Using in-stream extraction to accelerate the recovery of sand-bed rivers impacted by pulses of bedload sediment

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Abstract

Rivers can experience sudden pulses of sediment, from human and natural erosion processes, that can accumulate in the bed. Abundant studies have examined the sources and dynamics of bedload pulses, and problems they cause, particularly flooding, avulsions, and habitat simplification. Much less has been written about what managers can do about bedload pulses. This thesis examines the use of in-stream extraction to accelerate the recovery of sand-bed rivers impacted by pulses of bedload sediment. This thesis investigates the use of in-stream extraction by developing three conceptual models, and then testing each model in the Glenelg River catchment, SE Australia. The conceptual models are (1) bedload pulse dynamics at the catchment scale, (2) reach scale response of a river to a sequence of extraction pits, and (3) how a river responds to multiple interacting interventions at the tail of a bedload pulse. This thesis uses repeat channel surveys, hydraulic and sediment transport modelling, UAV surveys, geomorphic mapping and interviews with extractors to evaluate the conceptual models.

Bedload pulses in the Glenelg River do not behave as migrating waves. Instead, sediment accumulates upstream of valley constrictions and a series of standing waves emerge along the river. Wave crests are static, but sediment is exchanged between each of the waves during floods. At the centennial timescale standing waves are eroded one after another, from upstream to downstream, so that their overall behaviour resembles a single, catchment-wide Aggradation Degradation Episode. Extraction pits did not refill with sediment solely by migration of the upstream end. Instead, pit refill is discharge dependant. At bankfull discharge a zone of bedload transport forms between the migrating pit head and the tail of the pit. At the same time a lobe of suspended sediment intrudes into the pit, depositing sediment on the bed of the pit and along the margins of the pit. Point bar rebuilding is controlled by the pattern of secondary circulation in low angle meander bends, and by recirculating eddies on sharp mender bends. A series of extraction pits excavated along a reach interact and cause erosion in downstream reaches. Thalweg erosion increases in a downstream direction, but the presence of in-stream vegetation (*Phragmites australis*) causes a greater increase in channel complexity than extraction alone. Extraction prevents existing pools from infill but does not cause new pools to scour on the outside of meander bends. A particularly surprising finding of this thesis was that in reaches at the tail of a bedload pulse, where the source of sediment has already been controlled, local-scale interventions can produce highly localised recovery. In-stream vegetation is a key component of the sequence-of-pools morphology that forms in reaches where stock have been excluded. Reaches at the tail of a bedload pulse do not interact, but become disconnected, which is in direct contrast to existing paradigms of rivers as connected systems.

Managers can use these results to decide if, where and how in-stream extraction can be used to accelerate recovery in sand-bed rivers impacted by a bedload pulse.

Declarations page

I declare that this thesis comprises only original work carried out by Alexander James Sims towards the Doctor of Philosophy (PhD).

Due acknowledgement has been made in the text of all other material used.

This thesis is fewer than 100,000 words excluding tables, maps, bibliographies and appendices

Alexander James Sims (24 March 2020)

Preface

Description of contribution

The candidate is primarily responsible for the planning, execution and preparation of the work for publication (Chapters 2 and 8). In all cases the candidate wrote the first draft of the publication and contributed more than 50% of the content of the publication. The candidate performed subsequent editing of the publication in response to co-authors' and editors' reviews. The candidate's co-authors provide their consent for the publication to be included in the thesis. The candidate claims all work presented in the thesis as original work.

Sources of funding

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I also wish to thank Geoff Vickery for providing data and being generous with his time during field work. I am also grateful to the many landowners who live and work beside Bryan Creek and the Glenelg River for allowing me to access the river via their properties, and for being happy to answer my questions.

A very big thank you to all members of the Rutherfurd River Research Group (3RG) for being great friends, office mates and colleagues over the past four years. I feel lucky to have been part of such an enthusiastic group and look forward to working with you again someday. A special thanks to those who assisted me with field surveys: Alissa Flatley, Nuosha Zhang, Jonathan Garber, Hong Jiang.

I am extremely grateful to my wife Katherine Lyttle, who moved to Australia so I could undertake my PhD. For supporting and encouraging me over the last four years, for spending many hours compiling and proofreading early drafts of this thesis, and for maintaining crew morale at difficult times.

Finally, I wish to thank my entire family for supporting me and making sure I don't fall into the trap of taking myself too seriously.

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Chapter 1: Introduction

1.1 Introduction

Sediment from human and natural processes can enter rivers as a sudden pulse. When sediment pulses accumulate in the channel bed, and then disperse downstream, they are termed bedload pulses. This thesis is concerned with the challenge of what managers can do to accelerate the recovery of rivers impacted by catchment-scale bedload pulses.

Bedload pulses fill pools, simplify the channel bed, reduce channel capacity and can lead to widening, avulsions and a switch from meandering to a braided planform (Kondolf, 1994; Madej and Ozaki, 1996; Brierley and Fryirs, 1999; Sutherland et al., 2002; Abernethy et al., 2004a; Page et al., 2007; Madej et al., 2009). Much research has focused on describing these impacts in different rivers and on developing conceptual models of how bedload pulses migrate downstream.

Bedload pulses occur naturally in streams, with the unusual volumes of sediment coming from gullying (e.g., Hancock and Evans, 2006), debris flows (e.g., Hoffman and Gabet, 2007), volcanoes (e.g., Gran and Montgomery, 2005; Pierson *et al*., 2011), collapse of natural dams (e.g., Hancox *et al*., 2005), or a series of large floods (Erskine, 1986; Madej, 1992). Human activities enhance these natural processes. For example, by accelerating catchment erosion rates (Erskine, 1994; Davis and Finlayson, 2000; Gomez et al., 2003; Abernethy et al., 2004b; Page et al., 2007; Verstraeten et al., 2017), or by destabilising streambanks that then erode and liberate large volumes of sediment (Erskine, 1986; Knighton, 1991; Rustomji *et al*., 2006; Hubble and Rutherfurd, 2010).

Human activities can also introduce bedload pulses that have a calibre, minerology or delivery rate outside of a catchments 'natural' range or variability. These anthropogenically-triggered bedload pulses are a particular class of legacy sediment (Wohl, 2015; James, 2018). Examples of anthropogenic pulses are the extraordinary loads of sediment from mine tailings in California (Gilbert, 1917; James, 1989, 1991, 1999, 2006, 2015, James *et al*., 2009), in the Fraser River, Canada (Nelson and Church, 2012) and in the Ok Tedi River, Papua New Guinea (Parker *et al.*, 1996; Cui and Parker, 1999). Another example is the sediment pulse that can be liberated by dam removal (Pizzuto, 2002; Magirl *et al*., 2014; East *et al.*, 2015), or by catastrophic failure of tailings dams at mining sites (Hudson-Edwards *et al*., 2003; Garcia *et al*., 2016a; Hatje *et al*., 2017; Byrne *et al*., 2018).

This thesis is concerned with the catchment-scale bedload pulses generated by accelerated erosion. However, studying the dynamics, impacts and management of such large-scale disturbances still requires an understanding of how bedload pulses move at much smaller scales, such as a single river reach. A large body of literature describes the impacts of bedload pulses, and the mechanisms by which they migrate downstream (Cui *et al*., 2003a; Cui *et al*., 2003b; Cui *et al*., 2005; Fryirs *et al*., 2007; Sklar *et al*., 2009; Zinger *et al*., 2011; Nelson and Dubé, 2016; Gran and Czuba, 2017; Morgan and Nelson, 2019). One of the main motivations for understanding catchment-scale bedload pulses is the ability to better manage their impacts. Most studies have focused on the interventions used to mitigate the impact of bedload pulses on flooding (Gob *et al*., 2005; James *et al*., 2009; USACE, 2010b), channel navigability (James and Singer, 2008; USACE, 2014; Yuill *et al*., 2016a) and bank stability (Thomas *et al*., 2015). These studies are about how to minimise the damage to infrastructure and the environment. Much less has been written about how managers can accelerate geomorphic recovery in rivers degraded by a bedload pulse.

The premise of accelerating the natural process of recovery relies on an understanding of a river's natural recovery trajectory. A recovery trajectory is the series of channel adjustments that take place as the boundary conditions (flow regime, sediment supply, constraints on channel adjustment) decline back towards some pre-disturbance range of variability (Phillips, 2009; Brierley and Fryirs, 2016; Fryirs and Brierley, 2016). Alternatively, the boundary conditions of a river may permanently shift into some new, altered state with a completely different range of variability (Brierley and Fryirs, 2016; Phillips and Van Dyke, 2016; Fryirs, 2017). Many catchment-scale bedload pulses are generated by a sudden, permanent shift in boundary conditions, so the impacted reaches will never return to their pre-disturbance state (Fryirs and Brierley, 2000; Dufour and Piegay, 2009; Palmer *et al*., 2010).

Irreversible change to a river means the term recovery does not describe a return to some reference state. Managers cannot use an intact reference reach to guide target morphology, so must adopt some vision of what the river will become under the altered boundary conditions (a *Leitbild*) (Kondolf and Larson, 1995; Muhar *et al.*, 1995; Fryirs *et al.*, 2012). In these cases, the term recovery is better thought of as improvement in stream condition. This improvement is still limited by pressures still acting on the river (for example stock access, altered flow regime and clearing of the riparian zone) (Dufour and Piegay, 2009). The term recovery is used in this thesis with the improvement of physical condition in mind.

Instead of returning a river to some pristine state, managers are interested in ways they can steer a river along a particular recovery trajectory (avoiding further degradation), or accelerate a rivers movement along an existing, natural recovery trajectory. Although there is an increasing body of work that conceptualises the natural recovery trajectories of river's impacted by a bedload pulse (Erskine, 1994; Major *et al*., 2000; Bartley and Rutherfurd, 2005b; Erskine, 2008; Keene *et al*., 2008; Fryirs *et al*., 2012), much less has been written about the specific interventions managers can use to accelerate the recovery process in these rivers.

1.2 Background

In-stream extraction has been proposed as a way to accelerate recovery in downstream reaches, and to prevent sand ingress to downstream pools (i.e. preserve intact habitat) (Rutherfurd and Budahazy, 1996; Brizga *et al*., 2000b; Wilkinson *et al*., 2006). The premise of using in-stream extraction to accelerate recovery is that extraction pits will trap incoming sediment and reduce the supply of sand to downstream reaches. Downstream reaches then compensate for the sediment deficit by eroding their beds. For in-stream extraction to effectively accelerate recovery, the decrease in bed elevation must be associated with the kinds of channel adjustment that would otherwise have taken much longer to occur. Examples of these channel adjustments are the re-emergence of a well-defined low flow channel in the bed, the scour of pools on the outside of meander bends, channel contraction and an overall increase in bed relief, channel complexity and landform stability.

The kinds of channel adjustments associated with recovery from a bedload pulse in gravel bed rivers (Knighton, 1991; Knighton, 1999; Major *et al.*, 2000; Madej, 2001) and sand-bed rivers (Fryirs and Brierley, 2000; Abernethy et al., 2004a; Bartley and Rutherfurd, 2005a; Keene et al., 2008; Erskine et al., 2009a; Fryirs and Brierley, 2016; Mould and Fryirs, 2018) are now well-described. The management of excess sediment in gravel bed rives is also well-described (Gilbert, 1917; James, 2005; James *et al.*, 2009; USACE, 2010a; Wang and Kondolf, 2014). What has not been well-described is if, and how, management interventions in sand-bed rivers accelerate recovery. In particular, whether in-stream sediment extraction is an appropriate way of accelerating recovery in sand-bed rivers.

I now turn to the specific gaps in our undertsanding of if, how, and where, in-stream extraction is able to accelerate recovery in rivers impacted by a pulse of bedload sediment.

1.3 Knowledge gaps and rationale

Using in-stream extraction to accelerate recovery requires balancing the potential benefits of decreased sediment supply with the potentially detrimental impacts of extraction. Most research has focused on the historical over-extraction from large, gravel-bed rivers (Simon, 1989; Kondolf, 1994; Meador and Layher, 1998; Davis *et al*., 2000; Surian and Rinaldi, 2003; Rinaldi *et al*., 2005; Rovira *et al*., 2005; Padmalal *et al*., 2008a; Martin-Vide *et al*., 2010; Anthony *et al*., 2015). While historical studies illustrate the dangers of unregulated over-extraction and can be used to explain historical changes in channel form in many rivers, they provide little information regarding the boundaries within which extraction may be an appropriate way to accelerate recovery. To understand whether extraction is useful as a tool to accelerate recovery from a bedload pulse, mangers need to understand where in a catchment extraction is appropriate (relative to the distribution of a bedload pulse), the best technique to use when extracting sediment and the rate of extraction. Overall there are four main gaps in our current understanding of the interaction between bedload pulses and in-stream extraction. I consider each of the four knowledge gaps in the section below.

1.3.1 How multiple bedload pulses, injected at different points along a sand-bed river, move through a catchment and interact with each other

Models of bedload pulse dynamics are used to predict two things (1) how and when different reaches will be impacted by a bedload pulse, and (2) the recovery potential of reaches already degraded by the passage of a bedload pulse. Existing conceptual models of catchment-scale bedload pulse dynamics were developed in large, gravel bed rivers (Gilbert, 1917; Pickup *et al*., 1983; Knighton, 1989; Knighton, 1991; Parker *et al*., 1996; James, 1999; James, 2006a). The source of sediment in many of the published studies is some distance from the study reach. Gravel bed rivers are prone to adjust their width in response to a bedload pulse (Church, 2006; Church and Ferguson, 2015). A clear gap in our understanding is conceptual models that describe how multiple bedload pulses injected into a trunk stream by tributaries spaced along the river length migrate through a sand-bed river with cohesive banks (which is less likely to adjust its width in response to a bedload pulse (Darby *et al*., 1996; Parker *et al*., 2011)).

1.3.2 How a sequence of extraction pits refill with sand, and interact with each other as they refill

Existing conceptual and empirical models of extraction pit evolution have mostly been derived from flume studies, and only consider a single pit (Lee *et al*., 1993; Gill, 1994; Lee and Chen, 1996; Chen *et al*., 2010; Barman *et al*., 2018b; Barman *et al*., 2019). The focus on single extraction pits, flume studies and the emphasis on large dredging pits to maintain navigation (Gob *et al*., 2005; USACE, 2010; Yuill *et al*., 2016) means that the original flume models have not been well tested in natural channels. There is a need to test the engineering models, derived in flumes, in natural sand-bed channels. Furthermore, the processes by which extraction pits excavated in straight channels and on meander bends actually refill with sediment has not been described for medium-sized sand-bed rivers. This presents a clear gap in our understanding: do extraction pits excavated in medium-sized sand-bed rivers behave as the engineering models predict?

1.3.3 Whether a sequence of extraction pits excavated in a sand-bed river accelerate the recovery of downstream reaches

The erosion observed downstream of extraction sites in rivers of different size is usually regarded as an example of river degradation (Galay, 1983; Kondolf, 1994; Davis *et al.*, 2000; Kondolf *et al*., 2002; Padmalal *et al*., 2008b; Martin-Vide *et al*., 2010). In-stream extraction is a promising means of accelerating recovery and protecting intact reaches because the revenue generated by commercial extraction could fund the improvement in condition. There are no studies that examine whether extraction from medium-sized, sand-bed rivers impacted by a bedload pulse, accelerates *recovery* in downstream reaches. This is a gap that needs to be addressed so that managers have information to decide if instream extraction is an appropriate restoration technique.

1.3.4 How extraction interacts with other management interventions to shape the recovery of a river impacted by a pulse of bedload sediment

A key tenet of the river recovery literature is that unless the catchment-scale drivers of degradation have been addressed, local-scale interventions are futile (Bernhardt *et al*., 2005b; Wohl *et al*., 2005; Brierley and Fryirs, 2009; Bernhardt and Palmer, 2011). But what is the situation where the catchment-scale drivers of degradation (increased sediment supply in the case of a bedload pulse) have already been addressed? In-stream extraction is an example of a local-scale intervention used to accelerate recovery. Extraction may be targeted at the tail of a bedload pulse, where sediment supply is declining, and channel recovery has begun. However, local-scale interventions, whether they are intended to prevent degradation or accelerate river recovery, are seldom undertaken in isolation. Rivers behave as connected systems (Hooke, 2003; Cooper, 2007; Page *et al*., 2007) so the change in sediment storage or river behaviour caused by an intervention in one reach can be expected to impact downstream reaches. This leads to a gap in understanding: how does in-stream extraction interact with other local-scale interventions at the tail of a bedload pulse? Addressing this gap means that managers can better understand if, and how, extraction is an appropriate way to accelerate recovery at the tail of a bedload pulse, where recovery potential is high.

1.4 Research questions

Thus, this thesis will address the four knowledge gaps listed above by answering four research questions about a river affected by a sand pulse. The four research questions are:

1. How do multiple interacting bedload pulses, delivered by tributaries spaced along the length of a sand-bed river, migrate through a catchment?
2. How do extraction pits in straight channel sections and on meander bends refill with sediment?
3. Does a sequence of extraction pits accelerate reach-scale recovery in downstream reaches?
4. Do multiple, interacting local-scale interventions accelerate recovery at the tail of a bedload pulse?

The thesis approaches the four research questions by developing three conceptual models, and then testing each model in the Glenelg River catchment, SE Australia. The conceptual models are:

1. A conceptual model of bedload pulse dynamics at the catchment scale (Chapter 4).
2. A conceptual model of reach-scale response of a river to a sequence of extraction pits (Chapters 6 and 7).
3. A conceptual model of how a river responds to multiple interacting interventions at the tail of a bedload pulse (Chapter 8).

1.4.1 Thesis structure

The body of the thesis is laid out as a thesis with publications. My literature review (Chapter 2) was published in the journal *Geomorphology* in 2017, but an amended version is included in the body of the thesis, to avoid unnecessary repetition. The published version of Chapter 2 is included in Appendix A. Chapter 8 has been submitted to the Journal *Applied Geography* and is currently under review. An amended version of that manuscript is included in the body of this thesis and the submitted version is included in Appendix B. Other chapters have been written with publication in mind.

This thesis investigates the research questions in the order that they appear above. The thesis first narrows its scope from the management of bedload pulses more generally, to the movement and management of bedload pulses in sand-bed rivers (Chapter 2). I describe the Glenelg River catchment, where field site for this thesis (Chapter 3). Next, I develop a conceptual model of bedload pulse dynamics for the Glenelg River (Chapter 4). The thesis then investigates in-stream extraction in order of increasing complexity and spatial scale (Figure 1.1). Many of the concepts and methods used to study the behaviour of individual extraction pits (Chapter 6) and the reach-scale response to a sequence of extraction pits (Chapter 7) are the same. To avoid repetition, the concepts and methods used in my investigation of in-stream extraction are presented first, in Chapter 5.

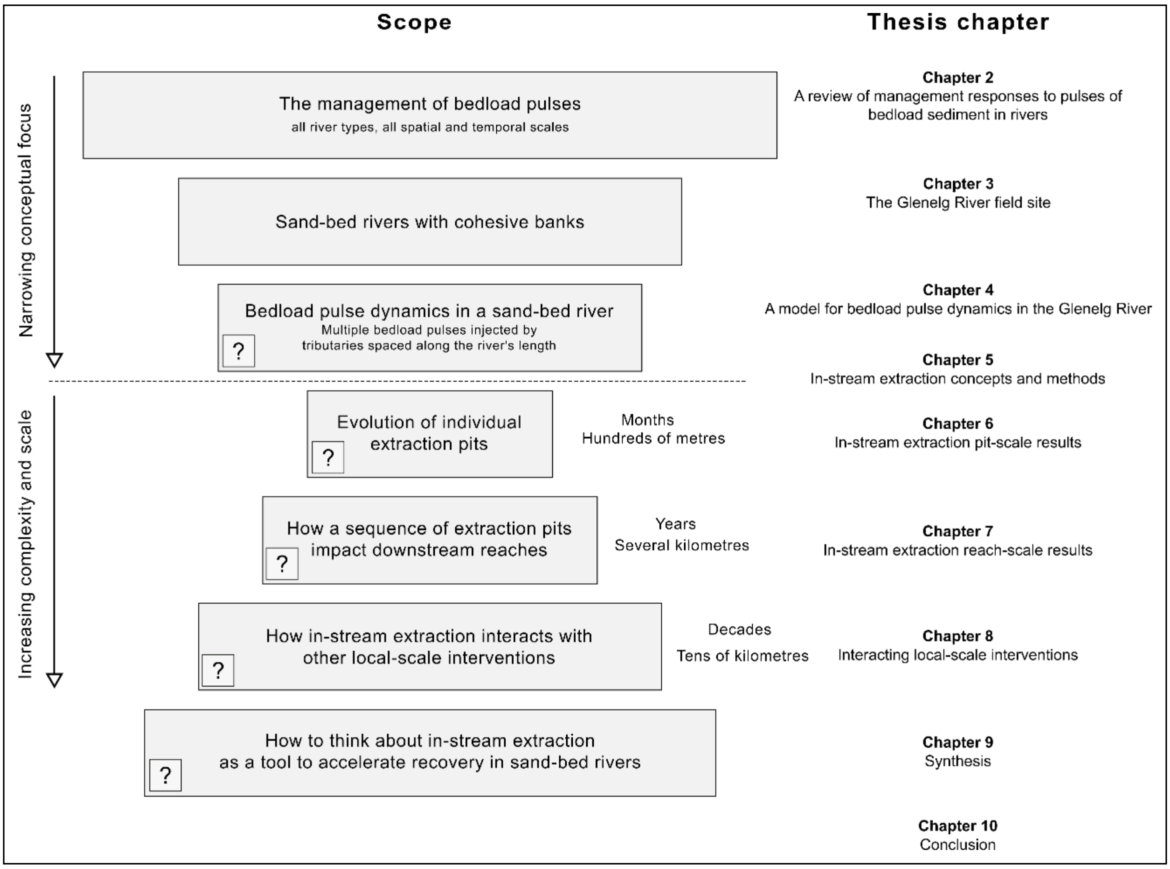


Figure 1.1: The conceptual structure of this thesis and how that structure translates into thesis chapters.

The chapters of the thesis are as follows:

Chapter 2: A review of management responses to pulses of bedload sediment in rivers

This chapter reviews the different types of interventions used in rivers experiencing pulses of bedload sediment. The focus of the interventions considered in this thesis is recovery. The chapter considers sand and gravel bed rivers and the different types of bedload pulses delivered to those rivers.

Chapter 3: Description of the field site

This chapter introduces the Glenelg River catchment, where my investigation of in-stream extraction was undertaken. The chapter covers the environmental history of the catchment and management interventions undertaken there.

Chapter 4: A model for bedload pulse dynamics in the Glenelg River

This chapter develops, and then tests, a conceptual model of bedload pulse dynamics for the Glenelg River. The conceptual model is the basis of the 'do nothing' option when managing bedload pulses and provides the context for all interventions in the Glenelg River. For example, the extraction pits are superimposed on this catchment scale pattern of sand storage and movement.

Chapter 5: In-stream extraction concepts and methods

This chapter does two things: (1) it develops a conceptual model to predict how individual extraction pits will refill with sediment in a natural channel and the reach-scale impacts of a sequence of extraction pits, and (2) it outlines the methods used to test the conceptual model in the Glenelg River. The methods were: repeat channel surveys (cross-section and more detailed total station surveys of pit infill), hydraulic modelling, sediment transport modelling, channel mapping and calculation of a sediment budget.

Chapter 6: Pit-scale results

This chapter tests the pit-scale part of the conceptual model developed in chapter 5 in the Glenelg River. I do this by using a combined hydraulic and sediment transport model for the study reach, and by conducting repeat surveys of the extraction pits before infill had begun (right after extraction) and twelve months later, once infill had progressed.

Chapter 7: Reach-scale results

This chapter tests the reach-scale part of the conceptual model developed in chapter 5. The reach-scale part of the conceptual model was tested in three ways: with repeat channel cross-sections that were surveyed before and after the most recent phase of extraction, using hydraulic modelling and finally, by using the calibrated sediment transport model to build a sediment budget for the reach.

Chapter 8: Interacting local-scale interventions

This chapter adds an additional layer of complexity by considering the impact of multiple local-scale interventions superimposed on the tail of a bedload pulse. The study site for this chapter is Bryan Creek, a tributary of the Wannon River (itself a tributary of the Glenelg River).

Chapter 9: Synthesis

This chapter draws the findings from chapters 4, 6, 7 and 8 together and considers the implications for the over-arching research question that this thesis investigates: Can in-stream extraction be used to accelerate the recovery of rivers degraded by a bedload pulse? The chapter also considers future research that can build on the findings of this thesis.

Chapter 10: Conclusions

This chapter summarises the findings of this thesis and compares what we knew before this research (from the literature) and what we know now. This chapter articulates the fundamental contribution to knowledge that this thesis has made.

Chapter 2: Management responses to pulses of bedload sediment in rivers

A note to the reader: This chapter was originally published as a paper in *Geomorphology* (Sims and Rutherfurd, 2017). The paper chapter has been modified from the published version to better integrate with the rest of the thesis. A copy of the published manuscript is included in Appendix A.

2.1 Introduction

Rivers can experience sudden pulses of sediment from human and natural processes. These pulses can accumulate in the stream bed, and move downstream, predominantly as bedload. Sediment pulses occur naturally in streams, with the unusual volumes of sediment coming from gullying (e.g. Hancock and Evans, 2006), debris flows (e.g. Hoffman and Gabet, 2007), volcanoes (e.g. Gran and Montgomery, 2005; Pierson *et al*., 2011), collapse of natural dams (e.g. Hancox *et al*., 2005), or a series of large floods (Erskine, 1986; Madej, 1992). Human activities can enhance these natural processes. Examples are where land use changes lead to a great increase in the frequency or magnitude of gullying, debris flows, or landslides. Human activities can also generate pulses of sediment that are outside the natural range of processes in channels. Examples are the extraordinary loads of sediment from mine tailings in California (Gilbert, 1917; James, 1989; 1991; 1999; 2006; 2015; James *et al*., 2009), in the Fraser River, Canada (Nelson & Church, 2012) and in the Ok Tedi River, Papua New Guinea (Parker *et al*., 1996; Cui and Parker, 1999). Another example is the sediment pulse that can be liberated by dam removal (Pizzuto, 2002).

