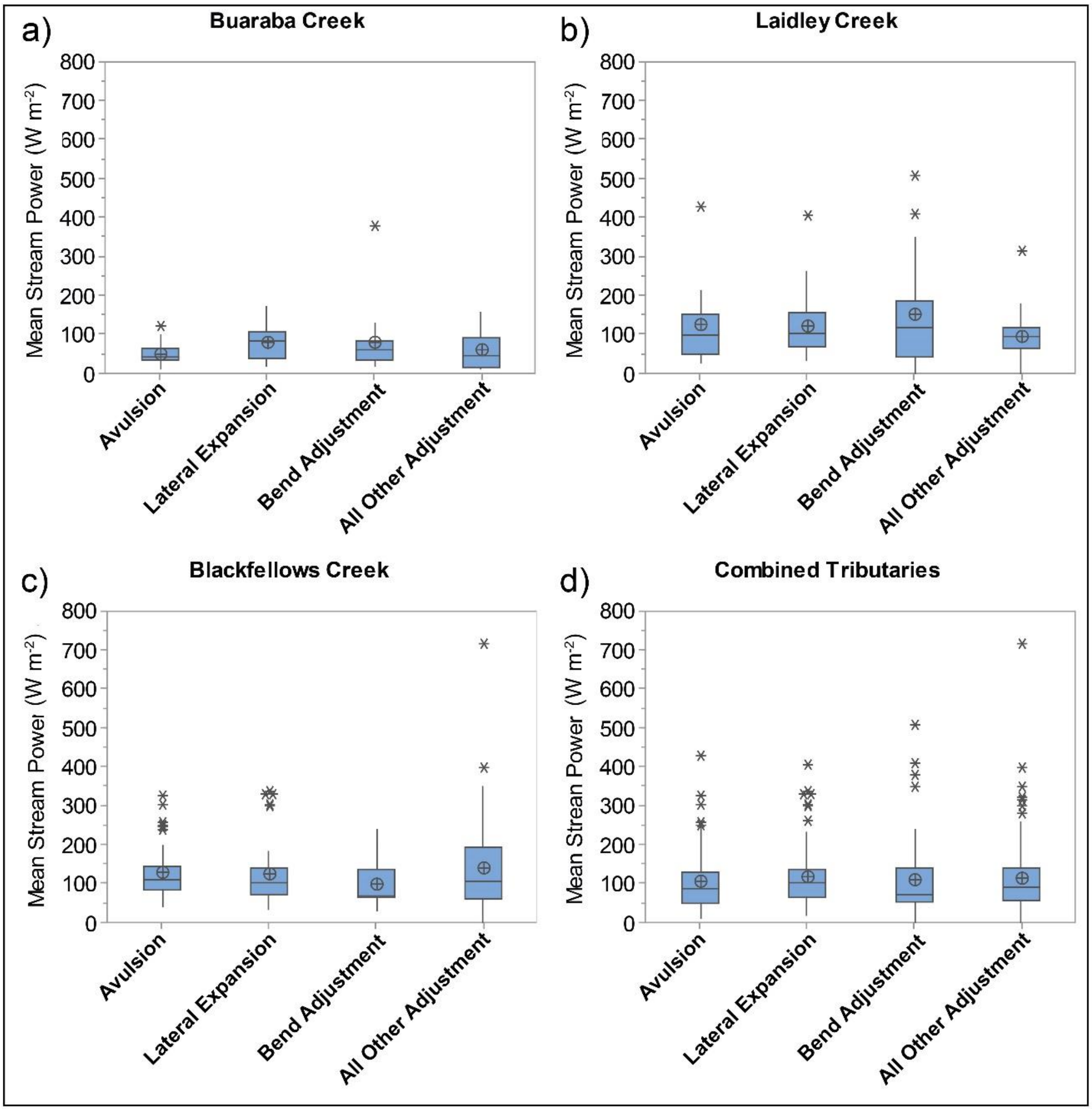


Figure S3. Box-and-whisker plots from one-way ANOVA analysis of mean stream power data for Buaraba (a), Laidley (b), Blackfellows (c) Creek, and the combined tributaries (d). Note that asterisks represent outlier values (at least 1.5x the interquartile range) and circles represent sample means. Letters above individual box plots indicate a statistical distinction (at a 95% CI) between the individual box plot data and the data plot represented by the letter where: A – avulsion, E – lateral expansion, B – bend adjustment, O – all other adjustment. Noted statistical distinctions correspond to Table 3. Interquartile ranges correspond to Figure 9.