Packets of sediment that migrate downstream following large inputs have been termed sediment pulses, sediment waves, bed waves and sediment slugs (Gilbert, 1917; Hoey, 1992; Nicholas *et al*., 1995; Rutherfurd, 2001). These terms have often been used interchangeably across varied spatial and temporal scales. Nicholas *et al.* (1995) prefers the term *slug* due to its generality and the difficulty in identifying coherent waveforms. Additionally, James (2010, 2006) notes that the term *wave* has been used to describe sediment waves (of varying size and particle size distribution), bed material waves, and sediment flux interchangeably. We conclude that any of these terms would suffice, but have decided to use the term *pulse* which better describes the discrete injection of sediment that is the focus of this review. The pulses we consider in this review are periodic injections of sediment at the scale of entire river reaches and have been termed 'superslugs' by Nicholas *et al*., (1995) and 'aggradation degradation episodes' (ADE) by James (2010). They are distinct from smaller, self-organized pulses of bed material (termed macroforms by Hoey, 1992) such as ripples, dunes, bars and bed-waves.

Sediment pulses have many impacts. They can raise bed levels, widen streams, and smother and simplify bed features such as pool and riffle sequences (Figure 2.1) (James, 2010; Wohl, 2015). The rising bed, and decreased channel capacity, can lead to increased flood frequency, more frequent channel avulsion, and restricted navigation. The sediment can also fill dams, reducing their function for flood mitigation and hydro-power production. Interventions aimed at managing these impacts are usually justified by way of protecting downstream reaches, re-establishing degraded habitat, increasing geomorphic complexity, or mitigating increased flood risk.

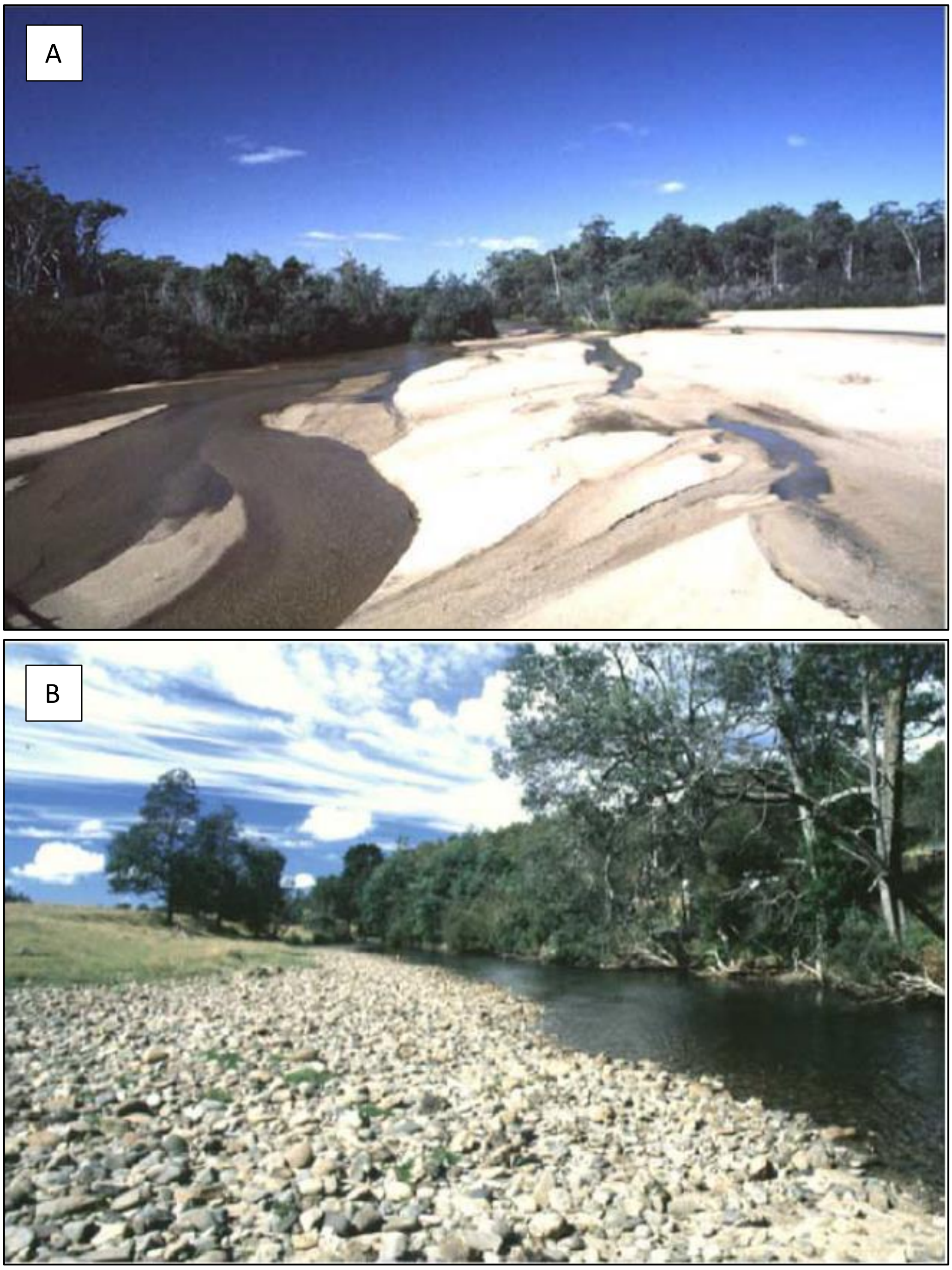


Figure 2.1: (A) Mine tailings have filled a reach of the Ringarooma River that used to resemble the comparable un-impacted reach (B) upstream of the tributary inputs (from Bartley & Rutherfurd, 2004).

Gilbert's (1917) classic work on debris from gold mining in the Sierra Nevada was the first serious study of anthropogenic sediment pulses into rivers. He described the movement of many millions of tonnes of mine tailings in detail, as well as the resulting problems of flooding, navigation, and smothering of agricultural land. Gilbert also described some management options to mitigate the damage. He described the implications of doing nothing, levees that concentrate flow and scour the sediment, and a dam that could trap the sediment. As is so often the case, Gilbert's work continues to stand the test of time. In fact, despite the large body of work describing the degradation of river systems by unusually large, anthropogenically-triggered sediment loads (Gilbert, 1917; James, 1989a; Knighton, 1989; Prosser *et al*., 2001b; Kondolf *et al*., 2002; Bartley and Rutherfurd, 2005b; James, 2006a; Simon and Rinaldi, 2006; James and Lecce, 2013; Wohl, 2015; Fryirs and Brierley, 2016) methods for managing their impacts have received less attention in the literature. In a recent example, in 2015, the Bento Rodrigues mine tailings-dam failed in Mariana, Brazil, releasing 60 million cubic meters of iron-ore waste into the Doce River (Garcia *et al*., 2016b) (Figure 2.2F). Although commentators on the disaster suggest that there will be a huge cost for 'rehabilitation', they are by no means clear on what exactly managers can do to hasten that rehabilitation, apart from a suggestion to plough contaminated soils on the floodplain (Garcia *et al*., 2016b). Despite an explosion of interest in stream restoration (Bernhardt *et al*., 2005a), and many streams being affected by large sediment pulses, there is little literature summarising what management options are available to accelerate the recovery of these systems, or to reduce the risks presented by the sediment.

In this paper we use case studies to review the five responses to sediment pulses that are available to managers. They can:

1. do nothing
2. reduce sediment supply at source
3. promote in-channel storage
4. accelerate sediment transport
5. extract sediment.

Implementing options 2 to 5 will affect sediment continuity, so we then discuss longer term complex response involving channel incision and tributary interactions that may arise from manipulating sediment supply. We conclude by outlining a management framework that links the management options that we identify to different management goals. Managers can use the framework to help decide when to undertake different management activities.

While large sediment disturbances affect both the active channel and the floodplain, we focus here on the active channel. We also restrict ourselves to physical aspects of this issue, without considering biological issue, such as impacts on biota, or chemical contamination associated with the sediment. Before discussing the five management options, we review the dynamics of sediment pulses.

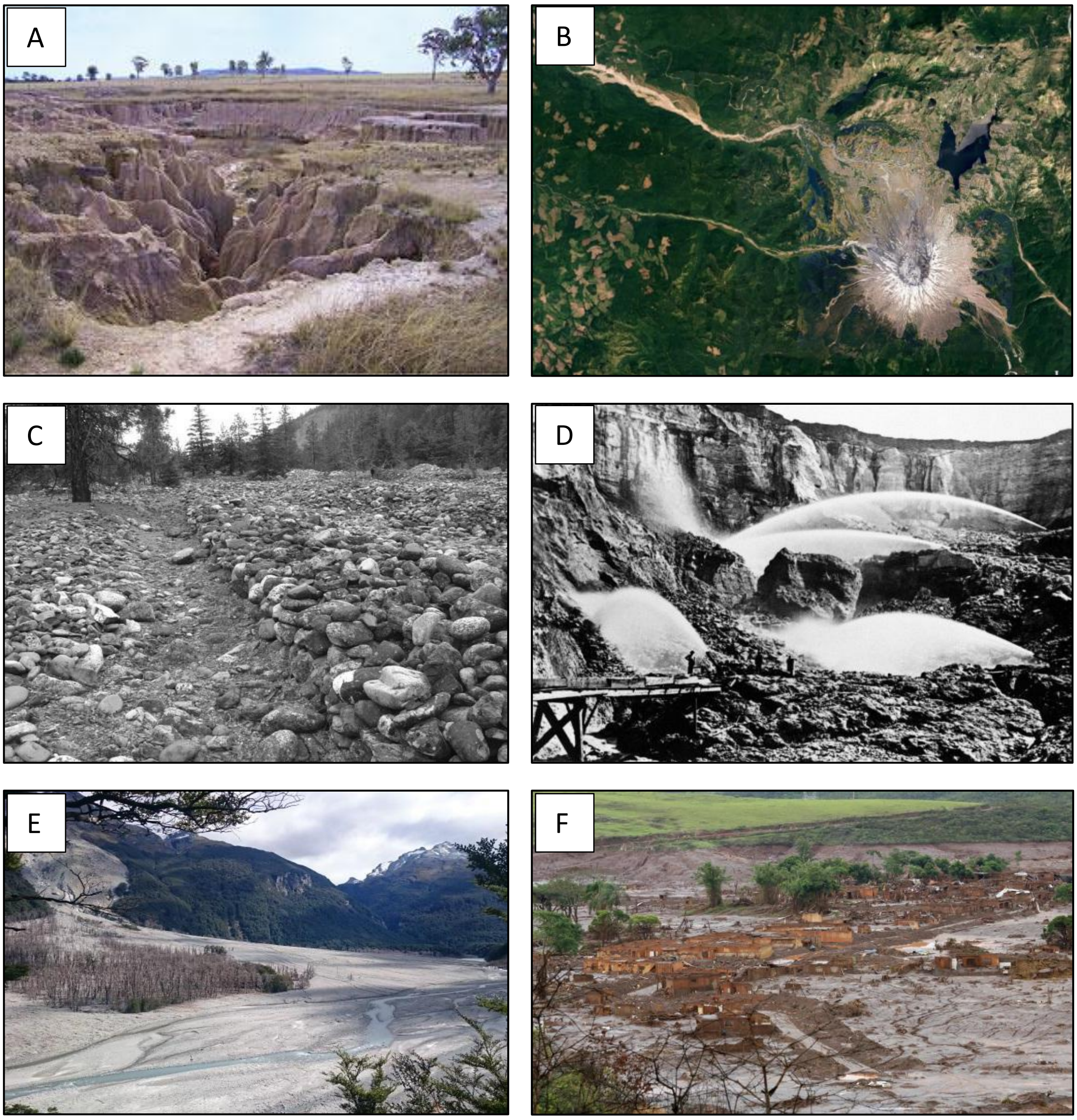


Figure 2.2: Examples of large sediment inputs: (A) Severe gully erosion in New South Wales, Australia (photo: B. Peasley/DECCW (obtained from Office of Environmental Heritage, NSW Government)), (B) Mt St Helens, Washington, USA the sediment-laden Toutle River flows to the north east (image: Google Earth), (C) Lag deposits of coarse sediment liberated by placer mining near the confluence of the Fraser and Thompson Rivers, British Columbia (source: Nelson & Church (2012)), (D) hydraulic sluicing at the Malakoff Diggings, Sierra Nevada in the 1870's (source; USGS/Bancroft Library, University of California), (E) Slip stream landslide and its debris fan, Dart Valley, New Zealand (photo: Alex Sims), (F) Tailings deposited by the Bento Rodrigues tailings-dam failure in Mariana, Brazil (source; Wikimedia Commons).

2.2 The dynamics of sediment pulses

Before deciding whether to intervene, managers need to understand how sediment pulses are generated, how they disperse or translate through the channel network over time, and what controls their celerity. This understanding is the first step when deciding whether or not to intervene, and helps managers prepare for the consequences of sediment pulses in the absence of intervention. For example, Gilbert (1917) concluded that sediment pulses from gold mining move as an attenuating wave, so if managers did nothing he suggested that the pulse would potentially move through, and the stream would recover its natural morphology. Managers could wait for the pulse to move through, or act to accelerate this rate of recovery. In this section we examine how sediment pulses move through river systems, and characteristic recovery times.

2.2.1 How is sediment delivered to the channel?

The first step in predicting the type of sediment pulse that will result from an input pulse is to understand the volume, spatial distribution and calibre of sediment inputs relative to those normally experienced by the channel. These input characteristics will depend on the source of the disturbance, and are a key determinant of how the sediment pulse will be shaped.

Sediment pulses can be defined in space as being from diffuse or point sources (Phillips, 2009); and in time; as being either a prolonged press or discrete disturbances (*sensu* Lake, 2000). Point sources are inputs such as landslides, tailing dam failures, or bank collapse. Diffuse inputs are more widespread, such as sediment liberated from gullies, the stream bed or stream banks (e.g. Benda and Dunne, 1997; Simon and Rinaldi, 2006). Importantly, inputs may be point sources at the reach scale, but diffuse at the catchment scale, e.g. the widespread occurrence of small landslides.

A temporally-discrete disturbance shows a clear rise, peak and fall of sediment inputs while a press disturbance is a more prolonged delivery that does not decrease with time (Figure 2.3). Management of discrete inputs is primarily concerned with the evolution of the resulting sediment pulse (annual to decadal), while press inputs must also consider the ongoing delivery of sediment to the network (decades to centuries), which can undermine downstream remediation efforts.

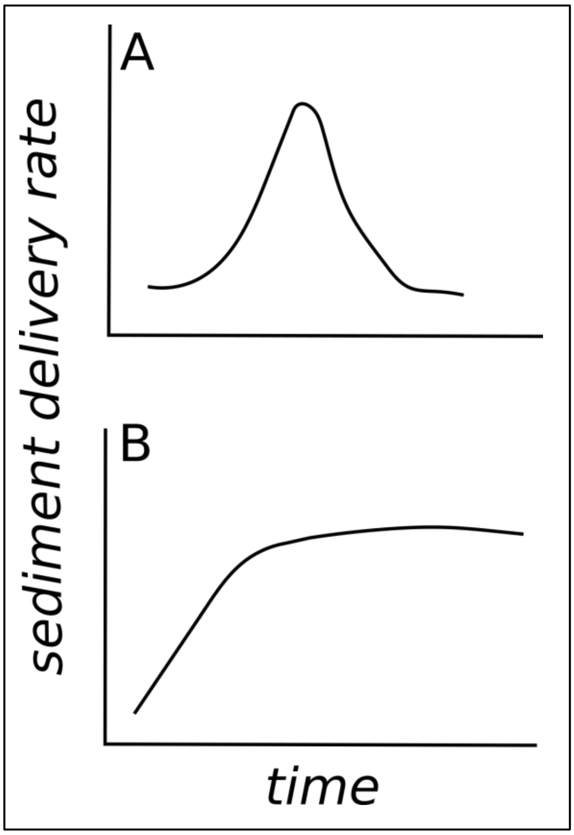


Figure 2.3: Two types of sediment disturbance; temporally-discrete (A) and press (B), distinguished by their temporal trends in sediment delivery to the channel. Source: Lake (2000).

Table 2.1 lists common sources of large sediment pulses, their style of delivery and typical impacts on channels. In general, sediment entering the channels in large pulses will have a longer residence time than their lower volume counterparts. Relatively large sediment pulses will reside in the channel network longer (either in the channel bed or in bars, islands or benches), especially when these the larger, slow moving sediment deposits are stabilised by vegetation. Interaction among channel deposits that enhance backwater effects (e.g. deposition behind tributary junction plugs) and a larger proportion of sediment being stored on the floodplain can also prolong sediment evacuation. Examples of these processes are given later in the paper.

Table 2.1: Summary of sediment pulses delivered to channels from natural and anthropogenic sources, whether the pulse is point source or diffuse (i.e. spread across the catchment), delivered as a temporally-discrete or press disturbances (*sensu* Lake (2000)), typical impacts on the channel, and studies describing the type of pulse.

Sediment source	Calibre of input	Point source/ Diffuse	Pulse/Press	Typical impacts of the pulse	References
Landslides and lahars	Can be coarse or fine	Point	Pulse	Can dam channels, channel avulsion	Madej and Ozaki, 1996; Page *et al*., 1999;Pringle and Cameron, 1999; Montgomery *et al*., 2000; Sutherland *et al*., 2002; Korup *et al*., 2004; Huang and Montgomery, 2012; Nelson and Dubé, 2016
Debris flow	Slurry of mud carrying coarse material	Point	Pulse	Scour of steep tributaries, can dam channels, damage to infrastructure	Hoffman and Gabet, 2007; Lin *et al*., 2008; Stock and Dietrich, 2003
Rapid stream widening, meander bend cutoffs	Fine material	Point	Pulse	Further channel widening	Erskine, 1986; Hubble and Rutherfurd, 2010; Zinger *et al*., 2011; Saynor and Erskine, 2016
Avulsions	Floodplain sediments (fine and coarse)	Point	Pulse or press	Bed aggradation, further avulsions	Perignon, 2008
Gullying	Fines washed from eroding soil & coarser material from rapidly incising gullies	Diffuse	Press	Loss of productive land, bed aggradation	Scott, 2001; Marden *et al*., 2005

Artificial channelisation	Coarse material from degrading bed, and fines liberated from undermined banks	Diffuse	Press	Bed aggradation	Simon, 1989; Simon and Rinaldi, 2006
Dam failure or removal	Initially fines as reservoir draws down, coarse material as bedload migrates past old obstruction	Point	Pulse	Smother habitat, increased turbidity	Pizzuto, 2002; Major *et al*., 2012; Wilcox *et al*., 2014; Warrick *et al*., 2015
Placer mining/hydraulic sluicing	Fines as a thick sludge/slurry, and coarse material from waste piles	Diffuse	Press	Constrain channel, increase flood risk	Gilbert, 1917; James, 1989; Nelson and Church, 2012
Tailings injection		Point	Press	Smother habitat, inject pollutants	Knighton, 1989; Parker *et al*., 1996

2.2.2 How do sediment pulses move through a river network?

The movement of sediment through a channel will be controlled by coupling between channel and hillslope, channel and floodplain and between channel reaches (Fryirs and Brierley, 2001; Hooke, 2003; Fryirs *et al*., 2007; Lamb *et al*., 2011). Downstream migration of sediment inputs along the channel bed is usually conceptualised as a moving wave (Gilbert, 1917). The 'shape' of such waves—measured as the temporal change of bed level at a reference site—is described as either dispersing or translating (Figure 2.4), but individual pulses may have elements of both (e.g. Lisle *et al*., 2001; Czuba and Foufoula-Georgiou, 2014). *Dispersion*—a decrease in pulse amplitude and increase in period—has been shown to be the dominant mode of movement for discrete inputs which are large enough to perturb the local flow field (Lisle *et al*., 2001; Sklar *et al*., 2009). Dispersion is enhanced by size selective transport (which is strengthened where the pulse has a wide grain size distribution) and deposition on the trailing edge of the pulse due to backwater effects (Lisle *et al*., 2001). The dominance of dispersion means that individual sediment pulses can quickly become difficult to discern from pre-existing bed topography (Lisle *et al*., 2001).

Translation is downstream migration of the pulse peak, but without a change in pulse period. This is most likely to occur when: inputs are finer than bed material, transport capacity is high, when the pre-disturbance bed is armoured, and when Froude numbers and bed and bank roughness are low (Cui *et al*., 2005; Venditti *et al*., 2010) (Lisle *et al*., 2001; Sklar *et al*., 2009). Thus, the degree to which a sediment pulse will disperse or translate depends on the calibre of sediment inputs relative to that of the pre-disturbance bed, the grain size distribution of input pulses, and the volume of inputs relative to stream transport capacity (Figure 2.4).

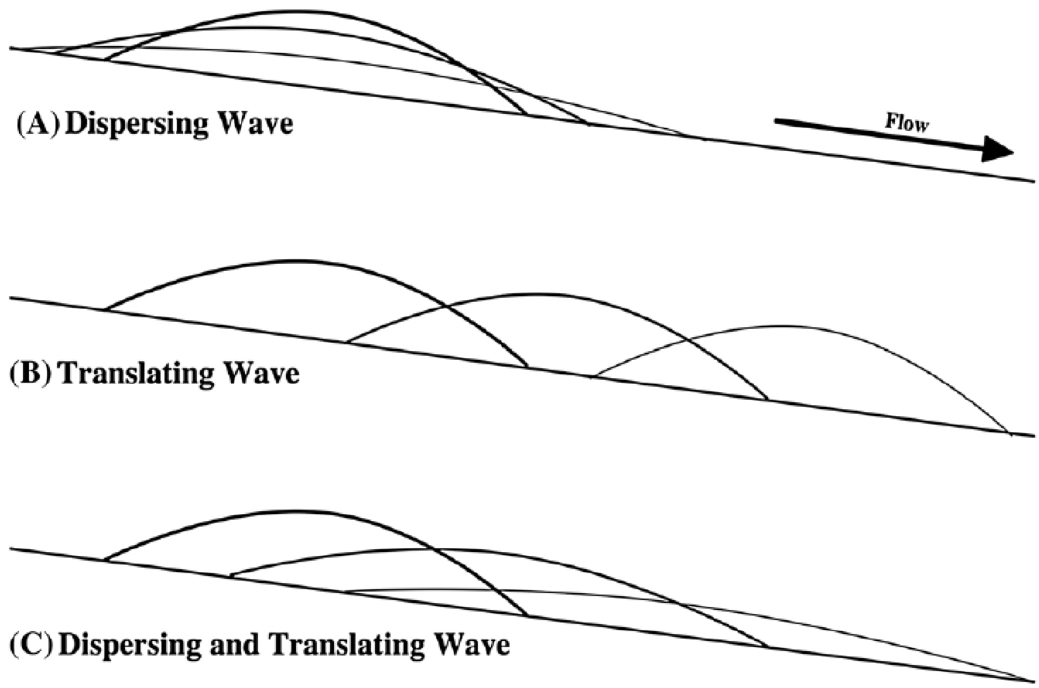


Figure 2.4: Idealized types of bed material waves in profile. The heaviest line represents the original wave profile; successively lighter lines represent stages in wave evolution; n, bed elevation; t, time; x, channel distance source; Lisle *et al*., (2001).

Pulses may also amalgamate at tributary junctions, or low-gradient reaches downstream of inputs, a phenomenon termed *synchronisation* (Czuba and Foufoula-Georgiou, 2014; Gran and Czuba, 2017). Several smaller pulses can synchronise into a single, larger pulse when a pulse stalls at tributary junction, forming a barrier to sediment movement. The leading edge of an incoming pulse is deposited on the trailing edge of the stationary pulse. In this way a chain of overlapping pulses are deposited in an upstream direction. Alternatively, sediment pulses can move into sedimentation zones where they are deposited on the channel bed. Incoming pulses are deposited on top, but reworking by flows mixes the two together.

The movement of both fine and coarse sediment can be conceptualised as a waveform, but the different size fractions will move into different storage zones in the catchment (Fryirs *et al*., 2007). Fine sediment can be deposited on the floodplain during floods, or move into the interstices between larger sediment on the bed. Coarse sediment will migrate between bedforms (bars, benches and islands) or along the channel bed (Hooke, 2003). The movement of bedload pulses along the channel bed through an entire catchment is considered in more detail in Chapter 4 of this thesis.

2.2.3 What controls the pulse celerity?

How fast the peak of a pulse migrates downstream is the wave celerity. Pulse celerity is greater when inputs are small compared to transport capacity, and channel roughness is low. The relative dominance of dispersion, translation or concentration—coupled with pulse celerity—determines how long sediment pulses take to migrate downstream, and whether they are expressed as a subtle but long lived change in bed level (dispersion) or a short-lived high magnitude change in bed level (translation).

Before considering how fast a pulse moves through a channel, it is worth asking; how can a manager judge that a pulse has passed? Assessing whether a sediment pulse has passed requires the use of some metric to measure recovery, the most common metrics are; return to pre-disturbance bed level (Gilbert, 1914; Knighton, 1989; Madej and Ozaki, 1996) return of the pre-disturbance thalweg, cross-section and sediment size variability (Knighton, 1999; Bartley and Rutherfurd, 2005a), establishment of stable features such as bars and benches (usually vegetated) (Erskine, 1996) or the return of pool-riffle sequences (Keene *et al*., 2008).

The celerity of the sediment pulse is controlled by the shape of the hydrograph (Humphries *et al*., 2012), the relative roughness of the channel (Kasai *et al*., 2004) and connectivity between reaches and with the floodplain (Fryirs *et al*., 2007; Fryirs, 2013). Sediment supply from many processes tends to decline over time. Gullies, for example, have a negative exponential erosion rate (Graf, 1977) and the supply of sediment from hillslope deposits and channel stores also tends to decline exponentially (Gran and Montgomery, 2005; Nelson and Dubé, 2016). A decline in sediment supply to pre-disturbance levels is required before the tail of the sediment pulse can begin to migrate downstream.

There can be a feedback between channel change caused by the sediment pulse and the transit time of the pulse itself. Sediment pulses fill pools and smother bedforms which homogenise the stream bed, reduces roughness and accelerates the passage of the pulse (Kasai *et al*., 2004). Conversely a rise in bed level increases the frequency of flooding, which has two effects; storing fine sediment on the floodplain (decreasing pulse height by removing sediment from the channel) and, decreasing downstream transport by distributing flow energy. Decreases in downstream connectivity, due to tributary plugs for example, will also slow the passage of the pulse.

Typical timescales for a return to pre-disturbance bed levels and reach morphology depends on the volume and calibre of inputs and transport capacity. In steep, high transport capacity environments the passage of sediment pulses from both single inputs (e.g. single landslides, Sutherland *et al*., 2002) or widely distributed inputs (e.g. earthquake induced landsliding throughout a catchment, Dadson *et al*., 2004; Lin *et al*., 2008; Hovius *et al*., 2011) tend to be at the rapid end, ranging from approximately five years to several decades (e.g. Gran and Montgomery, 2005). For example, a sediment wave in the Sandy River, Oregon was triggered by a sequence of lahars on the slopes of Mt Hood between AD 1781 and 1793. Up to 10^8 m^3 of coarse sediment was deposited in its headwaters at this time. The wave travelled 87 km downstream and caused up to 23 m of aggradation in the lower reaches (Pierson *et al*., 2011). It took at least half a century for the river to reach its current bed level which remains at least 3 m above its former elevation (Pierson *et al*., 2011).

Madej (1992) describes how a 50-year ARI flood in Redwood Creek in California increased the sediment stored in the downstream channel by 1.5 times. Sediment was stored in different areas of the system (Figure 2.5), with the active channel having a residence time of decades, but this increased to thousands of years for sediment stored on terraces. Overall, Madej concludes that the influence of this single flood will persist on Redwood Creek for centuries.

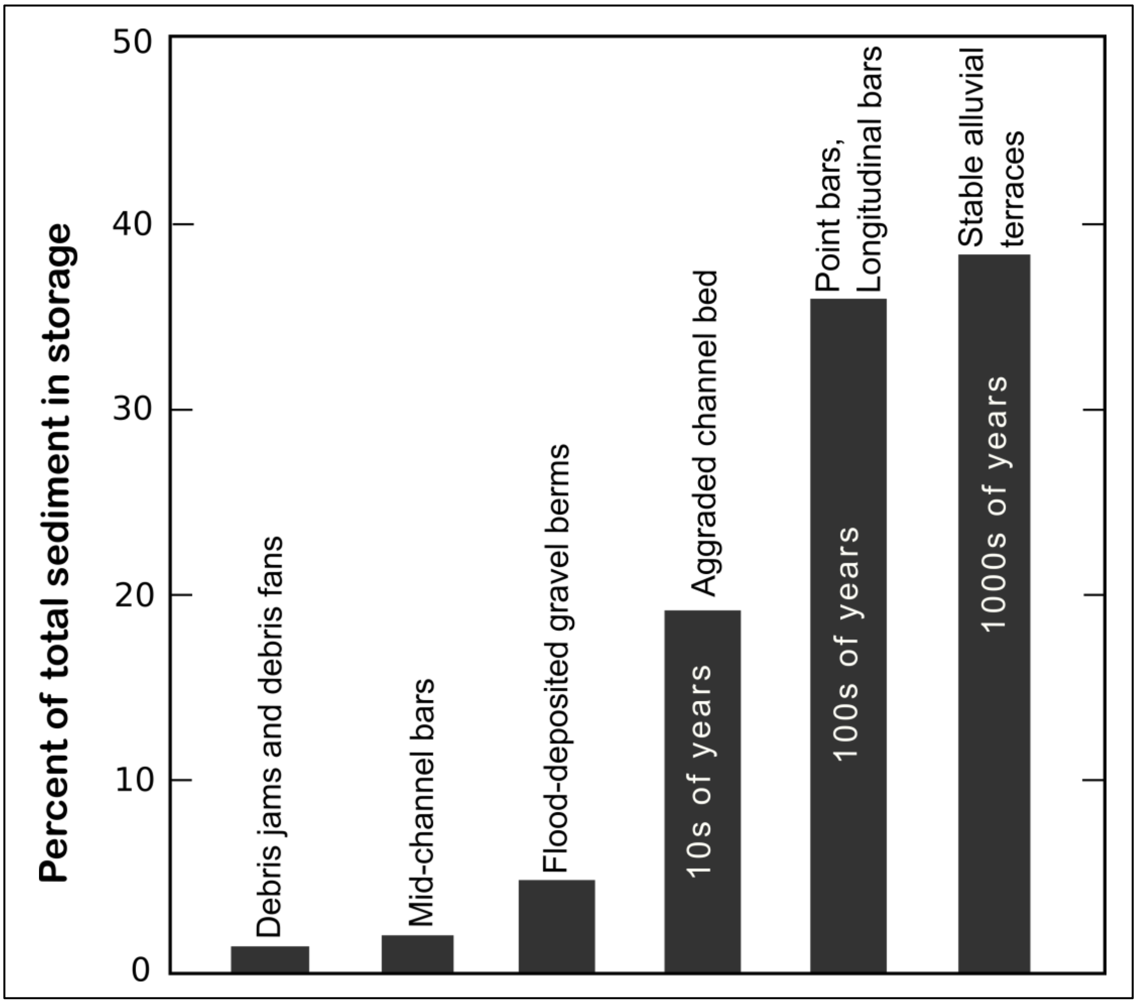


Figure 2.5: Sediment storage in Redwood Creek following the 1964 flood, also indicating the estimated period of storage in different features (Madej, 1992, Figure 13).

Extremely large sediment pulses that amalgamate in lower gradient reaches can take decades to centuries to pass. Knighton (1989; 1999) predicted that it would take at least 50 years after the cessation of mining in the 1980s, for the Ringarooma River to return to pre-disturbance bed levels, however, long sections of the river bed had already recovered their bed variability, relative to control sections, by the year 2000 (Bartley and Rutherfurd, 2005a). Gilbert (1917) used low-flow channel bed elevations to infer that large sediment pulses from hydraulic mining in the Yuba and Sacramento Rivers, California, would pass through in approximately a century (Gilbert, 1917; James, 1989a). However, James (1989) showed that transport rates remain elevated above pre-mining values for more than 40 years after the bed returned to pre-disturbance levels. James suggested that the rise and fall of bed level is the period of grade adjustment but it does not signify the complete passage of the sediment pulse

(James, 1989a; James, 1991; James, 1999; James, 2006a; James *et al.*, 2009; James, 2010). Sporadic but persistent re-mobilisation of sediment stores, and ongoing supply from the Yuba's upper tributaries, mean that the total sediment pulse is right-skewed with respect to time (James, 1989a; James, 2006a). This important modification of Gilbert's original model tells managers that the return of bed level is not always synonymous with pulse evacuation and the destabilising effects of high sediments loads may persist decades beyond bed level adjustment (Figure 2.6). Overall, examples in the literature suggest that sediment pulses seldom evacuate before decades or even centuries.

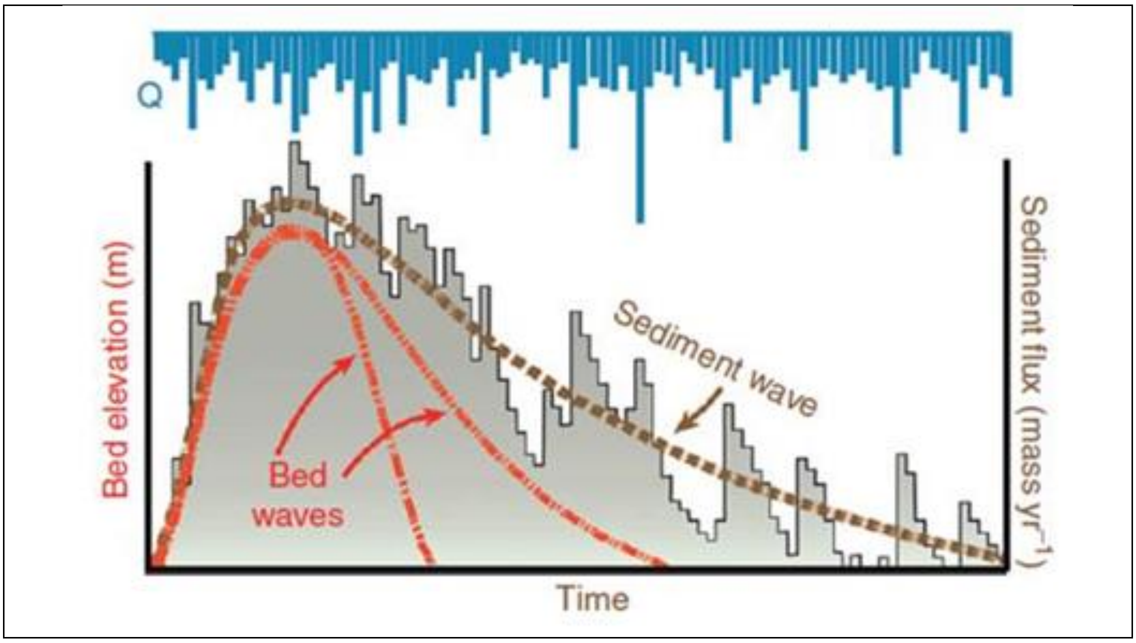


Figure 2.6: Conceptual model of right-skewed sediment pulse and bed pulse (time series of sediment fluxes) to represent the movement of material into storage. The sediment pulse consists of the entire input pulse, some of which moves into long-term storage on the floodplain or in high terraces. The bed pulse is the component which travels on the channel bed causing a reach to aggrade then degrade. The passage of the bed pulse is not synonymous with the complete evacuation of all inputs, which may lag behind changes in bed level as stored sediment is recruited during flood events. Adapted from; James (2006).

Additionally, pulses may completely stall in low gradient reaches where transport rates are very low. An example is when large volumes of sand were deposited in the lower reaches of Creightons Creek, SE Australia, following flooding in 1916. The low gradient of the creek means that the sand has stalled in the channel moving little over decades (Davis and Finlayson, 2000).

This section has reviewed sediment pulse dynamics, namely; how sediment is delivered to a channel, how pulses change as they move through a network, the controls on pulse celerity, and typical timescales for a return to pre-disturbance bed levels. Managers can use an understanding of sediment pulse dynamics to guide interventions. We now describe the five methods available to managers to manage sediment pulses.

2.3 Option one: do nothing, and accept the impacts of the bedload pulse in the channel

In order to make an informed decision to 'do nothing' managers need (a) a sound understanding of the consequences of doing nothing, and (b) to be prepared for the sequences of changes that will happen once the slug of sediment has passed, e.g. channel widening, bank erosion and a return to the pre-disturbance sequence of changes. As discussed above, the sediment pulse manifests as a rise in bed level, the filling of pools, smothering of bed features (e.g. riffles or LWD) and channel vegetation (James, 2006a). In resistant or bedrock channels, the sediment can simply pass through, producing no substantial change in the channel morphology. Petts (1979) has couched the term 'accommodation adjustment' when a dam produces no appreciable change in downstream channel morphology. The same term could be used to describe the situation where a sediment pulse transits through a stream reach with little impact on the channel. However, in many examples, the consequences of such dramatic increase in sediment load include widening, channel avulsions and tributary plugs. This section considers each of these changes.

2.3.1 Widening

Rivers confined by bedrock, or those that have banks with high clay contents and stabilising vegetation, are more stable and can remain unaltered as the sediment pulse migrates downstream (e.g. Rutherfurd, 2001). However, streams with less resistant banks commonly widen in response to rapid bed aggradation (e.g. Schumm, 1985; Simon, 1989; Simon, 1995). When mining sediments filled the Ringarooma River in Tasmania, the channel widened by between 15 % and 65 % in upstream reaches (Bartley and Rutherfurd, 2005a), and by over 300 % in downstream reaches (Knighton, 1987) (Figure 2.7). A slug of sediment into Creightons Creek in SE Australia led to a 25 % increase in channel width (Bartley and Rutherfurd, 2005b). Downstream widening is common when sediment pulses are released by dam removal (Pizzuto, 2002). Stream widening also liberates additional sediment from the banks which can increase the volume of the sediment pulse (Rustomji, 2008). Significant widening and bed aggradation increase the ratio of storage to transport in a reach and forms zones of sediment accumulation (Hoey, 1992; Pryor *et al*., 2011). As these zones transition from aggradation to degradation, and the reaches switch from sediment sinks to sediment sources, the celerity of the sediment pulse changes. Pulse celerity will decrease as material moves into storage, and increase as it is liberated by degradation and flushed downstream (Pryor *et al*., 2011).

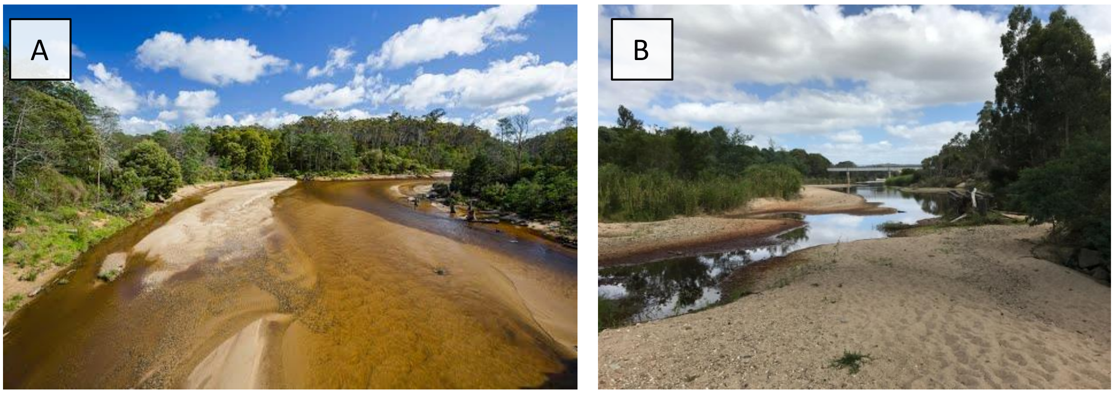


Figure 2.7: (A) Ringarooma River above the township of Pioneer, Tasmania widened by the passage of a sediment pulse introduced by tin mining, and (B) Tambo River above the township of Bruthen, SE Australia, where a large pulse of sand has raised bed level by several metres but the stable banks have not eroded. Photograph B: Ross Hardie.

2.3.2 Flooding

A major impact of sediment pulses is that they can reduce hydraulic capacity of the channel, and increase overbank flood frequency and duration. Increased flood risk due to channel aggradation is one of the most common justifications for managing sediment pulses. In addition to the usual effects of flooding, the increased connection between the channel and the floodplain will place more sediment into long term storage on the floodplain, reducing the size of the sediment pulse in the channel (James, 2010).

2.3.3 Avulsions

Flooding can also accelerate deposition on levees; perching the channel, leading to avulsions (Brizga and Finlayson, 1994; Nanson and Knighton, 1996). The effect of an avulsion is to store sediment in the abandoned section of channel, and introduce a new pulse of sediment downstream from the avulsion channel itself. This represents a nice example of complex response *sensu* Schumm (1973). An example is the Suncook River in Epsom, New Hampshire which, in 2006, scoured a new channel across its floodplain and deposited a pulse of approximately 100,000 m^3 of sand downstream (Wittkop *et al*., 2007; Perignon, 2008). The migration of the resulting sediment wave raised bed levels in downstream reaches of the Suncook River by over a metre, causing a second avulsion across a meander bend in early 2007 (Perignon, 2008). The probability of additional avulsions downstream will decrease as the sediment pulse disperses and bed levels lower. Similar avulsions have been triggered by pulses of sediment from landslides in the Southern Alps of New Zealand (Korup, 2004). Managers might be more likely to manage the sediment pulse if they suspect that it will trigger avulsions.

2.3.4 Tributary interactions

Sediment pulses interact with tributaries. If the pulse of sediment is moving down the trunk channel, it can block tributaries, producing a backwater lake. The lower Ringarooma, Tasmania is an example where trunk stream aggradation by a sediment pulse has blocked tributaries producing lakes that extend up to 2 km up the tributary (Knighton, 1989). If the sediment pulse is moving down a tributary, then it can similarly block the trunk stream. Several such 'tributary junction plugs' have formed across the Glenelg River in Western Victoria, Australia, where tributaries have deposited up to eight metres of sand in the trunk stream from gullying (Rutherfurd, 2001). In this case the blockage was enhanced by the more rapid arrival of tributary flood peaks relative to the more sluggish (and regulated) Glenelg River. Managers might decide to protect these new wetlands because they support a similar array of macroinvertebrates as downstream reaches (Lind *et al*., 2009).

To summarise, the first decision for managers faced with a sediment pulse is whether to do anything. This decision can be informed by predicting the celerity of the pulse, and whether it disperses or translates. In addition, the decision to act could be influenced by the consequences of the slug, namely flooding, widening, avulsions and tributary interactions. We now consider the four more direct management options.

2.4 Option two: controlling the supply of sediment at its source

Sediment inputs usually cease naturally as the source is eroded or becomes disconnected from the channel (e.g. landslide deposit) or activities driving the input, such as mining, stop. Cutting off the supply of sediment at its source can accelerate the recovery rate. This can convert a press disturbance into a pulse disturbance. The coarse sediment pulse will then migrate downstream as its sediment supply is cut off.

Typical examples of eliminating or reducing point source sediment inputs are controlling the erosion rate of an artificial reservoir following dam removal (e.g. Randle *et al*., 2015) and stopping tailings deposition in channels (e.g. Knighton, 1987). Arresting supply from diffuse inputs includes reforestation (Kondolf *et al*., 2002; Marden *et al*., 2005) or gully stabilisation (e.g. Herzig *et al*., 2011). These interventions initially transform inputs from a press to a pulse disturbance and decrease sediment supply; initiating bed coarsening (e.g. Knighton, 1999), armour development (e.g. Lisle, 2008), or rapid incision and channel contraction (e.g. James, 1991). The net effect of these changes is to decrease the size of the pulse and accelerate dispersion and translation. Secondary effects of controlling the sediment supply at its source are discussed in section2.8. In places such as Japan and Taiwan small dams (called Sabos) are used in steep first and second order streams to interrupt debris flows and stop them from reaching the main channel and forming a coarse sediment pulse. We will now describe Californian mining and reforestation in the North Island of New Zealand which provide good examples of sediment control at source.

2.4.1 Cessation of hydraulic mining, Sierra Nevada, California

A good example of controlling sediment supply at its source is when the state government of California passed a law in 1884 prohibiting the discharge of mining debris into the Sacramento River and its tributaries, effectively ending all hydraulic mining in the region (James, 1991). The large sediment pulse that already occupied the channel continued to disperse downstream and the lower reaches of the Bear and Yuba Rivers aggraded by as much as 5 metres, and fine sediment was deposited across the floodplain of the Sacramento River (Gilbert, 1917; James, 1989a; James *et al*., 2009). Ending mining effectively eliminated the supply of sediment to upper tributaries but the volume of material stored in piedmont streams remained a source of sediment to the lower Bear, Yuba and Sacramento Rivers (James, 1989).

2.4.2 Reforestation in the Waipaoa River Catchment, New Zealand

The East Coast of the North Island of New Zealand is just 2.5 % of New Zealand's land area but this disturbed landscape produces 33 % of its annual sediment yield (Hicks *et al*., 2002). Forest clearing and conversion to agriculture in the late 19th and early 20th centuries accelerated gully development, landsliding and earthflows in the steep upper portion of the catchments (Herzig *et al*., 2011) and caused up to 7 metres of aggradation in tributaries of the Waipaoa River (Gomez *et al*., 2003).

In an effort to control erosion the New Zealand government undertook extensive planting of exotic Douglas fir (*Pseudotsuga menziesii*) in eroding gullies (Marden *et al*., 2005; Page *et al*., 2007; Herzig *et al*., 2011), which reduced annual sediment yield from gullies by 62 % (Gomez *et al*., 2003). Furthermore, reforested areas showed remarkably few landslides during a 100 year return period storm in 1988 (Page *et al*., 1999; Kasai *et al*., 2005) (Figure 2.8).

While inputs from eroding gullies have declined, 48 % of all material eroded in the catchment between 1950 and 1988 was stored in the lower 8 km of the Te Weraroa channel (Gomez *et al*., 2003) from where it is dispersing downstream and into the Waipaoa River where it is either deposited on artificial levees or across the adjacent floodplain at rates of ~ 60 mm a^{-1} (Gomez *et al*., 1999). Levee deposition has led to channel narrowing and a steady (albeit slow) reduction in channel capacity.

The Te Weraroa and neighbouring catchments demonstrates the effectiveness of reforestation at controlling sediment supply. However, due to the catchment's naturally high sediment yields, and the large volume of material already stored in the upper tributaries of the Waipaoa River, it will take several decades for the benefits of reforestation to be felt downstream on the Poverty Bay flats (Gomez *et al.*, 2003).

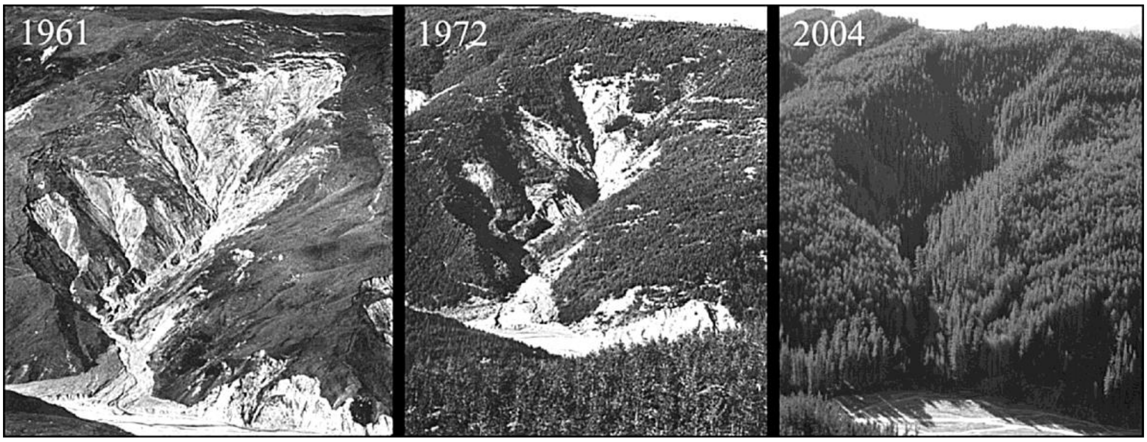


Figure 2.8: Pre (1961) and post-reforestation (1972, 2004) photography of a medium-sized gully in Te Weraroa Stream, Mangatu Forest, north east North Island, New Zealand. Reforestation in this example reduced the area of active erosion from 7.6 ha to 0.8 ha between 1974 and 2004, source; Marden *et al.* (2005).

Controlling the supply of sediment promotes the dispersion of the sediment pulse by reducing the amount of material released into the channel, allowing the tail of the pulse to begin migrating downstream. Controlling the supply of sediment at the source should be prioritised so that the magnitude of the disturbance (and its impacts) can be minimised and any downstream remediation efforts are not undone.

2.5 Option three: promoting in-channel storage

The sediment pulse can be trapped using in-stream structures such as check dams or by re-vegetation of bars or benches. Trapping the sediment pulse protects downstream reaches from high sediment loads.

Vegetation can naturally colonise channel deposits (e.g. Friedman *et al*., 1996; Nelson and Dubé, 2016) but managers can undertake additional revegetation to accelerate the rate of trapping. Vegetation encourages deposition by shielding underlying deposits from erosion and by increasing channel roughness, which slows the flow and encourages further deposition (Rominger *et al*., 2010; Gurnell, 2014). In this manner, vegetation stores sediment in the channel. The colonisation of bedforms also influences channel morphology as bars are converted to benches and the channel contracts (e.g. Erskine, 1993; Erskine *et al*., 2012; Gurnell, 2014; Erskine, 2015). Because vegetation narrows channels and enhances incision (e.g. Friedman *et al*., 1996b), overall transport capacity is reduced which slows the passage of the sediment pulse (unless channel narrowing is accompanied by significant channel incision, in which case the channel may contain larger flows which cause the sediment transport rate to *increase* at some flows). Revegetation has been used in the Genoa River, SE Australia to stabilise stream banks and trap large ‘sand slugs’ washed into the river during a series of floods in the 1970s (Erskine, 1993; Pearson, 2012) (Figure 2.9).

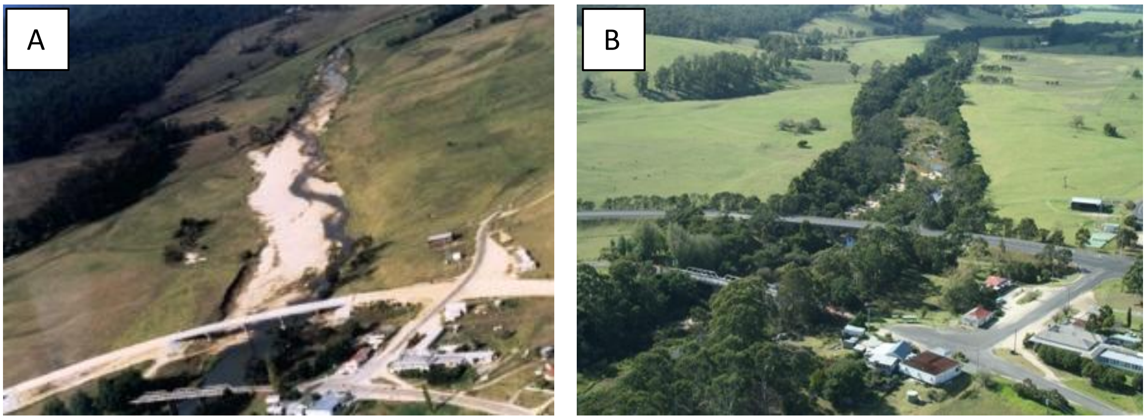


Figure 2.9: Genoa River before revegetation of stream banks and channel sand deposits in 1979 (A) and after in 2009 (B) Source East Gippsland Catchment Management Authority.