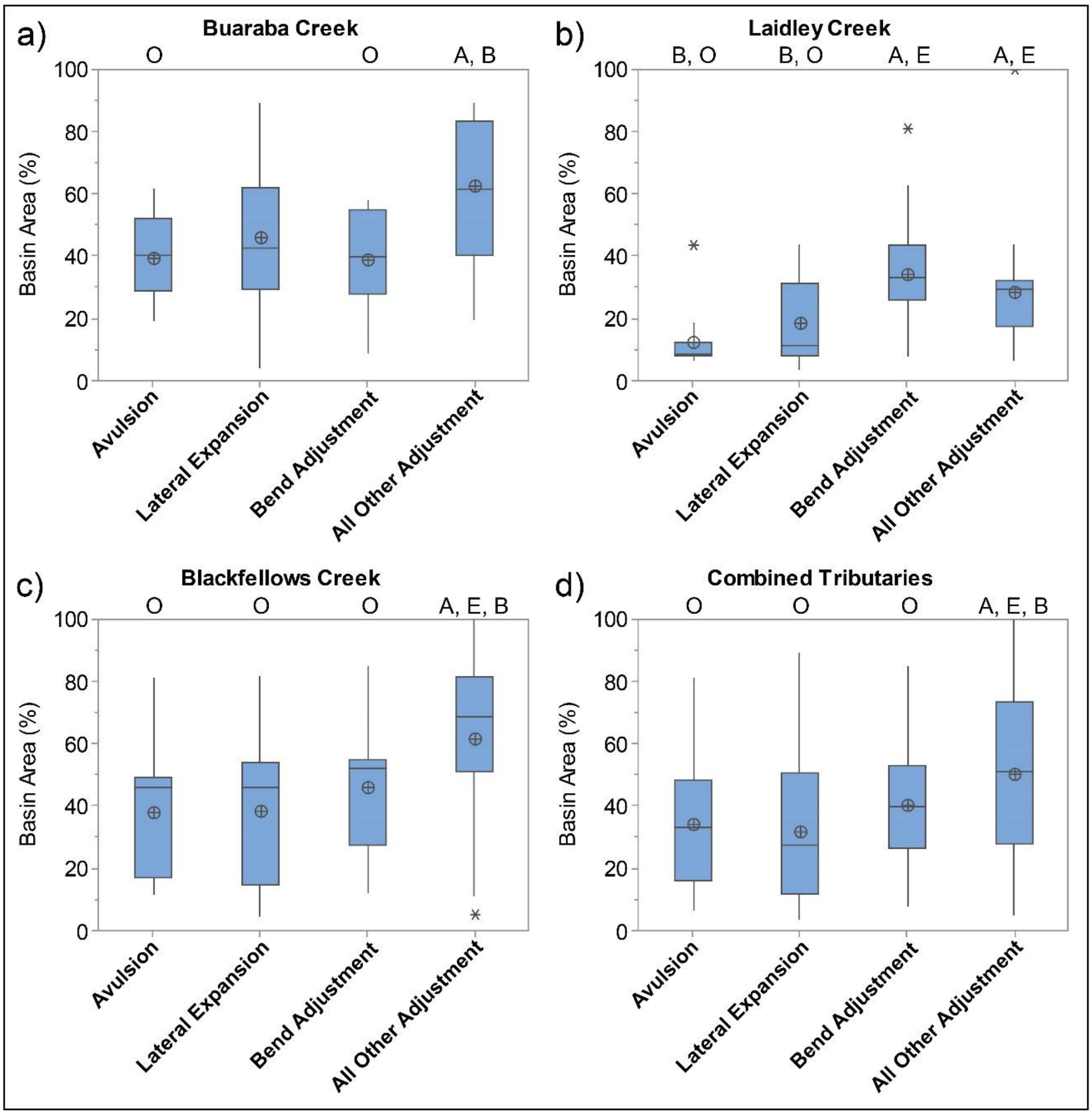


Figure S4. Box-and-whisker plots from one-way ANOVA analysis of basin area data for Buaraba (a), Laidley (b), Blackfellows (c) Creek, and the combined tributaries (d). Note that asterisks represent outlier values (at least 1.5x the interquartile range) and circles represent sample means. Letters above individual box plots indicate a statistical distinction (at a 95% CI) between the individual box plot data and the data plot represented by the letter where: A – avulsion, E – lateral expansion, B – bend adjustment, O – all other adjustment. Noted statistical distinctions correspond to Table 3. Interquartile ranges correspond to Figure 9.