In-stream structures, often called sediment detention dams, trap sediment by intercepting bedload, decreasing stream gradient, and encouraging deposition upstream. Sediment accumulates behind the structures until it is either excavated or the structure fails (Wang and Kondolf, 2014). Several such small brush and log dams were constructed in the upper Yuba River in the early 20th century to trap mining debris, and Gilbert (1917) documented their rapid in-filling and, in some cases, collapse (Figure 2.10A). The much larger Englebright Dam (86 million m^3) was constructed in the Yuba Basin in 1941 for the same purpose. The dam is now being considered for removal in an attempt to re-introduce fine gravels into the lower Yuba which provide critical spawning habitat for anadromous fish (James, 2005). In addition to trapping large sediment pulses in the trunk stream, smaller Sabo structures have seen widespread use in Austria (Figure 2.10C), Japan and Taiwan as a means of trapping debris flows in steep tributaries (Ikeya, 1989; Chanson, 2004; Wang and Kondolf, 2014).

Without regular excavation these structures are a short term solution and in rapidly eroding areas have a lifetime of several decades (Wang and Kondolf, 2014). Once dams have filled, sediment can pass directly over retention structures, so that managers will be forced to intervene again to control sediment. Filled dams can also fail catastrophically, unleashing secondary pulses of sediment as debris flows. For example, the Barlin Dam was one of a series of structures constructed along the Dahan River, Taiwan to trap and store sediment before it entered a downstream hydro-electric reservoir. The 38 m high structure was completely full by 2003 and failed during Typhoon WeiPa in 2007, releasing a 10.5×10^6 m^3 pulse of sand and gravel to the Dahan River (Tullos and Wang, 2014). For this reason, filled retention structures can pose a serious and ongoing hazard to downstream infrastructure. Deliberate breaching of filled dams in order to flush sediment downstream, is discussed in the next section.

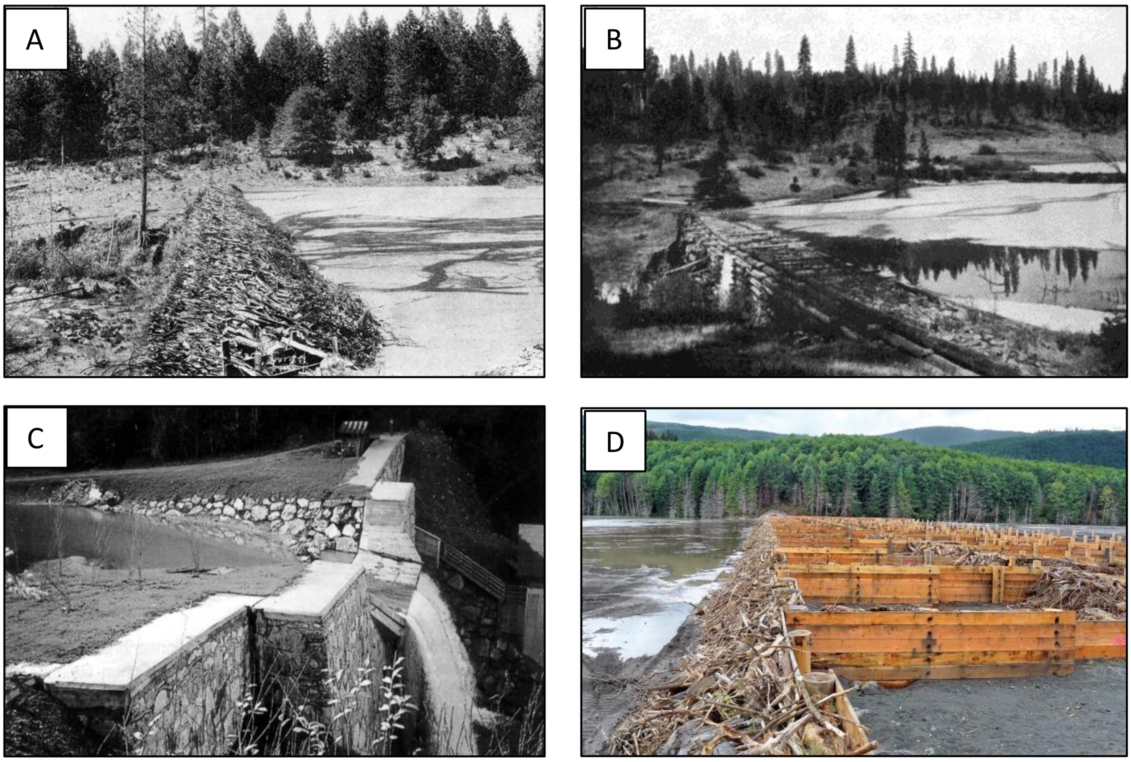


Figure 2.10: (A) Brush dam below Murchie Mine in South Yuba basin in 1908, source: Gilbert (1917; Plate 26A), reproduced from James (2005), (B) Log-crib dam on Spring Creek below North Columbia mine in 1905, source: Gilbert (1917; Plate 27A) reproduced from James (2005), (C) Sediment retention structure in Wagrainer Ache, Salzburg, Austria, Source: Huebl & Fiebiger (2005), (D) A cross-valley structure designed to trap sediment moving down the north fork of the Toutle River, Washington, USA, source: US Army Corps of Engineers.

2.6 Option four: accelerating sediment transport rate

Increasing the sediment transport rate accelerates evacuation of the sediment pulse and reduces recovery time. Removing sediment from affected reaches by increasing the sediment transport rate can be achieved in regulated rivers by increasing discharge (flushing flows) or in un-regulated systems by concentrating flows – usually by levee construction.

We expected that targeted flow releases from dams would have been used to flush bed sediments downstream. Flushing flows from dams are certainly used to maintain a particular channel form, and to turn-over bed material to reduce colmation (Kondolf and Wilcock, 1996; Wilcock *et al.*, 1996). However, we could find no evidence that managed releases from dams are used to specifically accelerate recovery of sediment pulses. Acreman (2000) in a comprehensive review of flushing flow releases from global dams, made no mention of releases to flush sediment downstream.

A similar strategy is that of ‘store and flush’ where sediment is deliberately trapped and stored behind detention dams during low flows, and is then rapidly flushed downstream during flood peaks. While the technique has been used to avoid generating a coherent sediment pulse during hydro-electric dam removal (e.g Major *et al.*, 2012) and to flush accumulated sediment from floodwater detention dams in urban stormwater systems (Yu and Tan, 2006), the authors are not aware of any examples where ‘store and flush’ has been used to specifically manage existing sediment pulses.

Concentrating flow within constructed levees is more common. This practice is often justified for flood protection because sediment has elevated bed levels. Engineers predicted that levees would have the dual-benefits of containing higher magnitude flows and increasing bed scour, historically making levee construction an attractive tool. For example, narrowly spaced levees constructed along the lower Feather River, California in the late 19th century were designed to accelerate transport of a pulse of mining debris being fed to the channel from the Bear River. Levee spacing was narrowest at the confluence of the Bear and Feather Rivers, a site of historical deposition (James, 2010). The levees successfully encourage the bed to self-scour, accelerating sediment transport and maintaining navigable bed levels (James and Singer, 2008; James *et al*., 2009).

In some cases levee construction has had the effect of *increasing* bed levels, exacerbating flooding and increasing the likelihood of channel avulsion. For example, flood control levees built along the lower reaches of the Waiho River, South Westland, New Zealand have reduced the transport capacity of the bedload-dominated Waiho River and resulted in up to 5 m of aggradation since 1985 (Davies *et al*., 2003). The management response of periodically increasing the height of levees means that the river bed is now perched ~15 m above the adjacent Tartare River, and an avulsion is likely (Davies *et al.,* 2013). The avulsion would cause a hiatus in aggradation in the Waiho for decades, after which sediment would fill the bed of the Tartare and aggradation would resume (Davies *et al*., 2013).

Flushing flows and concentrating flow are both options to accelerate the sediment transport rate. Flushing flows are not commonly used. Concentrating flow using levees works in some cases (e.g. along narrow sections of the Feather River, California) but may restrict transport capacity in high bedload rivers where avulsion is a threat.

2.7 Option five: extracting sediment

Probably the most radical response to a sediment pulse is to physically remove it from the channel. This can be achieved by extracting the material directly from the channel using excavators or by dredging.

Extraction induces an abrupt increase in channel accommodation space that interrupts the downstream passage of sediment until the bed discontinuity is either smoothed by degradation, or filled with incoming bedload (Lee *et al*., 1993; Rutherfurd *et al*., 2000). The deficit-induced erosion in the extracted reach is distributed upstream via knickpoint migration and downstream via ‘clear water’ effects (Lee *et al*., 1993; Kondolf, 1997; Wu and Wang, 2008). Extraction decreases the amplitude of the sediment pulse by removing material and dramatically reduces wave celerity.

The negative effects of commercial over-extraction are well documented (Kondolf, 1994; Kondolf, 1997; Rinaldi *et al*., 2005; Padmalal *et al*., 2014). Commercial extraction, which has the added benefit of providing economic as well as environmental value, may be an under-appreciated tool to preserve reaches downstream of migrating sediment pulses. However, to the author's knowledge, there has been no comprehensive study on the potential for commercial extraction to be used as a management tool in channels affected by unusually large sediment loads. Commercial extraction has been used as a management tool for the past two decades in the Glenelg River, SE Australia. In this case, extraction has primarily been used to prevent migration of the sediment pulse to non-degraded reaches. Studies to evaluate the effectiveness of this technique are currently underway. Below we describe extraction in New Guinea rivers.

2.7.1 Examples of extraction of sediment pulses

There are several examples where dredging has been used to maintain navigation in rivers affected by sediment pulses including:

- the Colwitz River, Washington where a large sediment pulse from the eruption of Mt St Helens is migrating downstream (USACE, 2010b)
- the Feather and Sacramento Rivers in California, where a large pulse of hydraulic-mining debris is slowly being delivered by rivers draining the Sierra Nevada (Gilbert, 1917; James and Singer, 2008)
- the confluence of the Wabash and Ohio Rivers, Indiana, where an upstream bend cutoff in the Wabash River generated a large sediment pulse (Zinger *et al*., 2011).

Figure 2.11: Satellite view of the Ok Tedi mine which discharges mine tailings directly into the upper Ok Tedi River, source; Google Earth.

Possibly the largest example is in the Ok Tedi and Fly Rivers, which lie in the high rainfall highlands of Papua New Guinea's Western province (Figure 2.11). These rivers have been heavily degraded by inputs from mining since 1984. The Ok Tedi mine discharges approximately 150,000 t day^{-1} of tailings (delivered as a slurry rich in fines) and overburden (coarse waste rock) to the headwaters of the Ok Tedi River (Markham and Day, 1994). The massive inputs amount to a forty-fold increase in annual sediment yields and have transformed the Ok Tedi River's channel, above its confluence with the Fly River, from being highly sinuous to a wide, braided channel (Parker *et al*., 1996). High abrasion rates enhance pulse dispersion as fine material is more rapidly flushed downstream, where it is either exported to the Fly River or deposited on the floodplain of the lower Ok Tedi and Fly Rivers (Parker *et al*., 1996; Cui and Parker, 1999). Sand deposition in Ok Tedi's lower reaches has dramatically increased flood frequencies; causing the dieback of 1,924 km^2 of floodplain vegetation (OTML, 2014).

Concern that siltation would restrict export of mined product by large ships navigating the Fly River, and a desire to reduce flood-induced forest dieback, led to a dredging program beginning in 1998 which continues today. Dredging occurs immediately upstream of the Ok Tedi – Fly River confluence (100 km downstream from the mine), removing approximately 18.8 Mt of material per annum which is only 25 % of annual mine inputs, but 85 % of the sand load passing the dredge (OTML, 2014). Dredged sediment is pumped to engineered stockpiles on the adjacent floodplain where it remains in storage. The dredging programme has succeeded in keeping the Fly River open to shipping, and has decreased the frequency of overbank floods and associated forest dieback. Dredging stops the sand component of the sediment pulse from travelling further downstream but fines are still deposited on the floodplain of the lower Ok Tedi and Fly Rivers, where they are expected to remain in storage for centuries (Parker *et al*., 1996).

2.8 Longer term management: complex response & unintended consequences of intervention in sand pulses

All of the above options for managing sediment pulses in rivers will trigger secondary responses in the river. Catchment networks exhibit a complex response and their sediment yields continue to oscillate well beyond the initial disturbance (Schumm, 1973; Humphrey and Heller, 1995; Schumm and Rea, 1995). Interventions that alter the distribution of sediment, starving some reaches and storing it in others, also initiate a series of responses (e.g. Kondolf *et al*., 2002) that can lag behind interventions by decades. We highlight three examples of complex response that managers need to consider below: tributary rejuvenation, enhanced incision, and delayed incision.

2.8.1 Tributary rejuvenation: the Ringarooma River, Tasmania, Australia

The Ringarooma River and its tributaries in north east Tasmania, Australia, received over 40 million m^3 of mostly sand sized waste from tin mining between 1875 and 1984 (Knighton, 1989). Mainstem aggradation blocked tributaries, and sediment moving down the tributaries was trapped and stored. As the sediment pulse in the Ringarooma

River migrates downstream, the bed deepens, and the large volumes of sediment stored in the tributaries will be released into the river as a second pulse of sediment (Knighton, 1989; Knighton, 1991). As the pulse of sediment migrates downstream it is the upstream tributaries that will be affected first, adding new sediment to the back of the sediment wave, producing a complex sequence of sediment pulses over time. Attempts to trap or harvest sediment from the Ringarooma or its tributaries would affect the timing and sequencing of these tributary responses.

2.8.2 Enhanced incision

The morphological consequences of a reduction in sediment supply include; incision, channel narrowing, bed armouring and in some cases the transition from a braided to a single-threaded sinuous morphology (Schumm, 1985; Knighton, 1998; Surian and Rinaldi, 2003; Boix-Fayos *et al*., 2007). Whether or not such transformations are desirable depends on the context of the intervention and any target morphology. Such reductions in sediment supply have the potential to produce secondary, unintended consequences.

Natural regeneration of riparian vegetation, reforestation (37 % increase in area between 1835 & 1988), the construction of check dams and historical extraction from some reaches led to a large reduction in sediment supply to the Drôme River, France over the 19th century (Piégay and Landon, 1997; Kondolf *et al*., 2002). In response, the channel has contracted by up to 60 %, incised up to 5 m (Landon *et al*., 1998), and gravel bars have been colonized with woody vegetation (Kondolf *et al*., 2002). Drastic incision in the Drôme has had two consequences; lowering of the water table across the alluvial fan at its confluence with the Rhone—which support orchards and other high value agriculture—and migration of incision into tributaries, requiring additional grade control structures to be built. Water table lowering has led to the loss of an estimated 6 million m^3 of groundwater storage capacity formerly available for agriculture (Kondolf *et al.*, 2002). Feedbacks between vegetation establishment (both on islands and as a riparian buffer), and reduced bedload have compounded the impacts of incision and have led to reduced diversity of riparian ecosystems (Landon *et al*., 1998)

2.8.3 Delayed incision

An interesting consequence of a sediment wave is that it can delay processes that are occurring in a stream. A major pulse of sediment migrated into tributaries of the Glenelg River in Australia. Several of these tributaries (Bryans Creek, Wando Vale Ponds, Chetwynd River) were in the process of incising (they are valley floor incised streams) when the sediment moved through in the 1940s. Now, nearly 70 years later, the sand pulse has passed through, and the channels are returning to their delayed process of incision (Rutherfurd, 2001). Bryans Creek, for example has now incised over a metre since the sediment pulse passed in the late 1990s (Figure 2.12).

Figure 2.12: View downstream of the incising bed of Bryans Creek, Victoria, Australia. A renewed phase of incision began in the late 1990s after a sediment pulse passed though. Photo: Glenelg Hopkins Catchment Management Authority.

2.9 The impact of sediment supply regime on the management of bedload pulses

Many of the examples presented in this chapter (for example tailings-fed pulses in California and pulses in New Zealand fed by rapid hillslope erosion) exist in transport limited conditions- where the annual sediment supplied to a river network greatly exceeds the exceeds the rivers capacity to transport that sediment. As a result, the bedload pulses are superimposed on rivers with in-channel high sediment storage prior to the pulse forming (Nelson and Dubé, 2016), and strong connection between the channel and the floodplain (Page et al., 2007). In such sediment-rich environments the cooping between hillslopes and valley floors is strong (Harvey, 2002; Korup, 2004; Korup et al., 2004) and intermediate storage zones (such as alluvial fans) are more common. The abundance of sediment stores, which can be activated during storm events or earthquakes, mean that additional sediment pulses are also possible. Managers need to be aware of these storage dynamics and possible inputs when deciding on whether to intervene following the formation of a bedload pulse.

In contrast to transport-limited environments, supply-limited catchments, such as many of the rivers of SE Australia, are characterised by low in-channel accommodation space (and hence low in-channel sediment storage), and, potentially, strong swings between drought and flood dominated flow regimes (Erskine and Bell, 1982). In such environments, the formation of bedload pulses is a much greater departure in sediment regime than their transport-limited counterparts. Rivers in valley floors that have adjusted to a low sediment supply are suddenly overwhelmed. Managers need to consider that the channel adjustments triggered by the pulse (change in width, sinuosity or planform) in these cases may represent a permanent change in channel morphology. The recovery of such rivers is likely to be characterised by incision and channel contraction, as the channel re-adjusts to the low sediment supply that preceded the bedload pulse.

2.10 Landscape considerations when selecting management options

The source of excess sediment, how that sediment is delivered to channels, and the catchments flow regime are important considerations when choosing a strategy (or strategies) to manage a bedload pulse. This section (Table 2.2) outlines the key environmental factors that managers should consider when choosing a management option (or options) that are fit for purpose, as well as the potential unintended consequences of each management option.

Table 2.2: Key management considerations when selecting a management option that is fit for purpose, and the potential complex responses and unintended consequence so each of the management options.

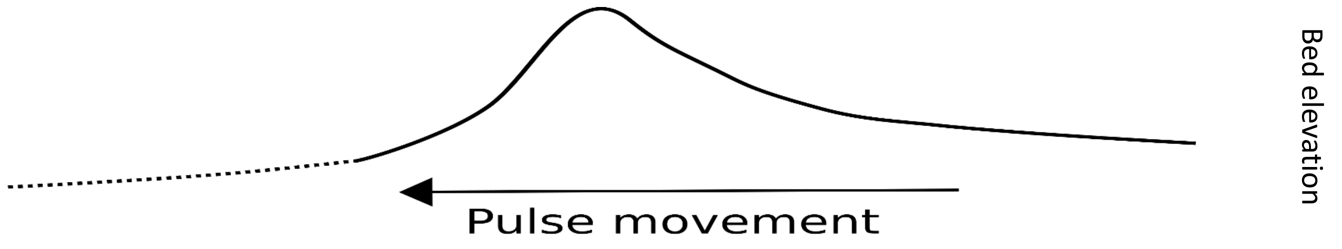
Management Option	Management considerations for landscape-type	Potential unintended consequences or complex responses of adopting management option
Do nothing	In very low sediment supply and low transport capacity rivers (such a low-gradient streams in SE Australia), pulse celerity is very low. Doing nothing may leave the river in an aggraded, low-value state for decades to centuries as the pulse is simply stored in the channel bed.	If the bedload pulse is allowed to migrate downstream without intervention, tributary streams could be dammed at their confluence with the trunk stream, spreading aggradation across more of the stream network
Control the supply of sediment at the source	Most suitable when discrete, local-scale interventions are able to limit sediment supply. For example, by arresting stream incision in eroding reaches on the valley floor (which supply sediment to downstream reaches) using a grade control structures. Less suitable when the source of sediment is widely distributed and interventions would need to be at the catchment scale (for example, when widespread landsliding on hillslopes following storms or earthquakes)	Potential unintended consequence of controlling sediment supply too effectively is a shift from a significant sediment surplus to a significant sediment deficit. The deficit could cause incision and bank erosion in downstream reaches, which generates a new sediment source for a bedload pulse to develop further downstream. The overall impact is to shift the bedload pulse in a downstream direction and create an eroding and an aggrading reach.
Promote in-channel storage	Caution must be exercised when promoting in-channel storage in ephemeral rivers that cease to flow doing dry months. Increasing bed levels may cause the river to become disconnected (pool separated by bare sediment) when flows	If the bedload pulse also contains contaminates (for example mining by-products that accumulate in tailings dam that then fail), then promoting in-channel storage can lead to unintended consequences for the reaches containing the contaminated sediment. Contaminants can leech into

	drop below some threshold	groundwater and accumulate in vegetation that grows on the sediment. In both cases, the contaminates are transported further afield and become difficult to trace. In such cases, sediment extraction may be a better option.
Accelerate sediment transport rate	More suitable in regulated rivers, where the magnitude and duration of flow events used to shunt sediment through high-transport areas can be optimised. Less suitable in bedload-dominated rivers, where constraining river width may result in aggradation	Consideration must be given to the long-term impact of artificially constraining a river reach. While a higher sediment transport rate at one point in the river may be suitable while the sediment pulse is moving through the reach, artificial levees that constrain river width have two potential unintended consequences over the long term: (1) encourage development on the adjacent floodplain where flood risk is supressed by the presence of the levees, (2) limit the ability of the river to adjust its morphology once the sediment pulse has passed
Extract sediment	In-stream extraction is time and resource intensive and is only likely to be feasible when protecting high value reaches or floodplain, or where a viable market for the extracted sediment can be used to fund extraction. Extracting sediment to lower bed levels may also reduce the frequency and duration of flooding, which can set a precedent for ongoing management.	If bed excavation is deep and coves enough of the river bed to later the energy gradient of the river, then a roasted knickpoint can migrate upstream. Passage of the knickpoint will liberate more sediment which is then delivered to the extraction reach. In this way, extraction from one point in the river may spread upstream and downstream.

2.11 A decision framework for managers

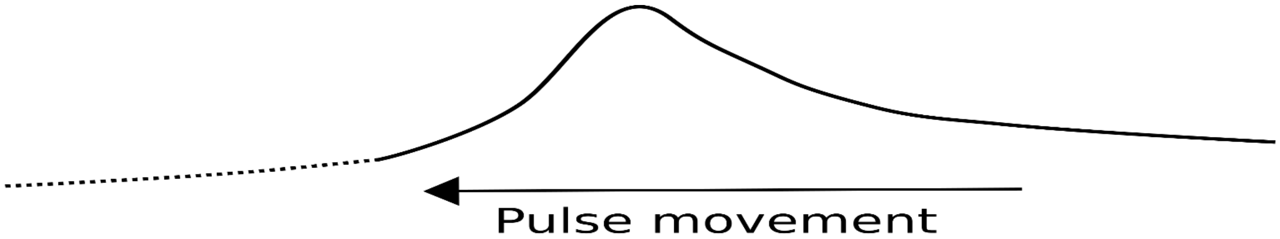
This section draws the management goals, sediment pulse dynamics, and the five intervention options together into a decision framework that managers can use. The framework helps managers decide when to undertake what methods when managing sediment pulses. The framework distinguishes between reaches yet to be affected by the sediment pulse, reaches being affected by the peak of the sediment pulse, and recovering reaches at the tail of the pulse. Each location will have appropriate management methods and managers often use a combination of methods across an affected catchment.

Table 2.3: Decision framework managers can use to select the most appropriate management method. The most appropriate method depends on the management goals, which in turn depend on the location of the sediment pulse.

Schematic of the pulse				
Pulse stage	Downstream of pulse (not yet affected)	Pulse peak	Tail of pulse	Source area
Management goal	Protection • Avoid damage to infrastructure. Protect restoration assets and high value reaches.	Mitigation • Reduce flood risk • Reduce risk of avulsion • Maintain navigability • Limit habitat destruction	Remediation • Accelerate recovery	Reduce further inputs
Management actions	• Trap and/or extract at leading edge of pulse. • Prepare for high sediment loading, projects to accelerate transport of approaching pulse.	• Accelerate transport, • Store and flush sediment • Trap and extract	• Stabilise sediment sources • Limit mobility (trap and store)	• Stabilise sediment sources • Cease activity contributing sediment

The decision framework (Table 2.3) links management goals to management actions. The management goals will depend on where the target reaches are in relation to the overall sediment pulse and the scale and celerity of the pulse being managed. Intervention methods can be used in combination, given managers may be dealing with multiple reaches that span all three zones of the sediment pulse. Importantly, if managers want to protect downstream reaches, they might have to opt for direct trapping or removal because reducing supply could take too long to have an effect. The variety of approaches is best illustrated by the use of two case studies, management of a large sediment pulse on the North Fork of Toutle River, Washington, USA, and the Glenelg River, Victoria, Australia (Table 2.4).

Table 2.4: Decision framework from Table 2.3 applied to two case studies: management of a sediment pulse in the North Fork of the Toutle River, Washington, USA generated by the eruption of Mt St Helens in 1980 (USACE, 1985; USACE, 2010b; USACE, 2010a; USACE, 2014) and, management of a series of sediment pulses fed to the Glenelg River by its tributaries after land clearing accelerated catchment erosion (Erskine, 1994; Rutherfurd and Budahazy, 1996; Rutherfurd, 2001).

Schematic of the pulse				
Pulse stage	Downstream of pulse (not yet affected)	Pulse peak	Tail of pulse	Source area
North Fork of the Toutle River, Washington, USA				
Management goal	Protection • Maintain navigability of the Colwitz River: prevent increases in flood risk in the lower reaches of the North Fork of Toutle River and the Colwitz River	Mitigation • Mitigate the increased flood risk for the 50,000 inhabitants of Longview, Kelso, Lexington and Castle Rock	Remediation • Not feasible due to the scale of the pulse and ongoing inputs from upstream	Reduce further inputs • Not feasible
Management actions	• Emergency dredging of the Colwitz River	• Increase levee heights to maintain flood protection standard • Sediment trapped and stored behind a series of large sediment retention structures, capacity (dam height) increased as required	• Allow vegetation to re-establish and monitor post-eruption recovery processes	• None: not feasible due to size of source area, steep slopes and ongoing disturbance from storms and the potential for future eruptions

Glenelg River, Victoria, Australia				
Management goal	Protection • Protection of downstream reaches with high environmental value	Mitigation • Reinstate habitat lost due to sedimentation • Limit bank erosion	Remediation • Accelerate recovery of tributaries	Reduce further inputs
Management actions	• Extraction from the leading edge of the sediment pulse to protect downstream reaches	• Directly remove sediment from the deepest section of the pulse with commercial extraction in order to protect downstream assets • Trap sediment using: fencing to exclude stock from the river, which allows vegetation to establish on sand bars and locks sand into storage; grade control structures to limit sediment movement • Trap sediment in transit by reintroducing large wood removed in the 1960s • Install bank protection structures to stop bank erosion	• Use fencing to exclude stock from the river and environmental flows to accelerate flushing of sediment downstream	• Reduce sediment supply from gullies by excluding stock, reducing sediment from erosion using re-vegetation and hard structures

The decision framework can guide where different options are most appropriate in relation to the location of the sediment pulse. Managers will also face decisions about when the most appropriate time to use each intervention option is, the scale at which to implement each option, and where specifically to intervene. In this section we use insights from the case studies to provide guidance on this sequencing.

2.11.1 When and how can managers control sediment inputs?

Controlling sediment at its source is the most commonly used method and provides the most long term benefit of the five options. In cases where the activity supplying material to the channel can be stopped, this should be a priority as doing so will limit the size of the resulting sediment pulse. Vegetation and erosion control measures are most effective for diffuse inputs at the catchment scale, but there will be a delay between intervention and reduced inputs. Vegetation takes decades to fully establish so managers can implement source control early and use other options to address the sediment pulse in the near-term.

2.11.2 How and where should managers trap the pulse?

When managers seek to protect downstream reaches, slowing or halting migration of the main body of the pulse is a priority. Trapping and storing, or extracting sediment at the leading edge of the pulse is one of the most effective and commonly used options to do so. Sediment can be trapped in lower value, upstream reaches where elevated bed levels do not threaten assets. Downstream barriers to sediment movement (which might be constructed first) can be used in conjunction with a sequence of upstream structures that enhance pulse dispersion - reducing the rate sediment is supplied to downstream reaches. By building detention structures in an upstream direction, downstream reaches are always protected and progressively more sediment is immobilised. Because the scale of trapping structures and the size of their storage basins will need to be large enough to trap a meaningful proportion of the sediment pulse, this option is more likely feasible for smaller pulses. However, when the value of downstream assets is high, interventions have been successful in trapping very large sediment pulses, e.g. along the North Fork of the Toutle River, Washington. If trapping sediment is not feasible managers could instead opt to accelerate transport through downstream reaches by constructing levees, or dredging sediment in high value reaches as the pulse passes through.

Once immobilised, sediment can either be stabilised by vegetation, or extracted from the channel. As with source areas, channel vegetation will take decades to properly establish and will be vulnerable to disturbance by floods and burial by further sediment inputs. Thus, revegetation of stored sediment should proceed in the opposite direction to sediment trapping, i.e. from upstream, where inputs are lower, to downstream. Managers could also use extraction to protect downstream reaches, in which case the annual volume of extraction needs to be as close as possible to the annual sediment supplied to the storage reach.

2.11.3 How can managers mitigate impacts at the pulse peak?

Mitigating impacts at the peak depth of sediment accumulation, in the main body of the pulse, is best achieved by removing the sediment. This can be achieved by accelerating sediment transport to evacuate the pulse, or where downstream reaches are to be protected, by directly extracting sediment from the channel. Managers will face a balance between mitigating impacts and the potential for secondary consequences of a rapidly falling bed level, for example, tributary rejuvenation and bank instability. In some cases the size of the pulse will be too large for mitigation measures to affect the pulse, and managers might focus instead on building structures to simply protect assets while the peak of the pulse passes through. Managers can use an understanding of the pulse celerity when deciding the most appropriate intervention for such reaches. For example, a rapidly moving sediment pulse will only affect target reaches for a short time, while a slow-moving pulse will require longer term management.

This section has presented a decision framework to help managers align management goals with management actions and provided insights into how managers could sequence these interventions. Ultimately managers are likely to use a combination of the options presented here in different parts of the catchment, depending on the size of the sediment pulse, resources available, and the most urgent management goal. I now consider how managers may sequence interventions across a catchment when pursuing the management options above (Table 2.5).

Table 2.5: How managers can sequence each of the four management options with one-another, across the catchment, and over time.

Management option	Reduce the sediment supply at source	Promote in-channel storage	Accelerate sediment transport	Directly extract sediment from the channel
Intervention priority	– A priority intervention -treat cause *alongside* symptoms in other parts of the catchment – Prioritise when inputs are delivered as a press (i.e. ongoing cf. short-lived delivery) – Prioritise when source of sediment is an ongoing activity (e.g. mining)	– Use in conjunction with accelerating sediment transport to funnel sediment into defined storage areas	– Prioritise in heavily modified rivers where artificial levees are present – Use in conjunction with promote channel storage and directly extract sediment so that sediment flushed though upstream sections is captured downstream	– Prioritise when pulse and river are large, and where channel navigation is a management goal – Avoid in sensitive rivers also subject to other disturbances such as removal of bank vegetation, or artificial straightening – Set extraction rate equal to annual sediment supply to extraction site, to minimise rapid erosion
Sequencing across catchment	– Define source area(s), consider controlling distributed sources of sediment, such as channel incision and bank erosion using grade control structures, limit stock access to streambed, and – Prioritise local-scale controls (i.e. sediment detention dams, erosion control) in the areas with the highest sediment yield to get maximum reduction in sediment supply	– Prioritise in low-gradient rivers where accumulation is likely – Concentrate storage as close to source of sediment as possible to minimise total length of river impacted – Trade some environmental values in storage reaches for protection of environmental values in downstream reaches.	– Accelerate sediment through high value reaches with modified floodplain, to protect infrastructure and limit aggradation – Promote at downstream end of catchment for example by keeping estuary moth open to prevent infilling and backwater from extending upstream	– Prioritise in storage reaches upstream of high-value infrastructure – Prioritise upstream of constrictions that limit sediment movement (and prevent excessive downstream erosion)

Sequencing over time	– Start early as may take years to decades for impacts to materialise in streams (i.e. as vegetation establishes)	– Trap sediment early if contaminates a management issue to limit the length of river exposed to contaminants – Allow morphology in storage reaches to adjust (e.g. widening) before planting vegetation, to avoid plant death due to burial – Develop recovery plan for storage reaches, shape recovery as tail of the pulse moves through storage reaches	– Trap sediment early if contaminates a management issue to limit the length of river impacted – Accelerate sediment once a management plan (for example trap and store, or extract) has been developed for downstream reaches	– Extract small volumes early and often, to spread the consequential bed erosion over time – Cease extraction as soon as bed levels begin a persistent decrease in elevation (which signals the tail of the pulse has arrived)

2.12 Conclusions

This review has investigated, using case studies, the options available for managers to manage pulses of sediment that move as bed material in rivers. There are now abundant studies into the sources and dynamics of sediment pulses. There are also abundant studies into the problems caused by these pulses, particularly around flooding, avulsions, and environmental effects. The rise of stream restoration has provided another good reason to accelerate recovery of streams from sediment pulses. Placing stream restoration projects in a catchment-wide context, with the help of geomorphologists, can increase their probability of success as they are less likely to be undermined by processes such as the passage of a sediment pulse.

What this review has demonstrated, however, is that there is not a correspondingly rich literature on what to do about sediment pulses. The many case studies, and the expanding theory of wave propagation (diffusion, translation, celerity) provide some basis for managers to decide the basic management question: should they do anything about a sediment pulse, and can they do anything about it? The case studies also demonstrate that managers should be aware that sediment pulses can cause secondary channel changes as they move downstream, including widening, avulsions, and tributary interactions.

If managers decide that something needs to be done about the sediment, they have four options: (1) reducing the sediment supply at source, (2) trapping sediment in the channel (3) accelerating sediment transport, and, (4) directly extracting sediment. The most common of these actions is undoubtedly to reduce the supply at source. This often happens naturally, and many types of human disturbance are characterised by a steeply declining sediment supply (gullying for example). Whilst there are examples of catchment management, and mining regulation, that have succeeded in reducing sediment supply to streams, there are far fewer studies of the consequences of that reduction for sediment pulses. The better documented examples relate to generally high sediment loads from catchments (such as the Drôme River in France, or the loess plateau in the catchment of the Yellow River in China), rather than to sediment pulses directly.

The other three management actions for sediment pulses (trapping, accelerating and extracting sediment) appear to be either rarely implemented, or rarely described. We suspect that the latter is probably the case. While the authors are aware of situations where sediment pulses have been managed, examples are difficult to find in the literature and we encourage practitioners to publish their experiences. There is great potential for managing sediment by stabilising benches and bars with vegetation, which can also have the effect of confining flow and narrowing and deepening the active channel. There should also be great potential for commercial extraction of sediment to accelerate recovery. If well managed, sale of the sediment could also fund the accelerated restoration of the channel. The literature also demonstrates that any action to control large sediment pulses will have secondary consequences that relate to tributary interactions, and to channel incision.

Finally, a framework that links management goals with management actions is presented. The framework can help managers identify the most appropriate management actions, and the sequencing of those actions through the catchment, based on their management goals.

Chapter 3: The Glenelg River catchment

3.1 Introduction

The environmental history of the Glenelg River catchment is typical of many SE Australian streams: a low-energy river profoundly and permanently altered by European settlement. This chapter summarises the impact of land clearing and grazing on the catchment and channel of the Glenelg River and its tributaries, and the management interventions that have taken place since. Specific reaches within the catchment are described in more detail in chapters that follow, so this chapter provides the large-scale context.

Many different interventions have been implemented in the Glenelg River and its tributaries. Recent large-scale remote sensing data sets and excellent records of interventions make the Glenelg River an excellent 'natural laboratory' in which to study how sand-bed rivers respond in-stream extraction in particular.

This chapter introduces the reader to the physical character of the catchment, and then briefly reviews the development of bedload pulses in the Glenelg River, and the history of interventions.

3.2 Values of the Glenelg River

Glenelg River is the longest river in western Victoria and boasts significant cultural, social and environmental values. The values of the Glenelg River shape the management actions undertaken by state, regional and local stakeholders who seek to preserve and enhance the ecosystem services provided by the Glenelg River and its tributaries.

3.2.1 Cultural values

Aboriginal people have lived alongside, drawn resources from and cared for the Glenelg River for at least 11,000 years (Glenelg Hopkins Catchment Management Authority, 2016). Evidence of Aboriginal land use in the Glenelg River catchment is widespread and includes scarred trees, stone arrangements, mounds, rock shelters, stone engraving sites, fish traps, burial places, stone house sites, quarries and axe-grinding places. (Glenelg Hopkins Catchment Management Authority, 2013). Indigenous knowledge is incorporated into management of the Glenelg River via the *Towards Cultural Flows* program, which modifies the timing of environmental flows to support environmental and Aboriginal values (Department of Land Water and Planning, 2019).

Arrival of European pastoralists in the Glenelg region in the mid-19th century profoundly changed the catchment (see section 3.3.6 for more detail). Early exploration and then permanent settlement mean several sites of historical significance are located in the catchment. Most sites significant to this period are homesteads on private farms and the initial establishment of towns located along the river, such as Coleraine, Casterton, Harrow, Dergholm, Chetwynd, and Balmoral.

3.2.2 Environmental values

The Glenelg River catchment is home to 173 of Australia's threatened species, including the red-tailed black cockatoo and the endemic Glenelg spiny freshwater crayfish, 94 federally listed species and 12 endangered Ecological Vegetation Communities (Glenelg Hopkins Catchment Management Authority, 2013). The catchment includes large swathes of two 'biodiversity hotspots' (in SE South Australia and SW Victoria) recognised by the Australian Government. Habitat supporting these species is provided by remnant stands of native vegetation in the catchment, abundant wetlands (especially upstream of Balmoral, and along the coastal plain to the south) the riparian zone and the bed of the Glenelg River and its tributaries.

The Glenelg River supports populations of river blackfish (*Gadopsis marmoratus*), platypus (*Ornithorhynchus anatinus*) the Glenelg spiny freshwater crayfish (*Euastacus bispinosus*) and short-finned eel (*Anguilla australis*). Several of the species can be found along much of the river's length, depending on flow season and water levels but the largest populations are concentrated in the lower 65 km of the river: the Glenelg River estuary. The estuary is intermittently closed to the ocean, is surrounded on both sides by native forest, and is protected from development by the Lower Glenelg National Park.

The natural beauty of the Glenelg River estuary, the habitat it provides and the recreational values it affords have led the lower Glenelg River to be designated a Heritage River reach – one of only eighteen such river reaches in Victoria.

3.2.3 Socio-economic values

The Glenelg River catchment is renowned for its visual amenity and provides a range of benefits to communities in the region. Recreation opportunities provided by the Glenelg River include swimming holes (for example at the townships of Harrow and Casterton), angling at a variety of sites, many of which are within stands of native vegetation (for example the Lower Glenelg National Park, Wilkin Reserve and Dergholm State Park), boating in the estuary reach and numerous streamside walking tracks. These recreational opportunities are an important way for communities to experience and connect with the Glenelg River.

The Glenelg River also provides economic benefits to the region: providing a water source for small towns, drinking water for dryland stock and enabling businesses associated with tourism and recreational activities (Glenelg Hopkins Catchment Management Authority, 2016). The combined economic activity enabled by the Glenelg River is estimated to contribute $34 million to the Victorian economy (Aither, 2015).

3.2.4 How sand threatens values in the Glenelg River

Pulses of coarse sand delivered to the Glenelg River by its tributaries travel downstream as bedload pulses. Several bedload pulses have aggraded large swathes of the Glenelg River and its tributaries and their continued movement undermines the environmental, social and cultural values of the Glenelg River catchment.

The migrating pulses bury large wood on the streambed, fills pools or scour holes that serve as habitat or swimming holes and smother vegetation establishing on the bed. In sections with deep but permeable sand deposits, low flows move downstream through the body of sand, rather than as surface flow, which disconnects the river during the dry summer months. By filling the channel with sand, bedload pulses reduce channel capacity, which increases the magnitude and frequency of flooding.

Bedload pulses are the major geomorphic control on in-stream habitat and recreational opportunities in the upper catchment. The degradation wrought by the pulses in the upper Glenelg River catchment has permanently transformed the morphology of the Glenelg River and its tributaries. Managers now intervene to shape the morphology developing as sediment supply decreases and as sand deposits are reworked. Interventions that are able to either prevent (or at least slow) pulses entering the highly valued estuary reach are especially useful. Having established the suite of values being managed in the Glenelg River catchment, I now turn to the physiographic aspects of the catchment in more detail.

3.3 Catchment setting

The Glenelg River has a catchment area of 12,660 km^2, falling from its highest point in the Grampian Mountain Range at 1000 m above sea level, to its outlet at the township of Nelson, just under 500 km downstream (Figure 3.1) (Victorian Environmental Water Holder, 2019). The study area for this thesis is the portion of the Glenelg River catchment enclosing the Dundas Tablelands, and the tributaries draining the tablelands and feeding sediment to the Glenelg River directly, or via its largest tributary, the Wannon River.

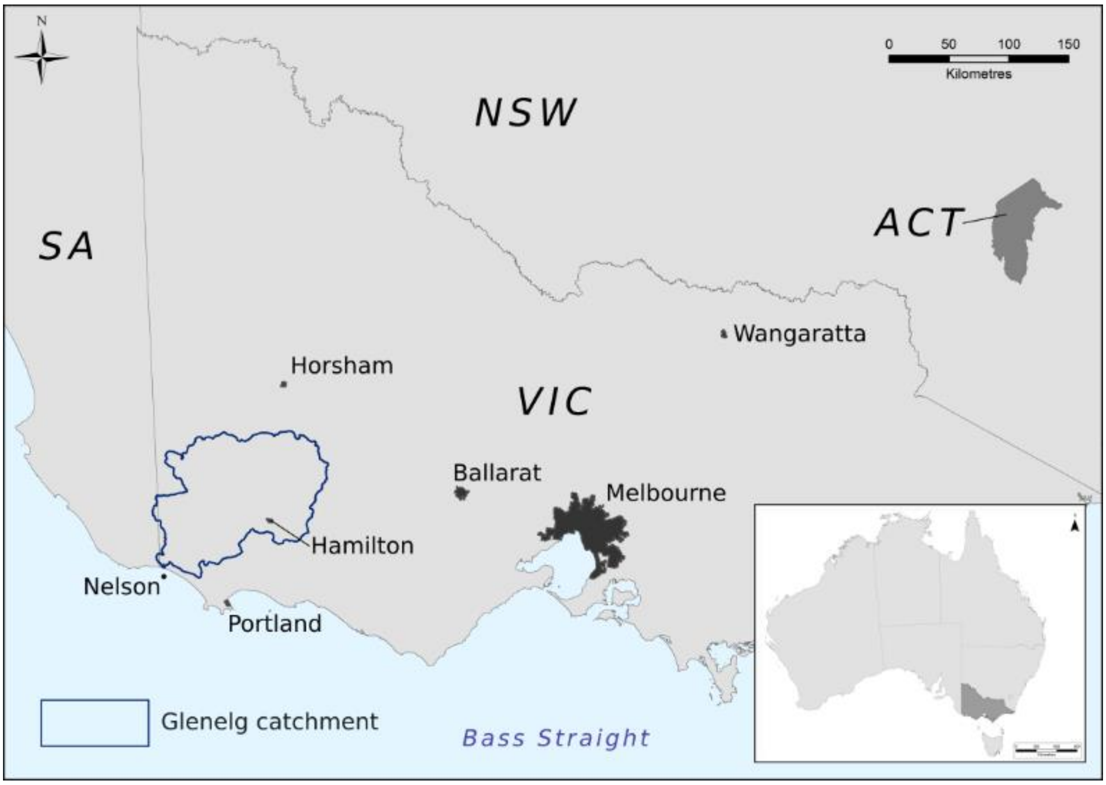


Figure 3.1: The location of the Glenelg catchment in western Victoria, Australia

3.3.1 Geological and topographic setting

The Glenelg River head waters lie in the Grampians Mountain Range, a sequence of steeply dipping sandstone beds that have resisted a long phase of erosion (Morand *et al.,* 2003). The Glenelg River then trends northwards before turning sharply to the south again as it meanders across a subdued plain of unconsolidated sand and gravel interspersed by a thick weathering crust (laterite) (Figure 3.2). The river then trends north west as it begins is journey around the Dundas Tablelands, a sandstone plateau capped in its southern section with a thick (up to 10 m) crust of laterite (an iron rich weathering profile) (Figure 3.2). As the river heads westwards along the northern margin of the Dundas Tablelands several tributaries, which have incised through the sandstone plateau to expose granites, schists and tillite, meet the left bank of the river. These tributaries have developed a radial drainage pattern across the Dundas Tablelands and are fed by a network of well-developed gullies (Figure 3.3).The Glenelg

River then turns south, cutting through sandstone bedrock to reveal basalt, schist and granites along the base of the narrow gorge (Morand *et al.,* 2003) (Figure 3.2).

As the river continues south the Dundas Tablelands give way to the more subdued Merino Tablelands: soft, eroded sandstones that replace the deeper, narrower gullies of the Dundas Tablelands with much wider valleys bound by rounded hills supporting remnant caps of laterite (Morand *et al.,* 2003) (Figure 3.3). The Wannon River drains this dissected landscape, and tributaries and hillslopes are prone to deep gullying and landslides (Soil Conservation Authority, 1981). Between the Wannon River junction and the mouth of the Glenelg River at Nelson, the river is more entrenched as it crosses the Kanawinka Escarpment and meanders across the South Victorian Coastal Plain relatively flat topography consisting of calcareous sands and swamp deposits (Agriculture Victoria, 2019) (Figure 3.1 and Figure 3.2Figure 3.3). The Glenelg River has cut into limestones in its lower 65 km, forming a deep, wide gorge. The lower 65 km of the Glenelg River is estuarine and has been designated a Heritage River Reach and site of international significance under the Ramsar Convention (Victorian Environmental Water Holder, 2019).

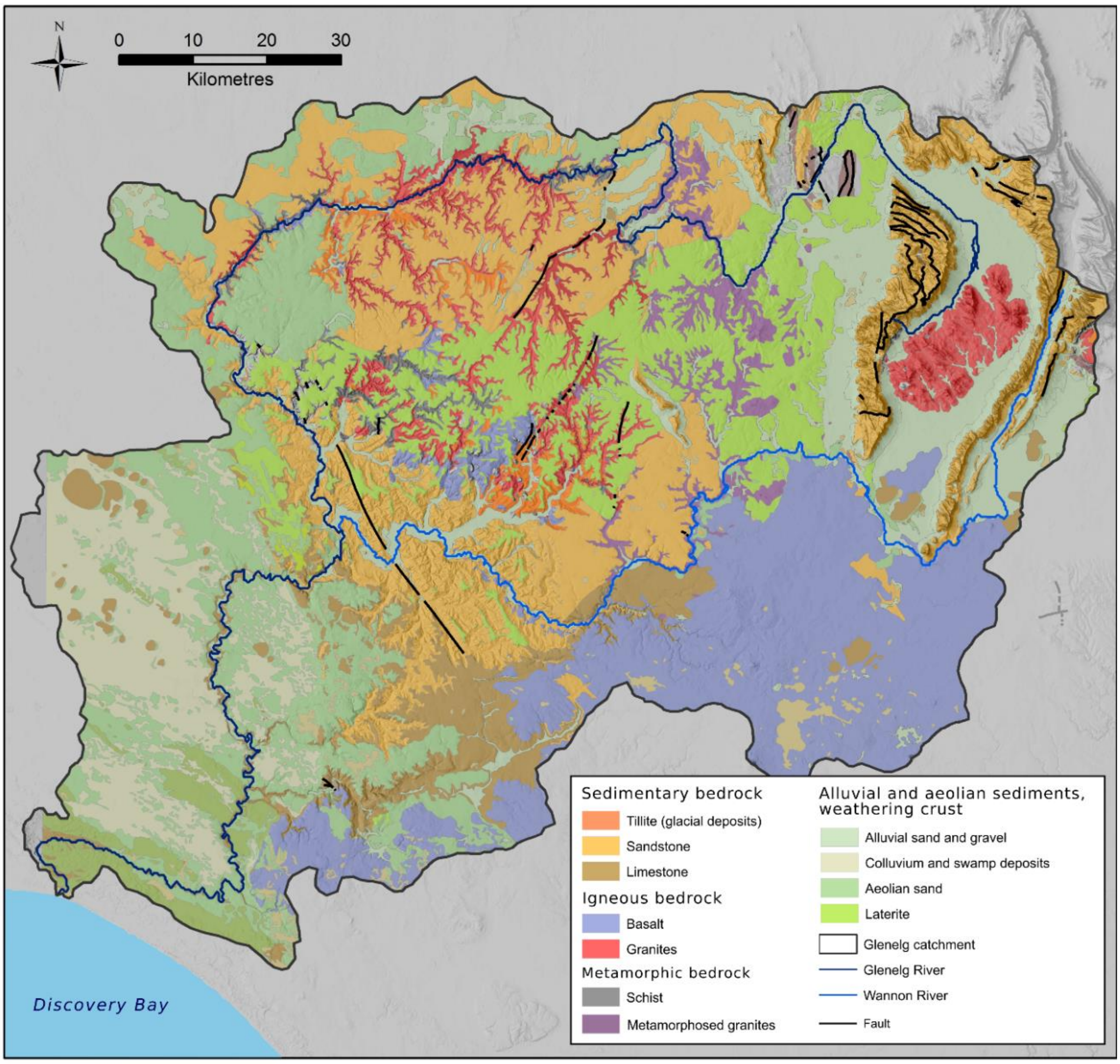


Figure 3.2: Geological map of the Glenelg catchment showing the distribution of bedrock. The Glenelg River and Wannon River are also shown.

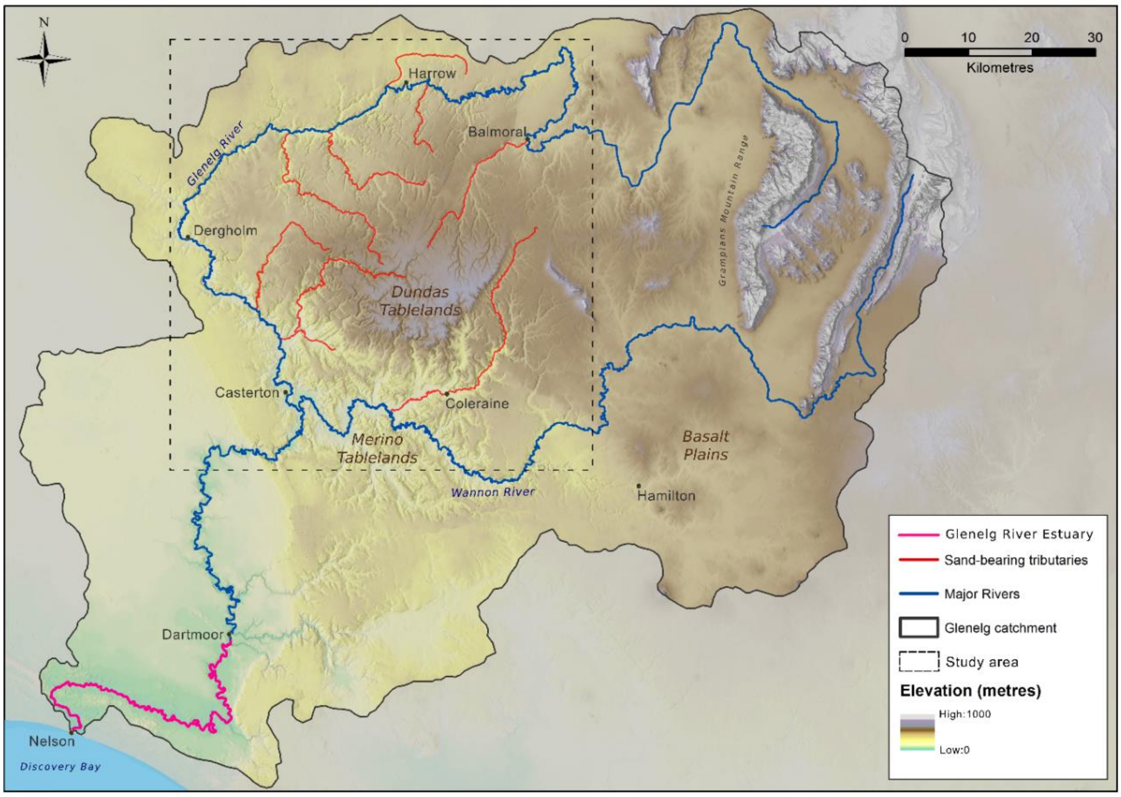


Figure 3.3: Topography of the Glenelg River catchment. The study area is centred on the Dundas Tablelands and the sand-bearing streams that connect this plateau with the Glenelg River.