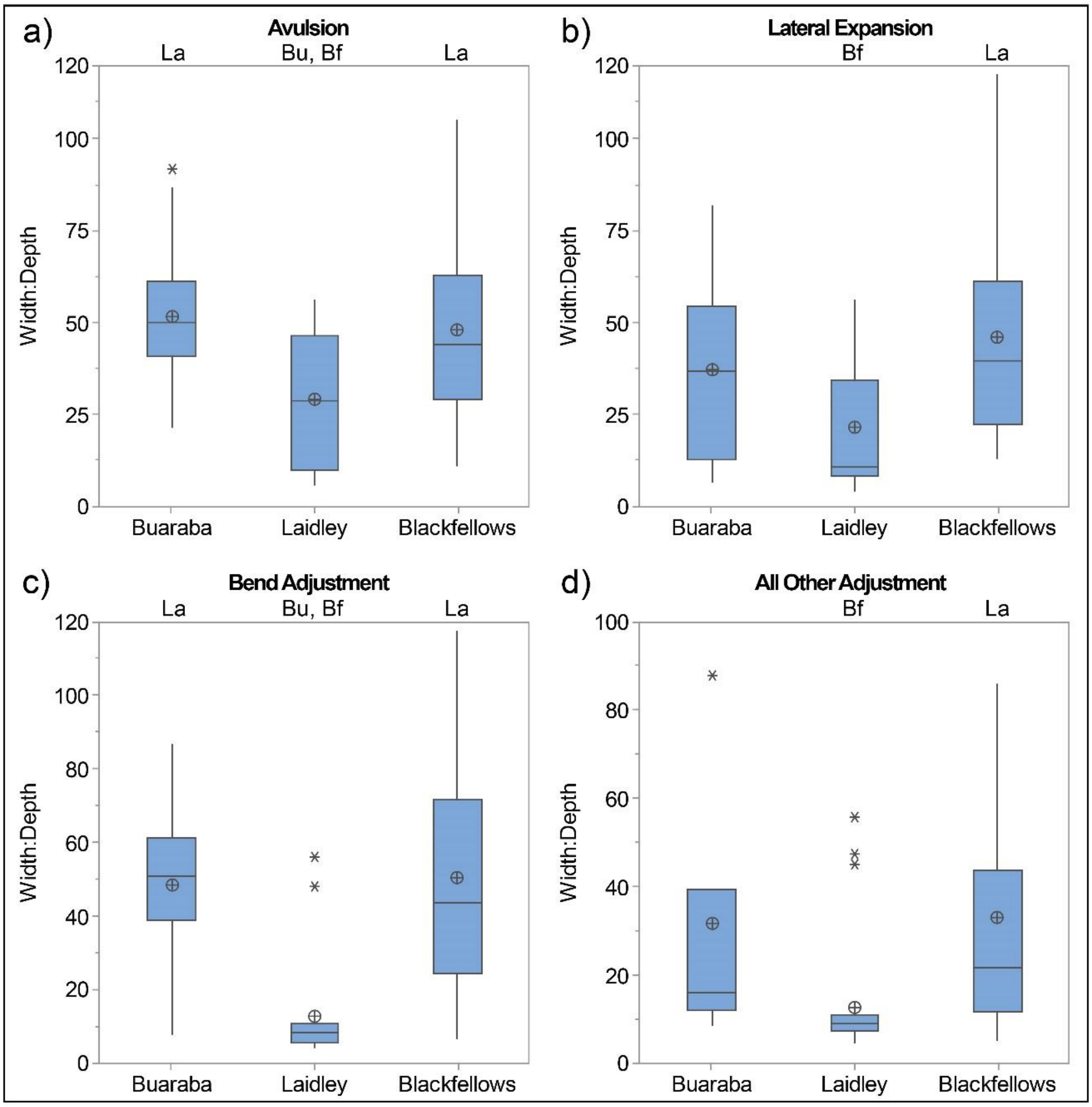


Figure S5. Box-and-whisker plots from one-way ANOVA analysis of width-to-depth ratio data for Buaraba (a), avulsion (b), lateral expansion (c) bend adjustment, and (d) all other adjustment. Note that asterisks represent outlier values (at least 1.5x the interquartile range) and circles represent sample means. Letters above individual box plots indicate a statistical distinction (at a 95% CI) between the individual box plot data and the tributary represented by the letter where: Bu – Buaraba Creek, La – Laidley Creek, and Bf – Blackfellows Creek. Noted statistical distinctions correspond to Table 4. Interquartile ranges correspond to Figure 10.

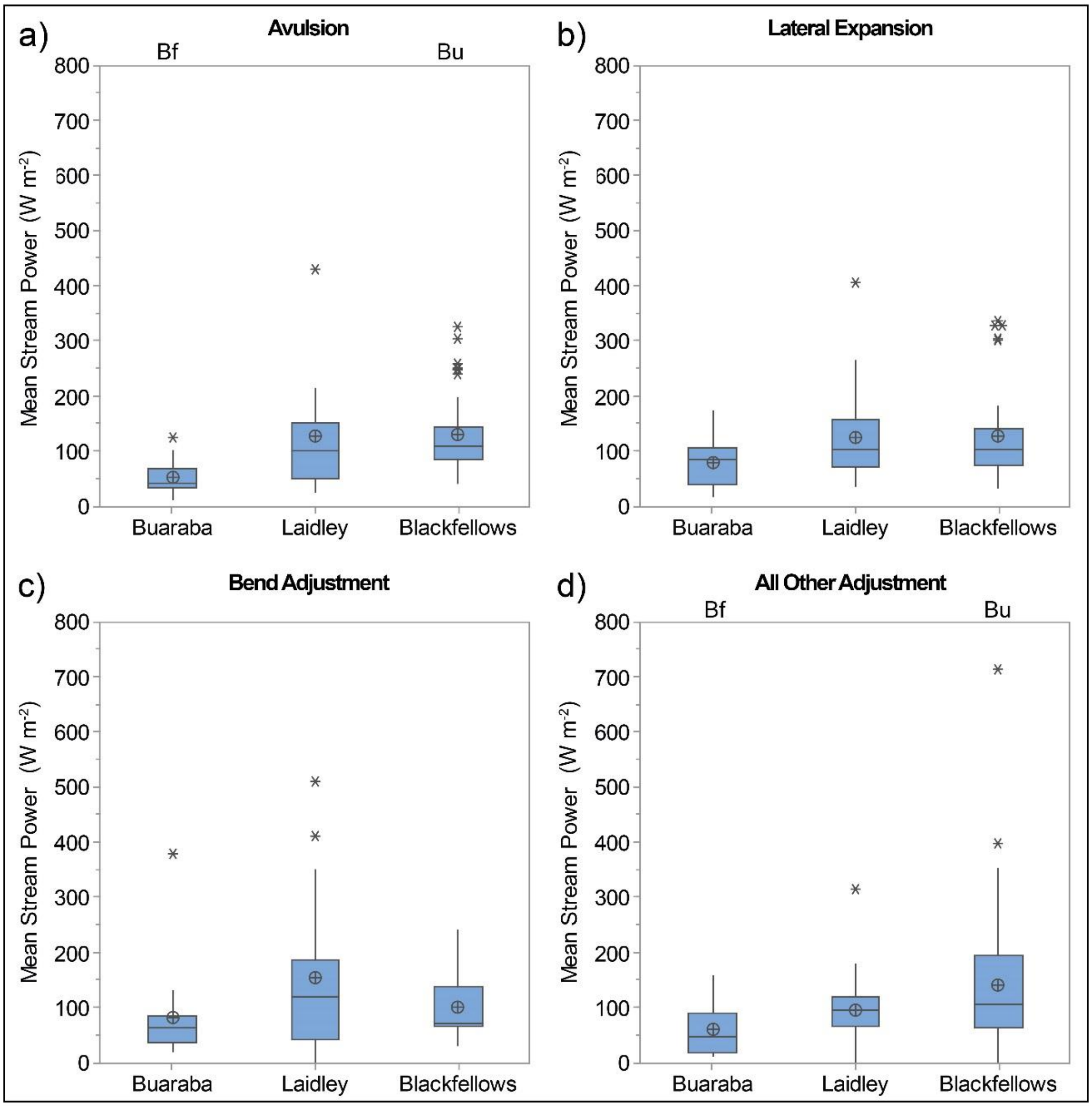


Figure S6. Box-and-whisker plots from one-way ANOVA analysis of mean stream power data for Buaraba (a), avulsion (b), lateral expansion (c) bend adjustment, and (d) all other adjustment. Note that asterisks represent outlier values (at least 1.5x the interquartile range) and circles represent sample means. Letters above individual box plots indicate a statistical distinction (at a 95% CI) between the individual box plot data and the tributary represented by the letter where: Bu – Buaraba Creek, La – Laidley Creek, and Bf – Blackfellows Creek. Noted statistical distinctions correspond to Table 4. Interquartile ranges correspond to Figure 10.