3.3.2 Study area

The study area for this thesis is the portion of the Glenelg River that encompasses the Dundas Tablelands and the northern segment of the Merino Tablelands (Figure 3.3). The upstream end of the study reach is Mather Creek junction, while the downstream extent is approximately 30 river km downstream from Casterton, where the Glenelg River emerges onto the coastal plain (Figure 3.4). The Glenelg River in this area is fed by six major tributaries that drain the Dundas Tablelands: Mather Creek, Schofield Creek, Pigeon Ponds Creek, Chetwynd River, Steep Bank Rivulet and the Wando River. The Wannon River meets the Glenelg River downstream of Casterton and is connected to the Dundas Tablelands by Bryan Creek, a large tributary (Figure 3.4). Tributary catchments supplying water and sediment to the Glenelg River vary in catchment area and drainage density (Table 3.1), but all are fed by a network of incised gullies.

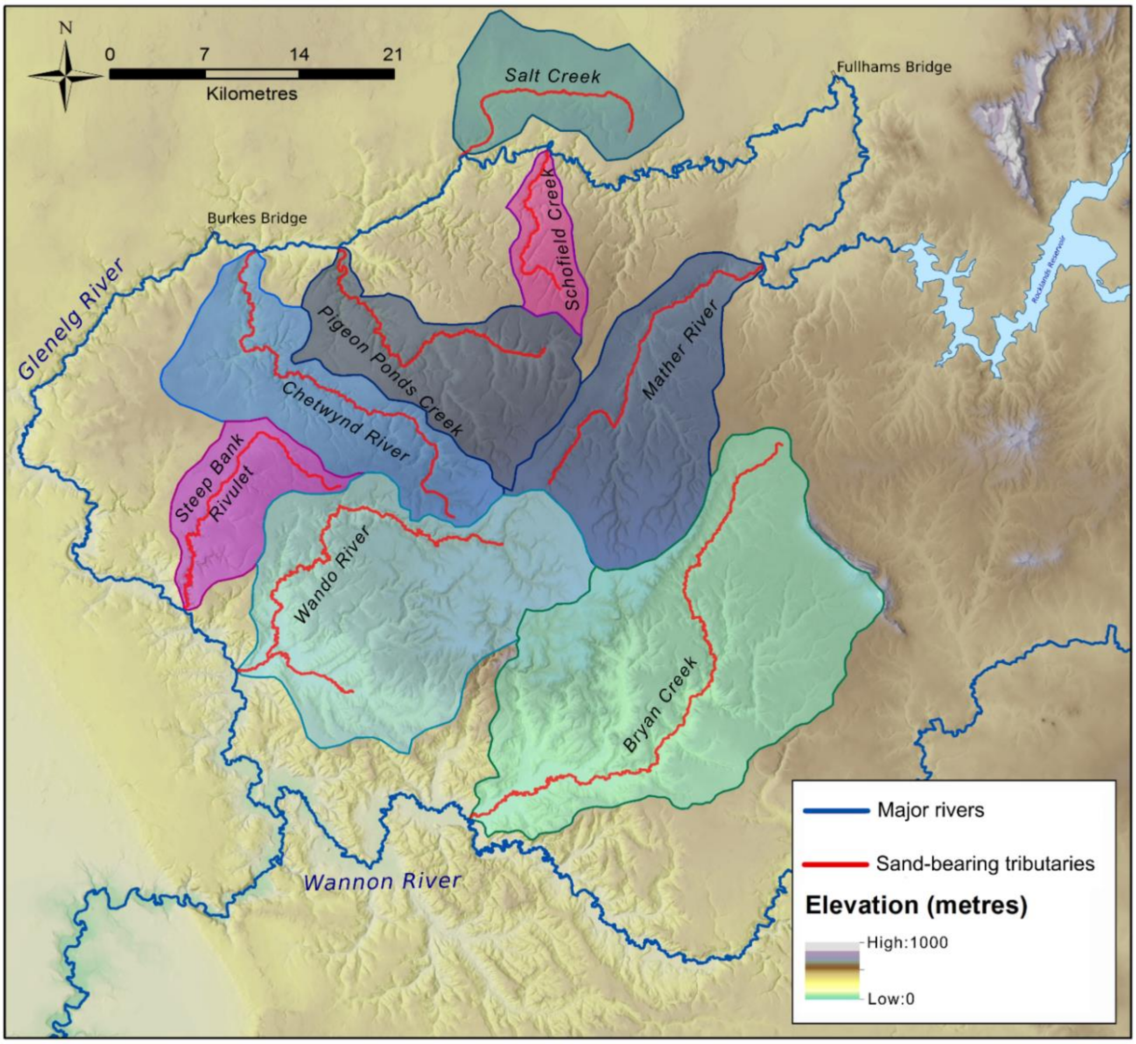


Figure 3.4: The study area for this thesis shown in Figure 3.3 with each of the eight major sand-bearing tributaries and their respective catchment areas shown.

Table 3.1: Catchment statistics for the major sand-bearing tributaries that feed the study area of the Glenelg River. Stream length was calculated using vectorized streamlines form the Bureau of Meteorology Geofabric (v2.2).

Tributary	Catchment area (km^2)	Length of drainage lines >2nd order (km)	Drainage density (km/km^2)
Mather Creek	226	176	0.78
Schofield Creek	49	47	0.96
Salt Creek	125	66	0.52
Pigeon Ponds Creek	181	145	0.80
Chetwynd River	195	146	0.75
Steep Bank Rivulet	95	70	0.74
Wando River	373	298	0.80
Bryan Creek	512	341	0.67

3.3.3 Climate

Average annual rainfall in the study catchment ranges between 500 and 700 mm (Figure 3.5). The study area falls within zone *Cfb* of the revised Köppen climate classification of Peel *et al.* (2007): temperate without a pronounced dry season and with warm summers.

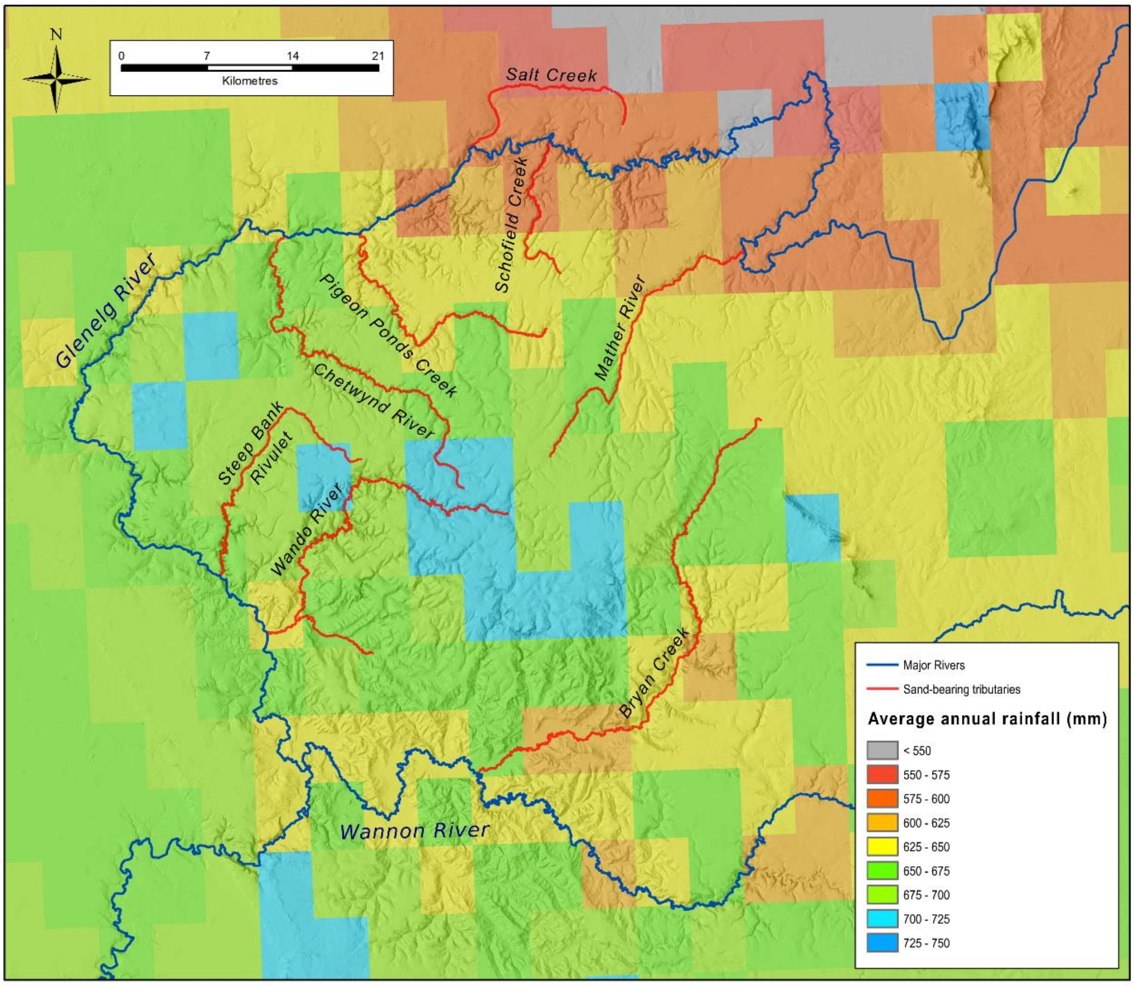


Figure 3.5: Average annual rainfall in the study area between 1960 and 1990. Data sourced from Bureau of Meteorology.

Most rain falls during the wetter 'winter' season (May to September) and the summers are relatively dry. Average maximum temperatures vary between 23°C and 28°C across the catchment and occur in February, while average minimum temperatures vary between 3°C and 6°C and occur in July. The combination of dry summers and flow regulation means the Glenelg River regularly ceases to flow in January and February each year.

3.3.4 Hydrology

Discharge of the Glenelg River and its tributaries tracks the annual pattern of rainfall: a wet winter season (May to September) and a dry summer low-flow season (October to April). Flows in the Glenelg River are regulated by two reservoirs that divert water northwards into the Wimmera water supply scheme: Moora Moora Reservoir in the headwaters of the Glenelg River in the Grampians Mountain Range (competed 1933), and the much larger Rocklands Reservoir, located 15 km east of Balmoral (completed in 1953) (Figure 3.4) (Glenelg Hopkins Catchment Management Authority, 2016). Environmental flows are released into the Glenelg River from Rocklands Reservoir.

The section of the Glenelg River upstream of Mather Creek usually ceases to flow at the peak of the summer season (February). South of the Mather Creek junction inputs from tributaries draining the Dundas Tablelands can preserve baseflow in the Glenelg River and limit the duration of the low-flow period in summer months. Several tributaries (such as Bryan Creek, Pigeon Ponds Creek and Mather Creek) are dry for most of the summer. Bankfull discharge for the Glenelg River averages 70 $m^3 s^{-1}$ (6000 ML/day).

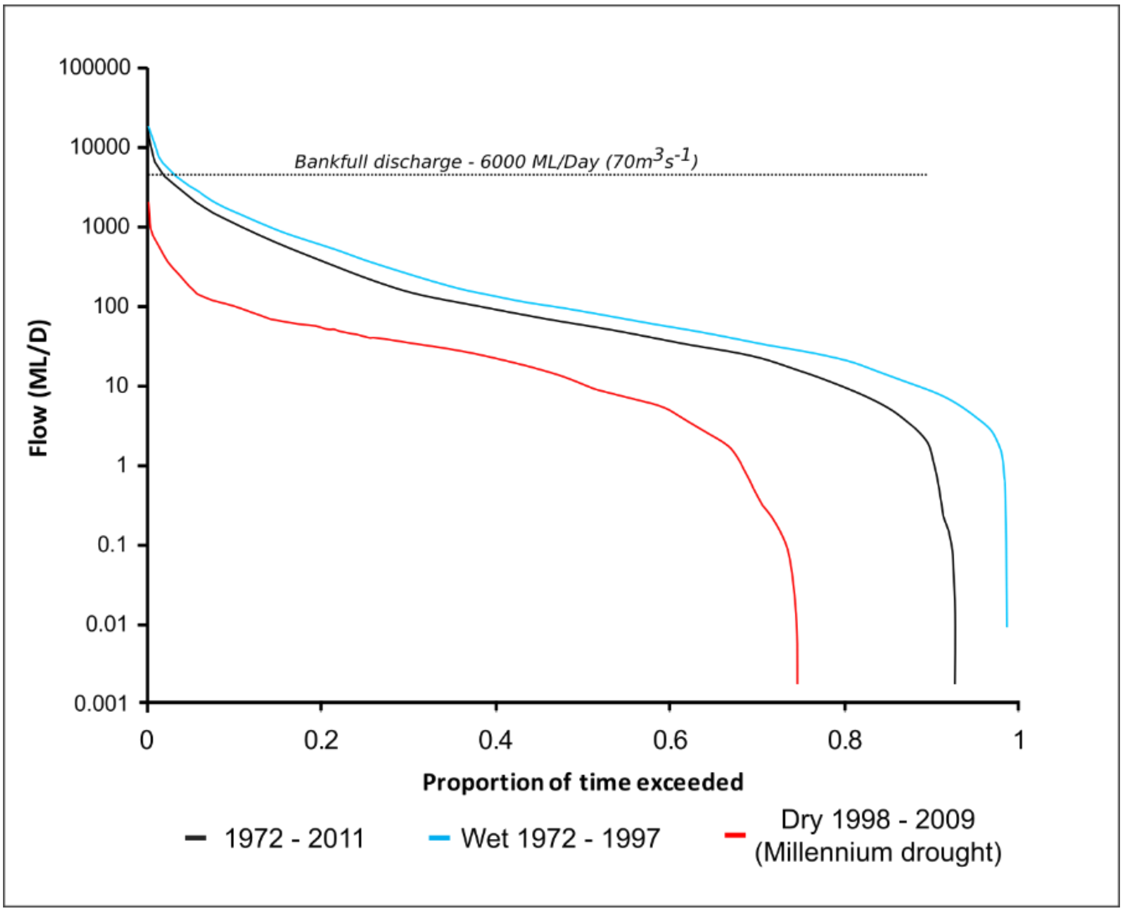


Figure 3.6: Flow duration curve for the Glenelg River at Dergholm (gauge number 238211) with the distribution of flows between 1972 and 2011 (black), the distribution of flows during a prolonged wet period (light blue) and the distribution of flows during the Millennium drought, between 1998 and 2009. Bankfull discharge is also annotated. The flow data is for the period after the Rockland reservoir was constructed (1953). The reservoir has reduced flow and to some extent sediment supply to the upper Glenelg River Figure adapted from Alluvium (2013).

3.3.4.1 Flood history

The Glenelg River catchment has been impacted by large floods several times since European settlements. Floods were recorded as soon as permanent settlements were established, including significant events in 1893, 1906 and 1909. The 1906 flood is thought to be the largest flood since European settlement, but no flow records exist for the time (Flood Victoria, 2018). The most geomorphically significant flood, and the largest on record, occurred in 1946. The 1946 flood (ARI 100 years) caused significant sediment movement in the Glenelg River and its tributaries, destroyed several bridges along the Glenelg River and registered a height of 6.45 metres on the Casterton gauge (Cardno Victoria, 2011).

Flooding continued to impact the river system after the Rocklands Reservoir was completed with events in 1975 (peak flow 221 m^3s^{-1} at Casterton), 1983 (peak flow 250 m^3s-1 at Casterton), 2011 (120 m^3 s^{-1} at Dergholm) and 2016 (6.1 metres depth at Casterton) (Water Technology, 2014; Laskie and Lillebuen, 2016). Floods generate widespread bank erosion in tributaries of the Glenelg River, landsliding in the catchment (although landsliding material is usually not connected to drainage lines) and sand movement in the bed of the Glenelg River (GHCMA, pers coms.).

3.3.5 Pre-European morphology of the Glenelg River

Between Rocklands Reservoir and Fullhams Bridge (Figure 3.4) the Glenelg River is anastomosing: a network of channel split and then re-connect downstream, generating vegetated floodplains between the network of narrow channels (Figure 3.7). Anastomosing rivers are a subset of the anabranching rivers and are found in low-energy, fine grained and organic-rich systems (Nanson and Knighton, 1996). This channel form has remained relatively unchanged since European settlement. Major Mitchell's 1836 expedition, which did not venture as far as Fullhams Bridge, documented the 'sudden' splitting of the Glenelg River into a series of smaller channels with thick vegetation on the banks (Rutherfurd and Budahazy, 1996). Major Mitchell's description suggests there were anastomosing reaches downstream of Fullhams Bridge prior to European settlement, but the exact location is unknown.

Downstream of Fullhams Bridge the Glenelg River is meandering. In some sections, especially on wider floodplains reaches, abandoned anabranches are present (Figure 3.7). Whether these now-abandoned anabranches were formed before European arrival is unknown and it is possible their current distribution may be related to the passage of bedload pulses (see below).

The most drastic changes in morphology in the Glenelg catchment have occurred in the tributaries of the Glenelg River which were originally chain-of-ponds type – deep pools connected by a narrow channel with densely vegetated banks (Eyles, 1977a; Erskine, 1994). Erskine (1994) found numerous mentions of chain-of-ponds morphology in historical parish surveys and early maps of the Glenelg catchment.

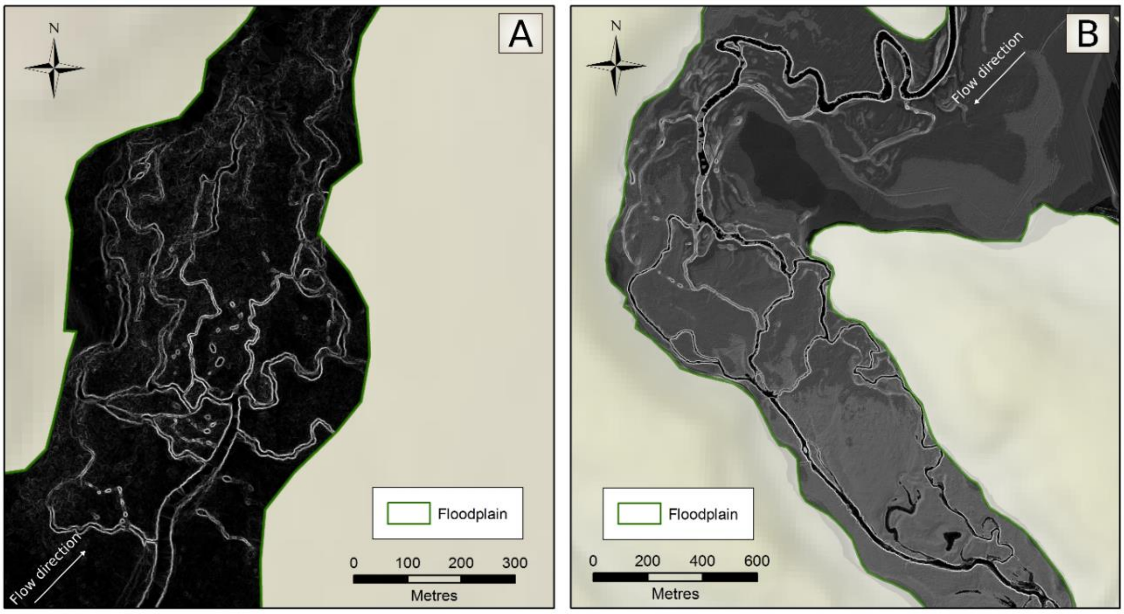


Figure 3.7: (A) A LiDAR image illustrating the anastomosing channel pattern of the Glenelg River between Rocklands Reservoir and Fullhams Bridge and, (B) a LiDAR image showing the anabranching pattern typical of sections of the Glenelg River within wide floodplains downstream of Burkes Bridge. Note the difference in scale between the two images.

3.3.6 Catchment clearing

Prior to European settlement the Dundas and Merino Tablelands and the valley that drained them, were covered in several different species of spear-grass (a native perennial grass), savannah woodland and a eucalyptus understory (Figure 3.8A) (Soil Conservation Authority, 1981). Catchment clearing began in earnest in the mid-19th century and included floodplains and the riparian zone of the Glenelg River and its tributaries. Cereal cropping was introduced to many of the steep slopes in the area, drainage lines were excavated along these hillslopes, swampy areas were drained and roads and cattle tracks were constructed along many of the chain-of-ponds tributaries feeding the Glenelg River (Soil Conservation Authority, 1981; Erskine, 1994; Rutherfurd, 2001). At the same time vegetation was being cleared from the catchment, rabbits were introduced and quickly became widespread. Except for selected stands of native forest, approximately two thirds of the Glenelg catchment had been cleared and converted to agriculture by the early twentieth century (see Figure 3.8B for the contemporary vegetation cover) (Glenelg Hopkins Catchment Management Authority, 2016).

Forestry blocks were established on sections of the tablelands in the early 1990s, predominantly of blue gum (*Eucalyptus globulus*), but these stands are small relative to the agriculture grasslands that now dominate the catchment (Australian Bluegum Plantations, 2019).

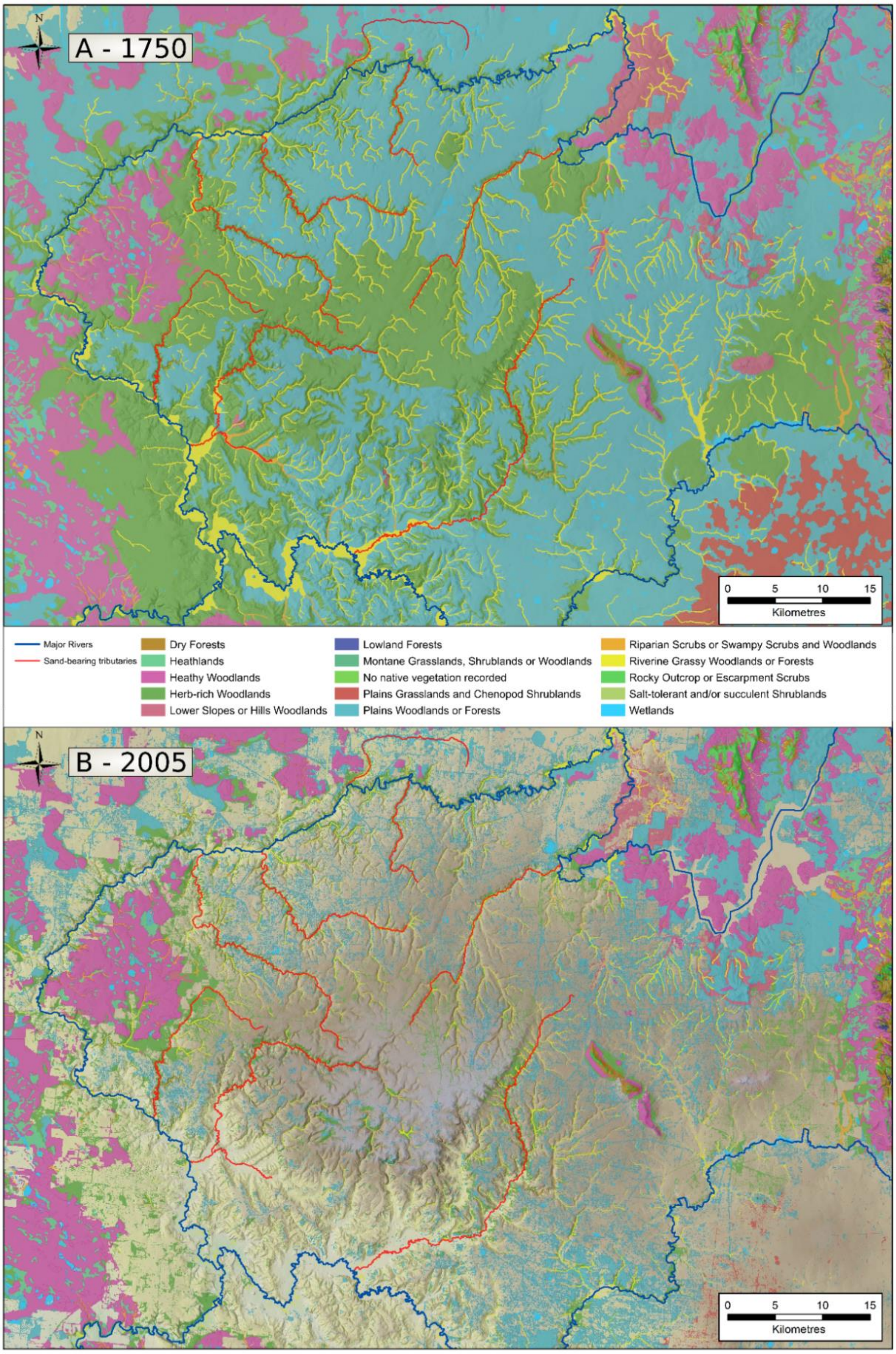


Figure 3.8: (A) Pre-European (1750) modelled vegetation type and distribution in the Glenelg catchment and (B) post-European (2005) modelled vegetation type and distribution in the Glenelg catchment. The drastic reduction in vegetation cover was driven by conversion to agriculture. Conversion to agriculture also included ploughing of new drainage lines and draining of swamps. Data supplied by Department of

Environment, Land, Water & Planning, Victorian State Government. Original mapping by Department of Agriculture, Water and Environment, Australian Government (2001)

3.3.7 Catchment erosion

The soils that mantle much the Glenelg catchment are highly erodible and readily dispersed by groundwater (Sinclair Knight Merz, 2005). When the stresses of vegetation clearing, ploughing of drainage lines (on steep slopes and valley floors) and the introduction of rabbits and cattle were superimposed the result was severe and widespread erosion. Erosion was predominantly in the form of gully incision, head migration and widening, but landslides were also common (Blackburn and Leslie, 1949; Soil Conservation Authority, 1981; Erskine, 1994). By 1853, gullying and landsliding was severe across swathes of the Glenelg catchment (Figure 3.9A).