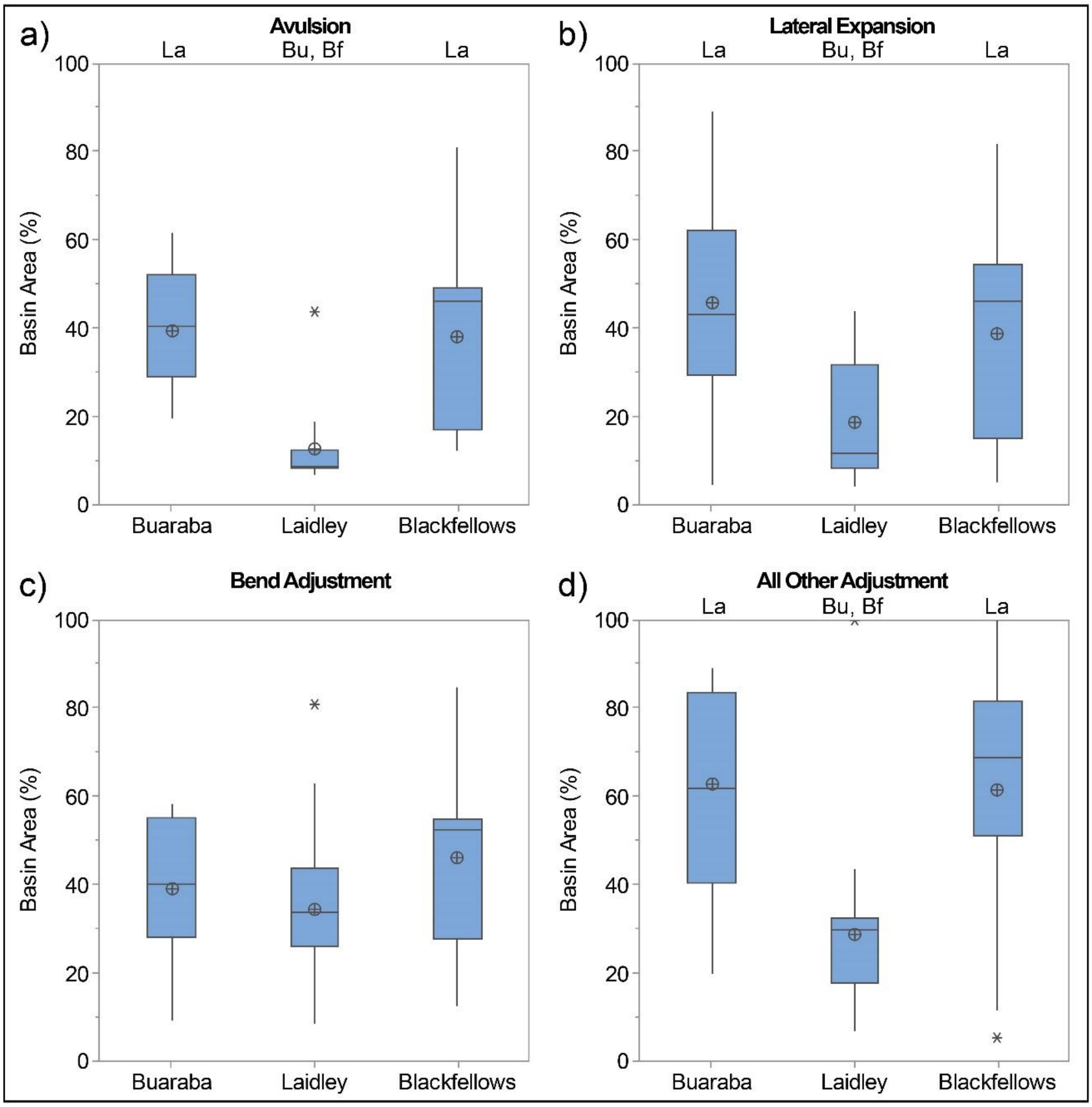


Figure S7. Box-and-whisker plots from one-way ANOVA analysis of basin area data for Buaraba (a), avulsion (b), lateral expansion (c) bend adjustment, and (d) all other adjustment. Note that asterisks represent outlier values (at least 1.5x the interquartile range) and circles represent sample means. Letters above individual box plots indicate a statistical distinction (at a 95% CI) between the individual box plot data and the tributary represented by the letter where: Bu – Buaraba Creek, La – Laidley Creek, and Bf – Blackfellows Creek. Noted statistical distinctions correspond to Table 4. Interquartile ranges correspond to Figure 10.