Disturbance of the valley floors and removal of riparian vegetation exacerbated incision in many of the Glenelg River tributaries, destroying the chain-of-ponds that slowly fed sediment to the Glenelg River. Chain-of-ponds were first converted to valley-floor incised streams and then filled with sand (Figure 3.9C) (Eyles, 1977a). There is little evidence that the bed and banks of the Glenelg River underwent significant erosion during this first period of adjustment (Erskine, 1994; Rutherfurd and Budahazy, 1996).

Gullying, landslides (when connected to drainage lines) and incision of tributaries created both the source material and storage space for the bedload pulses that quickly formed in tributaries of the Glenelg River. I now turn to the impacts of bedload pulses and the management interventions that followed.

3.3.7.1 Bedload pulse impacts

The drastic increase in sediment supply caused by erosion fuelled bedload pulse development in the tributaries draining the Dundas Tablelands. These tributaries then injected the migrating pulses into the Glenelg River at tributary junctions spaced along the river's length (Figure 3.4). The simultaneous injection of multiple bedload pulses caused several metres of aggradation along much of the bed of the Glenelg River. The aggradation generated wide, flat, featureless sheets of sand in place of the more variable streambeds present before bedload pulses formed (Bartley and Rutherfurd, 2005b). The lower reaches of tributaries were also quickly filled with sand (Figure 3.9B).

By the mid-twentieth century erosion had peaked in the catchment and drainage lines had largely adjusted to the change in land use (Soil Conservation Authority, 1981; Erskine, 1994). A large flood in 1946 caused widespread damage and mobilised significant volumes of sand, spreading the sediment throughout the catchment.

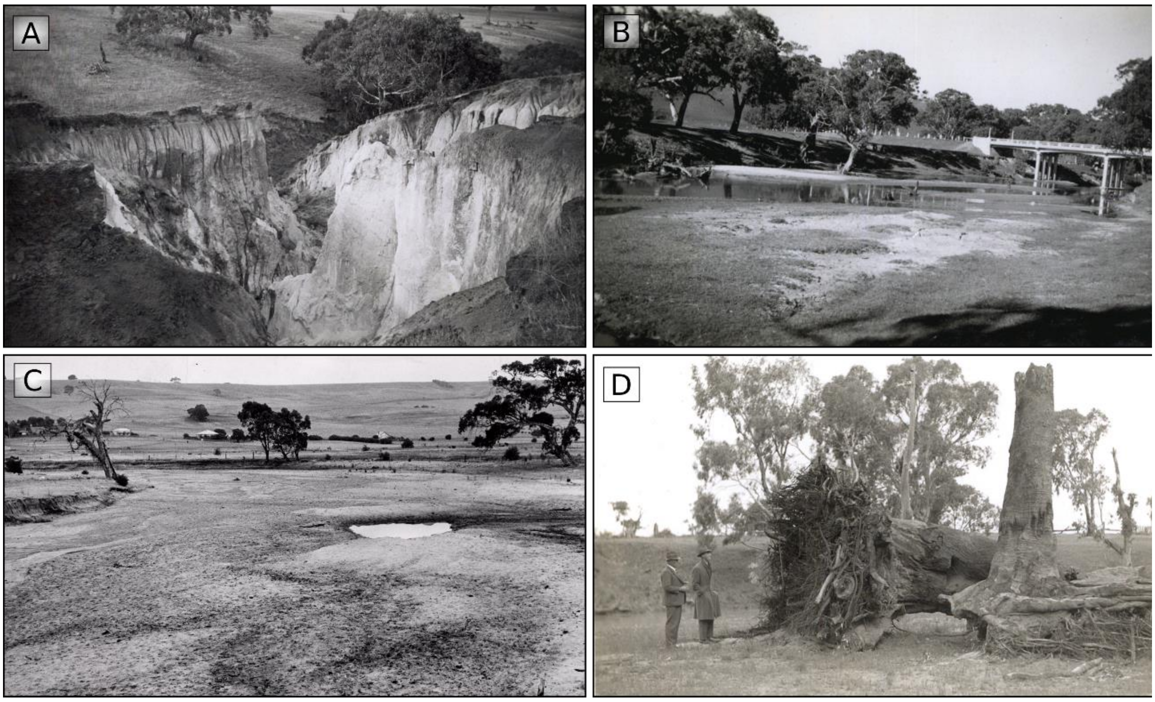


Figure 3.9: (A) Deep gullying in the Dundas Tablelands in the early 1940s, (B) A flat featureless sheet of sand in the bed of the Glenelg River adjacent Casterton in 1947, (C) the bed of Bryan Creek in 1947 after the chain-of-ponds was incised, widened and then filled with a bedload pulse, (D) an example of the size of large tree stumps removed from the Glenelg River during 'de-snagging' programs in the 1960s and 1970s. Photos courtesy of the Casterton Historical Society and the Glenelg Hopkins Catchment Management Authority.

3.4 Historic interventions in the Glenelg River catchment

When the Rocklands Reservoir was closed in 1953 the frequency of flood events capable of reworking the catchment-scale distribution of sand dropped significantly. This reduction in large flows essentially locked the distribution of sand that was generated by the 1946 flood in place.

3.4.1 Large wood removal 1960-1990

The near complete removal of in-stream wood from some sections of the Glenelg River during the 1960s and 1970s (particularly around Casterton) was motivated by the belief that wood removal ('de-snagging') would increase flow conveyance and reduce flooding (Rutherfurd and Budahazy, 1996) (Figure 3.9D). However, it is more likely that de-snagging accelerated sand movement by reducing bed roughness, and the mobile sand-chutes that now occupied the bed greatly reduced geomorphic complexity.

3.4.2 Erosion control structures 1961-1981

Interventions undertaken by the Soil Conservation Authority constituted the largest erosion control program undertaken in the state of Victoria at the time. The collection of interventions undertaken by the soil Conservation Authority coincided with the de-snagging program, which saw widespread erosion control measures in gullies of the Dundas Tablelands (Figure 3.10). Grade control structures, gully head revetment, bank stabilisation and flow chutes were installed to check erosion (Figure 3.11). At the same time improved pasture management reduced runoff intensity. These measures were motivated by a desire to protect valuable pastoral land, not to reduce sand inputs to the Glenelg River *per se*. At the same time that the source of sediment was being treated, in-stream structures were constructed to stabilise the bed and banks of several tributaries, especially Bryan Creek, the Wando River and the Wando Vale Ponds (Figure 3.10).

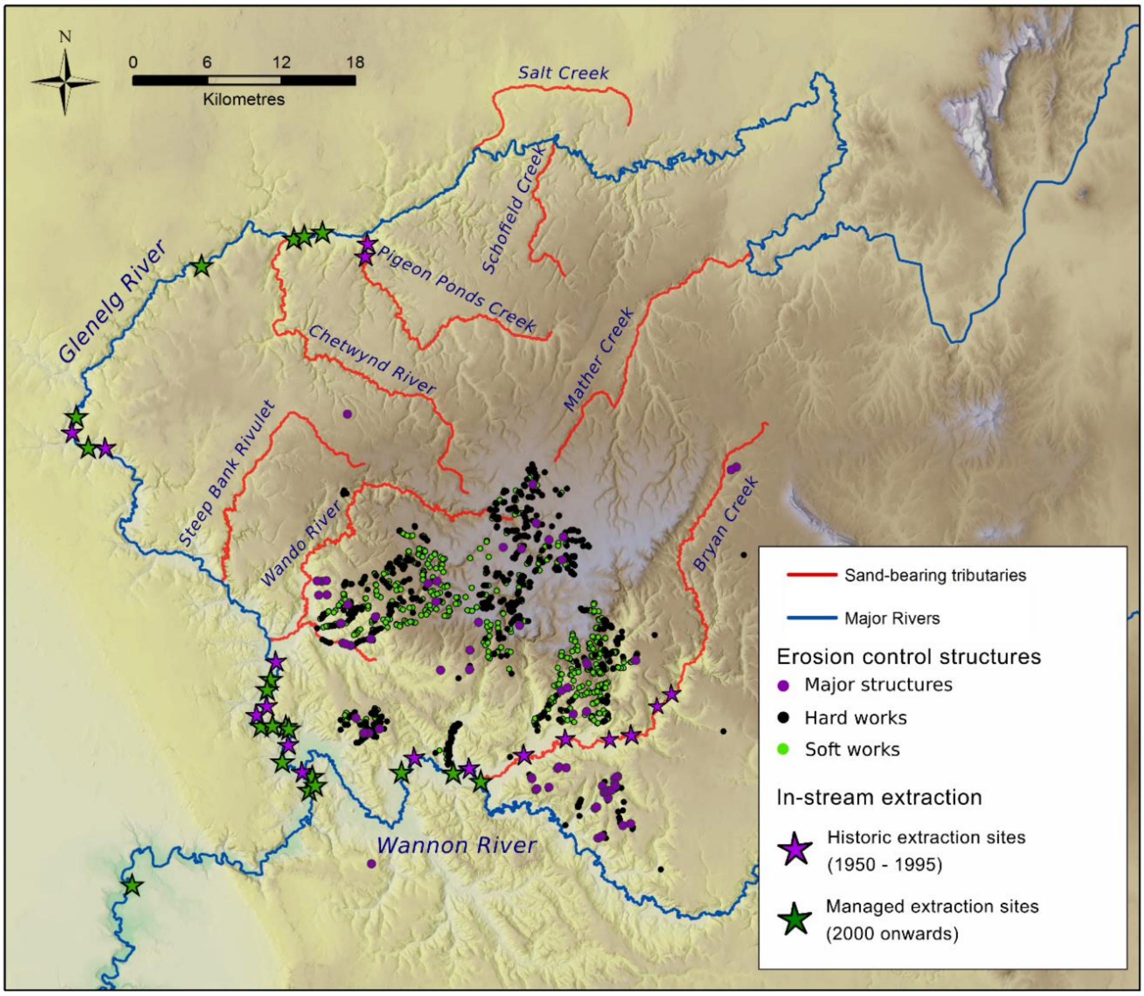


Figure 3.10: The location of historic management intervention in the Glenelg catchment, showing the extensive erosion control measures undertaken in gullies of the Dundas Tablelands and the distribution of commercial extraction sites.

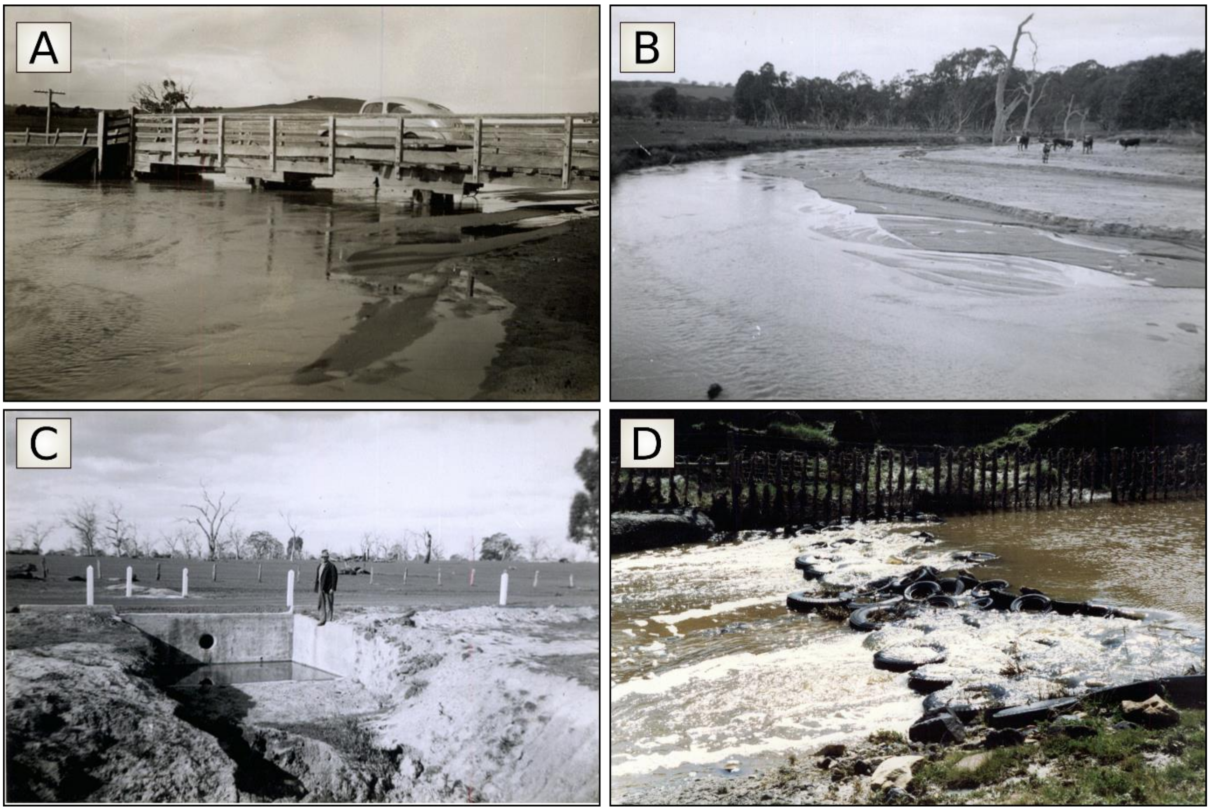


Figure 3.11: (A) The lower reaches of Wando Vale Ponds circa 1953, (B) the lower reaches of the Chetwynd River in 1945, (C) an erosion control structure preventing gully head migration in the Dundas Tablelands in 1945, (D) a tyre trap grade control structure in the bed of Robson Creek, a tributary of Bryan Creek, in 1988. Photos Courtesy of the Coleraine Historical Society and the Glenelg Hopkins Catchment Management Authority

3.4.3 In-stream sand extraction 1951 to present

The interventions outlined above were motivated by the desire to reduce flooding, protect productive land and later, to reduce sedimentation in the Glenelg River. The Glenelg River and its tributaries have also been subject to an extensive, decades-long sand extraction program. This program was driven by commercial imperatives: the coarse, well-sorted sand was the only readily available source of high-quality quartz sand in the west of Victoria and was sold as aggregate for concrete production or as an input to road materials. Between 1950 and 1990, an absolute minimum of 470,000 m^3 of sand was removed from the rivers in the catchment, 88 % of this from the bed of one tributary alone: Bryan Creek (Figure 3.12A) (Rutherfurd and Budahazy, 1996). The total volume actually removed was likely much larger, since extraction volumes are usually under-reported.

Significant sand extraction ceased in most of the Glenelg River catchment (and the state of Victoria more broadly) in the mid-1990s due to fears over-extraction was causing excessive bed and bank erosion in Bryan Creek. However, studies between the mid-1990s and early 2000s identified the potential for the careful use of commercial extraction as a tool to manage sand pulses in the Glenelg River (Erskine, 1994; Rutherfurd and Budahazy, 1996; Brizga *et al*., 2000a; Brizga *et al*., 2003). Using commercial extraction to manage sand in the Glenelg River was attractive for three reasons:

1. Extraction could be undertaken in an environmentally sensitive manner that accelerated recovery by removing sand and at the same time, minimising activities that destabilise the river (such as over-extraction, or certain extraction techniques) (Figure 3.12B).
2. Commercial extraction would be funded by the extractors. This would deliver environmental and commercial benefits without the need for additional funding.
3. There were several easily accessible sites within the Glenelg River that had significant sand stores.

This thesis is most concerned with this later program of managed commercial extraction.

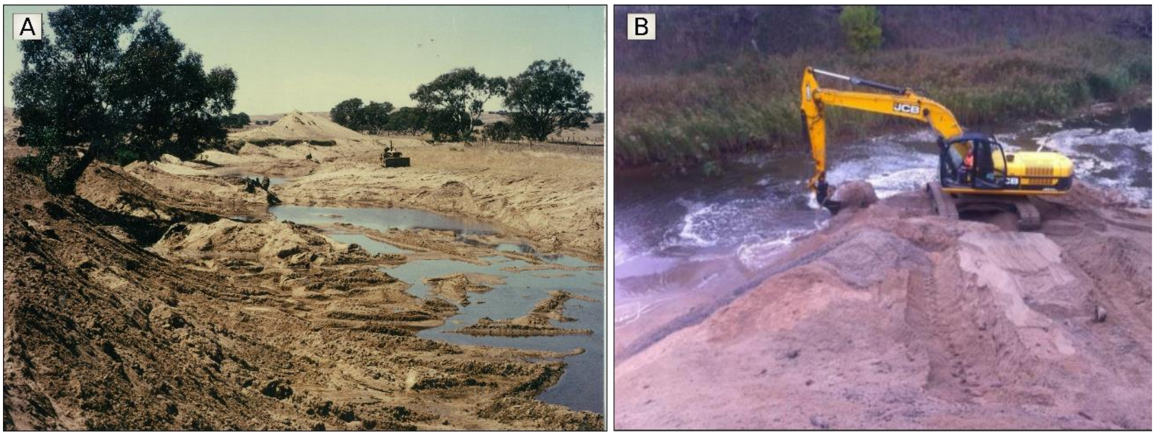


Figure 3.12: Typical examples of in-stream sand extraction techniques used in the Glenelg River in (A) Bryan Creek in 1988 using bulldozers and dump trucks to create a widely disturbed area and (B) managed extraction from the Glenelg River in 2015 where a bucket excavator is used to excavate a discrete hole that is intended to minimise disturbance of the bed and banks surrounding the pit. Photos courtesy of the Glenelg Hopkins Catchment Management Authority (A) and Vickery Bros (B).

3.4.4 Stock exclusion and re-vegetation 1998 to present

Since 1998 interventions aimed at improving the condition of the Glenelg River and its tributaries (other than managed in-stream extraction) have been organised by sub-catchments, a processed termed 'waterway action planning' (WAP). Interventions are undertaken in conjunction with local landholders and Landcare groups and consist of one or a combination of four types of activity: excluding stock from waterways with fencing, revegetating gullies and adjacent slopes to reduce erosion, spraying of invasive weeds and pest eradication (the focus is rabbits) (Figure 3.13).

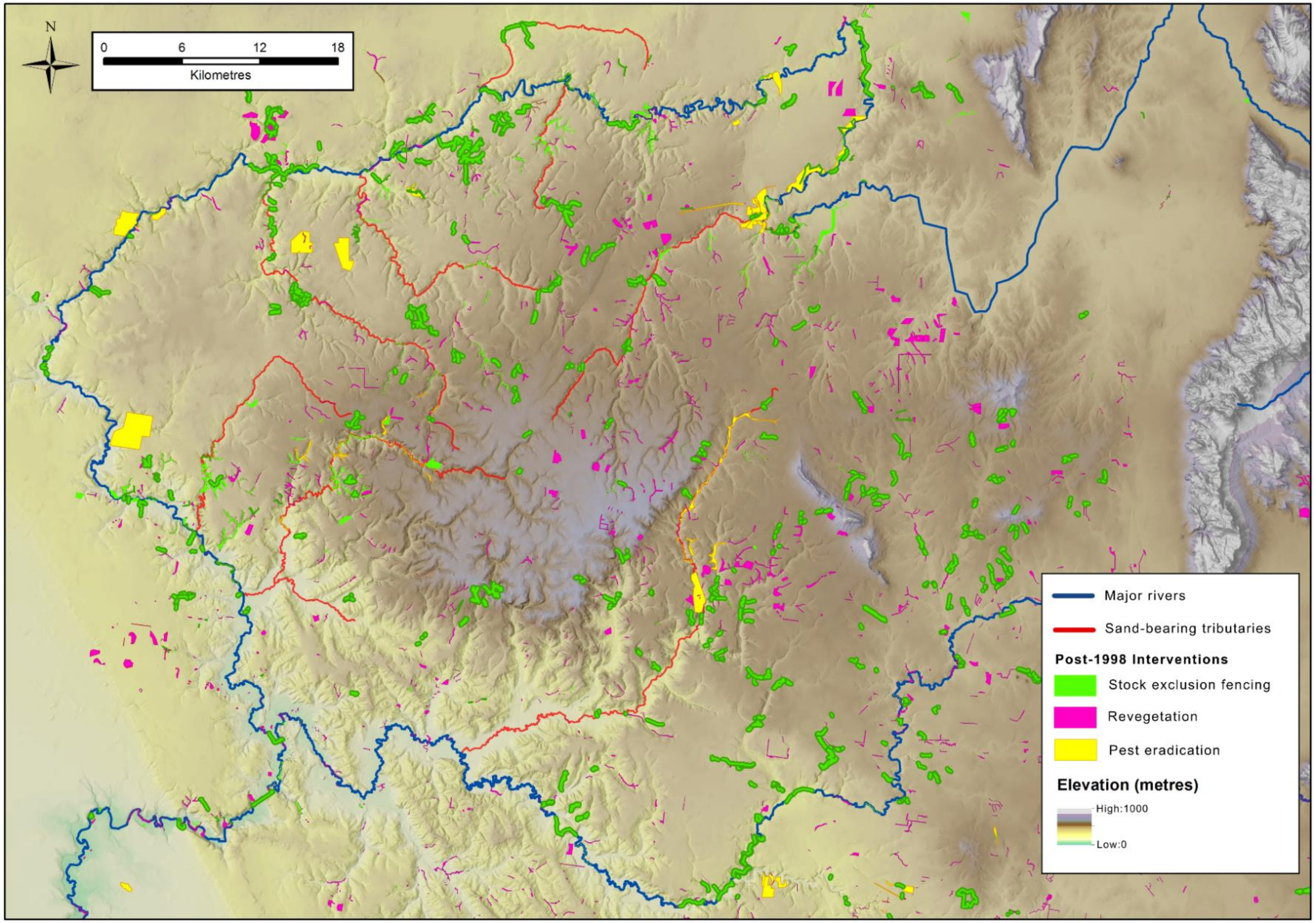


Figure 3.13: The extent and distribution of stock exclusion fencing, revegetation and pest eradication undertaken in the Glenelg catchment since 1998. Data courtesy of the Glenelg Hopkins Catchment Management Authority.

3.5 Summary

In many respects the Glenelg River is the archetype of post-European river change in SE Australia. The changes wrought by European settlement and conversion to agriculture have caused widespread erosion and led to the formation for several bedload pulses across the catchment. Managing these bedload pulses is of interest not only in SE Australia, but in sand-bed rivers more broadly. The history of channel changes and interventions are well documented, which makes the Glenelg River an excellent place to study the management of bedload pulses. A summary of the timeline of changes to the Glenelg River and its catchment is provided in Table 3.2.

Table 3.2: Chronology of changes to the Glenelg catchment following European settlement. Table adapted from SKM (2005).

Date	Event	Significance
Pre-1800s	Indigenous land management	Stable morphology
Mid 1800s	First settlement, with establishment and expansion of initial catchment disturbance (clearing) and sheep farming	Initial catchment clearing and introduction of stock
1853	First recorded references to "springs of salt water" in Wannon country	Increasing rates of sediment delivery to the channel network from gully erosion, sheet erosion, land slips and failing river banks
1862-1910	Increased settlement below the Dundas Tablelands: rabbits introduced, cultivation on steep hills, disturbance of drainage lines for roads	Accelerated rates of gullying, incision of chain-of-ponds creeks in tributaries of the Glenelg River
1930-1934	Water diverted from swampy headlands of the Glenelg River, Moora Moora Reservoir constructed	Commencement of flow regulation, decreased sediment movement in upstream, anastomosing section of the Glenelg River
1930s/1940s	Major in-stream deposition chocked the lower of Mather Creek, Pigeon Ponds Creek, Chetwynd River and tributaries to the Wannon River The bed of the Glenelg, as well as its floodplain, partially infilled	Sustained sediment delivery to the channel network, deposition in lower reaches of tributaries and throughout the Glenelg River
1946	Major flood	Major sand deposits enter streams, contemporary distribution of sand established by downstream movement of the merging bedload pulses
1950s	The Wando River and Bryan Creek begin to incise their beds in the former depositional zone	Indicates a reduction in the supply of sediment Suggesting that sediment delivery from gullies has peaked in the southern margin of the Dundas Tablelands

1953	Closing of the Rocklands Reservoir	Major flow regulation. Distribution of sediment generated by the 1946 flood is largely locked into place
1956	Sand extraction begins in Bryan Creek	Bed, bank and tributary erosion begin in Bryan Creek
1960-1990s	Glenelg River Improvement Trust established 1960: bank and bed erosion protection works, de-snagging of the Glenelg and Lower Wannon.	Slowed supply of sediment to tributaries of the Glenelg River, increased flow velocities in reaches where wood has been removed.
1960s-1970s	Pasture improvement	Slowed supply of sediment to gullies in the catchment, reduced rates of gully head migration in sensitive areas
1971	Flow extracted from the upper reaches of the Wannon River	Relatively minor flow regulation. The impacts of flow regulation on movement of bedload pulses in the Wannon River are unknown
1977	Standing Consultative Committee on river: increased flow velocities, improvement sought and obtained a grant for the clearing of along a 9 km reach of the Wannon River: 30 % of the obstructions were removed and/or relocated	Increased flow velocities and sand movement
1980s-2000s	Sand extraction from Bryan Creek, the Glenelg River (above and below Casterton), Wannon River (between Bryan Creek junction and Glenelg River junction) and Pigeon Ponds Creek	Extraction rates in Pigeon Ponds Creek and Wannon River are low and have resulted in little geomorphic change. Extraction rates in Bryan Creek were significant and generated erosion of the bed and banks. Extraction from the Glenelg River was slightly less, and imitated a trend of decreasing bed elevations, and channel contraction, around Casterton
1990/2000s	Millennium drought	Decreased flows and sediment movement in the Glenelg River and tributaries. Decrease in soil erosion rates
1990s/2000s	Spiny rush establish on streambeds where stock have continuous access. *Phragmites* and *typha* establish on sections of streambed where stock have been excluded	Increasing volume of sand locked into storage on the streambed where *phragmites* has established.