APPENDIX 3. Demonstration of concept for research presented in Chapters 5 and 6.

Published as:

Lisenby, P., Fryirs, K., 2016. Sedimentologically significant tributaries: Characterizing sediment connectivity in the Lockyer Valley, SEQ. In: G. Vietz, A.J. Flatley, I.D. Rutherford (Eds.), Proceedings of the 8th Australian Stream Management Conference. RBMS, Leura, NSW. 435-443.

Pages 240-248 (Appendix 3) of this thesis have been removed as they contain published material. Please refer to the citation above for details of the articles contained in these pages.

APPENDIX 4. Supporting information for Chapter 5.

Field surveyed sediment fractions[a] by count

	Sample Location[b]	Sand	Granule	Pebble	Cobble	Boulder
Lockyer Creek	3	0	8	105	35	2
	4	12	3	36	37	12
	6	7	8	110	2	1
	7	10	2	42	25	22
	9	51	7	61	29	3
	10	18	3	47	27	5
	11	38	8	41	13	12
	13	11	1	51	45	4
	14	6	1	62	30	1
	15	12	4	68	15	1
Tributaries	1	0	2	60	33	5
	2	22	10	55	13	0
	5	0	1	48	59	17
	8	22	4	47	35	0
	12	4	0	43	65	2

[a] sand (< -1 φ), granule (-1 to -2 φ), pebble (-2 to -6 φ), cobble (-6 to -8 φ), boulder (> -8 φ)
[b] sample locations are given in Chapter 5

Sieved sediment fractions[a] by weight (g)

	Sample Location[b]	Mud	Fine Sand	Medium Sand	Coarse Sand	Very Coarse Sand	Gravel
Lockyer Creek	4	5.63	71.71	700.54	1045.16	208.95	27.36
	6	8.28	59.40	588.23	2632.00	1943.57	608.77
	7	2.42	54.69	699.44	699.43	113.67	21.74
	9	1.51	6.21	357.91	1564.46	516.12	68.19
	10	27.86	350.50	1071.22	1319.65	325.82	45.09
	11	24.91	91.09	420.71	1798.02	1815.68	327.67
	13	20.97	141.73	442.28	1006.49	705.33	386.25
	14	8.30	71.08	504.42	1099.55	508.69	439.54
	15	43.12	350.50	996.23	590.77	308.98	1201.95
	17	11.78	82.90	389.91	2105.86	1653.60	1609.74
	18	41.36	188.44	657.32	3788.75	2805.11	849.81
	19	8.17	67.59	756.52	1457.64	159.76	12.11
	20	24.57	209.47	2428.47	1756.44	322.22	245.95
	21	141.19	398.94	1274.21	4846.29	1456.40	191.38
	23	14.98	116.43	917.87	2327.11	192.26	3.50
	24	31.94	147.64	1488.72	2939.28	481.79	94.36
	25	47.25	204.63	3239.44	3614.90	123.79	20.56
	26	24.53	79.95	327.52	1507.50	329.77	22.08
	27	17.25	1011.22	789.91	79.52	16.61	8.05
	28	43.47	284.46	698.67	700.65	159.95	48.34
	29	97.41	308.42	934.86	1129.01	604.00	284.70
	31	24.94	67.57	844.79	3362.68	826.09	189.39
Tributaries	2	4.29	33.83	314.81	1173.09	840.23	210.04
	8	15.29	63.32	372.99	1102.98	552.97	56.19
	12	0.87	2.41	52.67	579.95	320.79	33.55
	16	21.78	287.34	1681	218.51	2.00	0.32
	22	17.67	107.56	539.62	1299.1	393.81	214
	30	3.00	37.62	336	1365.5	327.11	7.04

[a] gravel (> -1 φ), very coarse sand (-1 to 0 φ), coarse sand (0 to 1 φ), medium sand (1 to 2 φ), very fine/fine sand (2 to 4 φ), mud (< 4 φ)
[b] sample locations are given in Chapter 5