Chapter 4: A model for bedload pulse dynamics in the Glenelg River

4.1 Introduction

The second chapter in this thesis ('Management responses to pulses of bedload sediment in rivers') identified the need for a model of bedload pulse dynamics that predicts how bedload pulses migrate through a catchment. Models of bedload pulse dynamics predict how sediment is distributed and can then be used to guide interventions. The review also presented a way of aligning management aims with management actions by dividing bedload pulses into three zones: the leading edge, the peak and the trailing edge. These zones correspond to increasing deposition, maximum deposition and channel change, and decreasing sediment supply, respectively. These zones provide a neat and useful model to guide management, but in practice, identifying these zones over an entire catchment is not straightforward. To identify where the different zones of a bedload pulse are within a stream network, and to predict how the distribution of these zones will change, managers need a model that predicts how bedload pulses migrate through a catchment: a model of bedload pulse dynamics.

Gilbert (1917) was the first to seriously study the movement of very large bedload pulses and introduced the migrating wave analogy. The migrating wave analogy is by far the most common way to conceptualise pulse dynamics. Most studies that refine Gilbert's (1917) migrating wave model were undertaken at the reach-scale, usually by tracking change in bed elevation at successive cross-sections along the reach. At the same time the wave model has been refined at the reach-scale, analogies at the catchment-scale have moved away from the 'simple' wave analogy to instead view bedload pulse dynamics as a suite of complex, discontinuous and spatially variable processes. Using concepts such as sediment cascades, sediment budgets, sediment delivery ratios, and sediment connectivity studies have questioned whether the wave analogy describe bedload pulse behaviour at the catchment scale (see James (2018) for a review of conceptual models).

Studying bedload pulses at these two different scales, using different methods and drawing different analogies has generated two distinct classes of conceptual models: wave-related models at the reach-scale, and a suite of closely related concepts at the catchment scale, most of which view pulse migration as the variable response of a complex, interconnected system of storage and transport zones. Bridging the gap between 1) wave model and 2) catchment models is a step towards more robust models of pulse dynamics. This chapter bridges this gap by undertaking a detailed survey of in-channel sediment stores across an entire catchment.

I have chosen the Glenelg River, a sand-bed river in SE Australia, as the place to address this gap. The Glenelg River is an especially good place to explore pulse dynamics because the catchment has a well-documented history of management which assumed that pulses move through the catchment as migrating waves: the very assumption now called into question by recent studies of catchment-scale bedload pulses. The approach used here is to draw reach-scale and catchment-scale concepts of pulse dynamics together into a single conceptual model, and then test the predictions of that conceptual model by mapping in-channel sediment stores at the catchment scale.

4.1.1 Terminology used in this chapter

The terms *reach*, *zone*, *compartment* and *segment* are used throughout this chapter. These terms have been used by other researchers to describe different concepts. I clarify how I use these terms below.

- *Reach* refers to a length of river with uniform geomorphic character. The length of a reach varies along the Glenelg River. Reaches are also the spatial scale where intrinsic factors control pulse dynamics (section 4.2.1). Reaches are also the length unit used to map sediment storage along the Glenelg River (see section 4.5.2.1 for more detail on how reaches were delineated along the Glenelg River for this study).

- *Segments* are lengths of the Glenelg River between major sand-bearing tributaries. A segment is comprised of multiple reaches that have the same bankfull width. Segments are only used as a means of analysing the pattern of sediment storage (see the methods section), they have no relationship to pulse behaviour or morphology in this study.

- *Pulse behaviour zones* are lengths of the Glenelg River where bedload pulses behave in some characteristic way. There are four pulse behaviour zones in the Glenelg River (see section 4.4.2). Each zone will contain segments and reaches.

- *Compartments* are a length of river that behave as a single unit and have some characteristic impact on sediment movement. They are analogous to the landscape compartments defined by Brierley *et al.* (2006). Sediment moves within compartments but also between compartments.

4.2 Conceptual models of bedload pulse dynamics

The migrating wave analogy lies at the core of most conceptual models of bedload pulse dynamics. Initially introduced by Gilbert (1917), the wave analogy was derived from the observed rise and then fall of bed level at successive gauging stations in the Yuba River, California (Gilbert, 1917; James, 1989; 2010). By tracking bed level fluctuations at successive downstream stations, the tendency for a sediment pulse to translate or disperse can be evaluated. I remind the reader that the term 'disperse' describes a decrease in wave amplitude and an increase in wave period. The term 'translate' describes situations where wave amplitude and period remain constant as the pulse migrates (Pickup *et al.*, 1983; Lisle *et al.,* 1997; Lisle *et al.*, 2001; Sutherland *et al.*, 2002; Sklar *et al.*, 2009; Venditti *et al.*, 2010; Gran and Czuba, 2017).

Most studies of pulse dispersion and translation focus on discrete sediment inputs migrating through a single reach (using repeated field surveys, flume experiments or numerical modelling) (Sutherland *et al*., 2002; Cao and Carling, 2003; Madej *et al.*, 2009; Morgan and Nelson, 2019), but the wave analogy has been extended to include pulses generated by diffuse inputs and pulses migrating through entire catchments (Nicholas *et al.*, 1995; Houben *et al.*, 2009; Gran and Czuba, 2017). In the case of the latter, floodplain deposition and flow regime influence how at-a-station bed level changes over decades. I use the distinction drawn by James (2006) between *bed waves* – the rise and fall of at-a-station bed levels as channel slope adjusts to, and then relaxes from, the sudden increase in sediment supply caused by a pulse, and *secular sediment waves* - the total flux of sediment through the catchment. Secular sediment waves include sediment travelling along the channel bed (the bed wave) *and* sediment that is temporarily stored in, and eventually recruited from, the adjacent floodplain.

Changes in successive at-a-station bed levels are usually used to track bed waves, while secular sediment waves are expressed as elevated sediment transport rates in the decades and centuries following pulse formation, and the passage of delayed bed waves that form when stored sediment is liberated from bank or floodplain storage by floods or channel erosion (James, 1989b; Zinger *et al*., 2011). Thus, secular sediment waves include an element of complex response. Bed waves, which are part of the wider secular sediment wave, are usually symmetrical with respect to time and pass through a reach in decades, secular sediment waves are positively skewed with respect to time, have a long tail and can take centuries to pass downstream (James, 1989b; James, 2006b; James, 2010).

Bed waves and sediment waves describe the timescales of pulse movement and the parts of the river system involved (in-channel cf. channel and floodplain, for a review see James (2018)). This chapter is focused on the passage of bed waves at the catchment scale: thus, I concentrate here on sand in the channel bed and not sand on the floodplain. I now turn to the controls on bedload pulse dynamics, which I argue can be viewed as a nested hierarchy.

At the base of this hierarchy are what can be termed *intrinsic controls*: the core elements that determine how a discrete packet of sediment, injected into a relatively uniform reach subject to uniform flow, evolve over hundreds of metres. Intrinsic controls are internal to the bedload pulse, and act as the boundary conditions for pulse movement at the reach scale. An analogue is the landscape unit in the River Styles Framework, which include measures of relief, morphology and landscape position and are the boundary condition for each River Style (Brierley and Fryirs, 2000). Intrinsic controls on bedload pulse dynamics include the grain-size distribution of the channel bed and the introduced pulse, the height and strength of the channel banks, the volume of sediment relative to the pre-pulse channel capacity and the flow regime the pulse is subjected to. Intrinsic controls can be considered internal characteristics of the bedload pulse.

As bedload pulses migrate through a drainage network they encounter reaches with varying morphologies, transport capacities and accommodation space, tributary junctions, other bedload pulses, and channel constrictions. I term these *extrinsic controls*. Extrinsic controls are the pre-existing elements of a drainage network that determine how large sediment loads are processed.

The intrinsic and extrinsic nomenclature was used by Phillips (2010) to classify controls on the evolution of the Trinity River, Texas. Phillips (2010) used the term extrinsic to distinguish exogenic controls on river evolution, such as climate, tectonics and lithology from endogenic controls, such as channel length, local-scale patterns and feedbacks between form and process that are internal to the river system. Phillips (2010) identified the intrinsic and extrinsic controls that control river morphology and change. I use the terms intrinsic and extrinsic to describe the factors that control how a single pulse migrates through a relatively simple reach.

I now review intrinsic and extrinsic controls in more detail, by considering controls at progressively larger scales.

4.2.1 Intrinsic pulse dynamics

The emerging consensus in the literature is that, with the exception of very particular circumstances (such as low Froude numbers in sand bed rivers and when the size of the pulse is small relative to channel capacity), dispersion dominates over translation in pulse behaviour (Lisle *et al*., 2001; Sklar *et al.*, 2009). This means that pulse amplitude decreases and pulse period (the length of river impacted by the pulse at any one time) increases as the pulse migrates downstream. Flow variability, a more variable pulse grain size (relative to the pre-pulse channel bed) and a larger pulse (relative to the pre-pulse channel capacity) all enhance dispersion (Morgan and Nelson, 2019). This inherent dispersive behaviour has been observed in flume studies (Lisle *et al.*, 1997; Lisle *et al*., 2001; Madej *et al.*, 2009), in mountain reaches following inputs from landslide debris (Madej, 2001; Sutherland *et al*., 2002; Cui *et al*., 2003b) and has been replicated with numerical models (Pickup *et al*., 1983; Cao and Carling, 2003; Cui *et al*., 2005). In most reaches pulse dispersion dominates because sediment transport is an inherently stochastic process and conditions that promote pulse translation are rarely satisfied.

Steady dispersion and minor translation can be seen when a sand pulse passes through a reach without modifying the underlying morphology. These intrinsic controls on pulse dynamics are essentially local-scale phenomena. When injected pulses are much larger and the distances they migrate much longer, extrinsic controls begin to dominate bedload pulse dynamics. I now add complexity by considering the literature that describes extrinsic controls that perturb this dispersing-wave behaviour.

4.2.2 Extrinsic factors

Extrinsic controls modify the tendency for pulses to disperse or translate by inducing or inhibiting sediment storage, or by increasing or decreasing longitudinal sediment connectivity. Reviewing studies of sediment pulse migration at the catchment scale I have identified three main extrinsic controls on bedload pulse dynamics. In order of increasing spatial scale the three extrinsic controls are: change in the underlying channel morphology at the reach scale, tributary junctions, and channel constrictions. I then consider how interaction between different reaches impact bedload pulse dynamics.

4.2.2.1 Change in reach scale morphology

When bedload pulses are large (sediment supply greatly exceeds transport capacity) a feedback between channel morphology and pulse dynamics is initiated. Pulses modify channels by inducing aggradation, aggrading channels have higher transport rates (Lisle, 2008; Madej *et al.*, 2009; Pryor *et al*., 2011), the higher transport rate increases pulse celerity. Although this is a reach-scale phenomenon, the controls are extrinsic because the initial form of channels, and their tendency to store or transmit sediment, varies through the network and is in place before bedload pulses are delivered (Lisle and Church, 2002; Pryor *et al.*, 2011). This reach scale view provides information on how a single stretch of river, which is fed by a suite of upstream interactions, transforms the shape of bed waves.

Some channels are insensitive to change. For example, a narrow bedrock gorge cannot adjust its width, and has little accommodation space, so tends to funnel sediment downstream without adjusting its form (Major *et al.*, 2012). Some reaches are highly sensitive to change. For example, reaches with erodible banks will widen in response to the aggradation caused by the pulse, which can actually *increase* the size of the pulse by liberating material from the stream banks (Wathen and Hoey, 1998). The bed of reaches subject to sudden aggradation can become elevated relative to the surrounding floodplain and be prone to channel avulsion (Korup, 2004) which causes loss of further sediment to the floodplain.

Changes in reach morphology can occur quickly. This can happen when input pulses are so large they either bury the pre-existing channel or fill it so rapidly that widening is near instantaneous. For example the massive pulses generated by volcanic eruptions (Major *et al*., 2000; Gran and Montgomery, 2005), mining inputs (Markham and Day, 1994) or the sudden release of sediment following tailings dam failures (Hudson-Edwards *et al*., 2003; Garcia *et al*., 2016a). When the sediment inputs are lower and more prolonged, reaches adjust gradually. Pools are an important mediator of this response because they are abundant in alluvial and bedrock rivers and are sites of preferential deposition (Lisle, 1982; Lisle and Hilton, 1992; Madej *et al.*, 2009).

4.2.2.1.1 How bed load pulses impact a sequence of pools

The impact of increased sediment supply on pools depends on the hydraulic mechanism acting on that pool. Forced pools at channel or valley constrictions may never fill, instead funnelling the additional bedload downstream (Church, 2006; Milan, 2013). Likewise, if the rate of sediment delivery does not overwhelm channel hydraulics, sediment may not enter the pool at all and instead be routed around the pool to the next downstream riffle (MacVicar and Roy, 2011). In these cases, pools can be expected to persist in the channel despite reaches upstream and downstream aggrading.

Reaches with pools can also transmit a bedload pulse without permanently adjusting their morphology. For example, in reaches without forcing-elements, pools can be thought of as the trough of low-amplitude bedforms, and the riffles the peak. The migrating pulse migrates into the reach as a kinematic wave (Langbein and Leopold, 1968; Andrews, 1979; Meade, 1985; Thompson, 1986; Tayfur and Singh, 2007). Local-scale bed waves may pass through the reach over some timeframe (for example a single flow 'season' hydrograph), moving from riffles into pools on the rising limb and then scouring from pools and depositing onto intervening riffles on the falling limb. The net result is stable morphology at timeframes longer than one season but cycling of aggradation and degradation at the seasonal and event scale. Importantly this would be expressed in at-a-station bed level records as periodic fluctuation of bed levels, with each period corresponding to a single bedload pulse.

Alternatively, the increased sediment supply may overwhelm local transport capacity (especially if the increase in sediment supply is abrupt and channel geometry cannot adjust in time) and fill the pool. In these cases, an incoming sediment pulse will *begin* filling a sequence of pools at the same time, but upstream pools (which are closer to the sediment source) will fill *faster* than downstream pools (Wohl and Cenderelli, 2000).

As the peak of a bedload pulse arrives, the channel begins to aggrade. Deposition in pools out-paces the subsequent scour from pools and deposition on intervening riffles. Because additional sediment is continuously exchanged across riffles (scoured material is immediately replaced from the next pool upstream), a large, migrating sediment pulse will begin to fill several pools in a sequence at the same time (not one after the other, from upstream to downstream). As aggradation continues, a series of shorter, shallower pools that are more widely spaced form in the reach. If the sediment pulse is large, then aggradation completely buries the morphology and a pool-free, flat bed morphology forms. If the injection of sediment is short lived, and sediment supply drops rapidly, then the process is steadily reversed: upstream pools begin to scour and empty of sediment first, then downstream pools (Wohl and Cenderelli, 2000). If the sediment inputs are long-lived or the pulse migrates very slowly, then changes in hydraulics driven by the altered channel width or sinuosity may prevent the re-scour of pools, or force pools to develop in areas that were originally pool-free.

4.2.2.2 Tributary junctions

Additional sediment inputs at tributary junctions are superimposed on top of the variability arising from reach-to-reach interaction. Tributary junctions can perturb pulse dynamics by either damming the trunk stream with a tributary mouth fan, disrupting downstream transport (Rutherfurd, 2001; Benda *et al.*, 2004; James, 2004; Hanks and Webb, 2006; Rice, 2016), or by damming tributaries, generating aggradation in lower reaches and stalling the input of additional sediment to the trunk stream (Knighton, 1989). The type of discontinuity that develops depends on the timing and magnitude of sediment delivered by the tributary relative to the size and position of the bedload pulse in the trunk stream.

Knighton (1989) documented the formation and destruction of tributary dams in the Ringarooma River, Tasmania. In this instance a bedload pulse in the Ringarooma River, sourced from mining debris injected by upstream tributaries, dammed several downstream tributaries. The lower section of dammed tributaries aggraded by several metres, generating a backwater zone that extended up to 2 km upstream (Knighton, 1989). As the bedload pulse in the Ringarooma River migrated downstream, bed levels dropped, and the tributary incised the dams. Tributary incision re-connected sediment connectivity and generated a second phase of sediment delivery to the Ringarooma River.

Tributary junctions regularly create discontinuities in the trunk stream profile by decreasing the slope of the trunk stream upstream of the junction, and increasing the slope immediately downstream of the junction (Benda *et al.*, 2004; Ferguson *et al*., 2006; Hanks and Webb, 2006). Tributaries delivering bedload pulses to a trunk stream exacerbate this tendency by damming the trunk stream entirely. For example, tributaries delivering bedload pulses to the Glenelg River in SE Australia dammed the trunk stream (termed tributary junction plugs by Rutherfurd, 2001), generating backwater swamps that extended several kilometres upstream along the Glenelg River. James (2004) documented thirteen separate tributary mouth fans that dammed the Yuba River, California with hydraulic mining debris liberated from headwater mines. The Yuba River has since incised through the dams stranding large (5-25 m high) terraces along the margins of tributaries and the Yuba River main stem. With sediment connection between tributaries and the trunk stream re-established, and longitudinal connectivity down the Yuba River, sediment stored on the bed and in terraces continues to supply mining sediment to downstream reaches.

Both the Ringarooma River and the Yuba River examples illustrate how the rapid sediment delivery associated with bedload pulse formation can longitudinally disconnect sediment cascades (*sensu* Fryirs *et al*., 2007), but that given sufficient time connection is re-established and a second phase of sediment delivery is initiated.

4.2.2.3 Constrictions

Constrictions are the sudden narrowing of the valley or channel where transport capacity and accommodation space abruptly decrease. Constrictions can arise from geological controls that shape catchment evolution, for example valley spurs (James, 2004), abrupt changes in lithology (Tooth *et al.*, 2002; Thompson *et al.*, 2011), or from constrictions of the main channel, such as natural or artificial levees (Davies *et al*., 2003; James *et al*., 2009).

As floodwaters move downstream they interact with the valley or channel topography (White *et al.*, 2010) and generate low-velocity backwater environments immediately upstream of constrictions. These backwaters promote deposition, which generate a sedimentation zone that aggrades the channel and floodplain. This behaviour has been observed upstream of valley constrictions in the Yuba River by Weber and Pasternack (2017) and by Heine and Pinter (2012) upstream of artificial levees. In this manner, valley constrictions act as barriers to sediment movement during floods, when sediment transport rates are high. Overall, constrictions further fragment bedload pulses by stalling their movement through the catchment and sequestering sediment into storage, either on the floodplain (secular sediment waves) or within the channel (bed waves). Whether the bed wave moving through the channel is affected by a floodplain constriction depends in part on whether bankfull flows or floods drive most bed wave movement.

4.2.2.4 Interaction between reaches

At the same time reaches are undergoing changes wrought by a bedload pulse, a sequence of reaches will interact to shape pulse dynamics. Low-gradient reaches with ample accommodation space act as sedimentation zones (Church, 1983; Schoorl *et al.,* 2014; Nelson and Dubé, 2016), temporarily buffering downstream reaches against the impact of a pulse. Steep, laterally confined reaches with little accommodation space act as transport reaches and quickly funnel sediment downstream (Nicholas *et al.,* 1995; James *et al.*, 2009; James, 2010; Wilcox *et al.*, 2014).

Transport and sedimentation reaches appear in couplets, with the increased sediment transport in one reach fuelling deposition in the downstream sedimentation zone (Macklin and Lewin, 1989; Nicholas *et al*., 1995). The notion of transport and storage reaches is relative. Contrast between reaches can be large, such as a narrow gorge emerging to a wide floodplain, or more subtle, where a more incised, low-sinuosity reach with little in-channel storage gradually transitions to a lower gradient, more sinuous reach with abundant in-channel storage zones. In this manner the pre-existing pattern of reach types (termed River Style by Brierley and Fryirs (2000)) determine how an individual reach is altered by a pulse, how successive reaches are coupled and interact, and the resulting impact on pulse dynamics. For example Fryirs and Brierley (2001) identified four response patterns (where a response pattern is a particular sequence of channel changes in successive reaches) in the Bega River catchment, NSW, following increased sediment delivery after European settlement. The tendency for sediment to be stored in the channel, on the floodplain or to be funnelled downstream varied by River Style, but the net effect was to sequester ~30 % of the sediment in tributaries, and funnel the remainder to the lowland plain of the Bega River (Fryirs and Brierley, 2001).

Coupling between reaches occurs at the same time one or both reaches undergo morphological change. For example Erskine and Melville (2008) and Erskine (2008) documented coupling between transport reaches and sedimentation zones in Wollombi Brook, NSW. A large flood drove deep, rapid channel incision, generating a bedload pulse. The pulse accumulated in the downstream, low-gradient reach where it caused massive overbank deposition, levee building and de-coupled the bed wave from the larger secular sediment wave. Levee building out-paced bed aggradation, so the resulting channel contained higher flows. The portion of the river with elevated transport capacity aids dispersion of the bed wave, which is migrating downstream into an intact, unaltered section of river (Erskine, 2008; Fryirs *et al.*, 2012).

The two-way interaction between a bedload pulse and a reach, plus the interaction between successive reaches, means that bedload pulses move through a drainage network in a complicated and often unpredictable way. Sediment routing models of increasing complexity have demonstrated how simple, discrete sediment inputs are quickly fractured into a series of smaller bed waves (Nicholas *et al.*, 1995; Benda and Dunne, 1997a). Gran and Czuba (2017) used a sediment routing model based on the Greater Blue Earth River, Minnesota, to demonstrate how a hierarchical river network with a spatially-varying transport capacity modified the shape of migrating bedload pulses. This modelling identified the tendency for pulses to disperse through some reaches, to merge with other pulses downstream (synchronization), to preferentially modify particular reaches (termed hotspots of geomorphic change by Czuba and Foufoula-Georgiou (2015)) and to have their migration restricted by narrow reaches that act as transport 'bottlenecks' (Gran and Czuba, 2017). The point here is that the larger the scale considered, the more reach interactions influence bedload pulse dynamics.

4.2.3 Summary of catchment scale bedload pulse dynamics

A drainage network can be viewed as a system of extrinsic controls superimposed on a migrating bedload pulse. As successive extrinsic controls are superimposed, bedload pulses become highly discontinuous in time and space, i.e. the pulse fractures across the network. At this scale (tens to hundreds of kilometres and decades to centuries), the migrating wave analogy breaks down: Identifying coherent waveforms across a catchment becomes difficult or impossible (James, 2006b).

For example, the Ringarooma River tailings pulse studied by (Knighton, 1989) migrated through reaches with varying transport capacity *and* was subjected to additional inputs from tributaries. The pulse did not migrate as separate waves. Instead, bed level and in-channel sediment storage accumulated in a downstream direction, with tributary inputs superimposing local peaks immediately downstream of their junction. Even the at-a-station, symmetrical bed wave originally conceived in the Yuba River by (Gilbert, 1917) was in reality a messy, discontinuous series of deposits spread along tens of kilometres of river (James, 2006b). Although discontinuous at the network scale, there is nothing precluding wave-like behaviour at the reach scale, or within a single compartment of the wider network.

4.3 Research gap

Bedload pulses are usually tracked through a catchment by measuring changes in at-a-station bed level (usually at discharge gauging stations) at different points along a river's length. This method adopts a Eulerian reference frame (James, 2018) and is implicitly tracking bed waves, not secular sediment waves. Sparsely distributed gauge sites provide information on how a single reach within a wider network responds to a bedload pulse over time, but these observations are necessarily limited in their spatial extent: only a small number of network segments can be sampled. What this view of pulse dynamics provides in temporal resolution it sacrifices in spatial resolution.

The alternative to at-a-station measurements is to map changes in sediment storage along successive reaches and then infer how pulses have moved between river segments (James, 2018). This method adopts a Lagrangian reference frame and implicitly tracks both in-channel bed waves and secular sediment waves migrating through the catchment. Changes in sediment storage are measured via a proxy such as: channel widening and lateral instability (Macklin and Lewin, 1989; Pierson *et al*., 2011; Thomas *et al*., 2015), the development of braiding (Knighton, 1989; 1991) or an increase in braiding intensity (Wathen and Hoey, 1998), floodplain aggradation (Gomez *et al.*, 1998), an increase in the frequency of sand splays and flood outs (Fryirs and Brierley, 2001; Fryirs *et al*., 2007; Erskine, 2008; Saynor and Erskine, 2016) or change in the size, type and frequency of in-channel sediment stores (Madej, 1992; Kondolf *et al.*, 2002).

The spatial snapshot generated using a Lagrangian reference frame requires detailed mapping from aerial imagery and/or field surveys. When in-channel sediment stores are obscured by high water levels, such mapping is difficult. Furthermore, because detailed field surveys are time-consuming, in-channel sediment stores are usually mapped at the reach scale, not over entire catchments.

Gathering the empirical data needed to evaluate catchment scale conceptual models of bedload pulse dynamics requires a trade-off between the temporal resolution afforded by at-a-station bed levels, and the spatial resolution afforded by mapping sediment storage along successive reaches.

These challenges have led to a clear gap in our ability to evaluate and then improve catchment scale models of bedload pulse dynamics: empirical data quantifying the catchment-scale distribution of in-channel sediment storage in hierarchical river networks which are subjected to multiple bedload pulses. Closing this gap provides a means to test existing theory about how bedload pulses migrate through a catchment, and provides a data set that can be used to calibrate catchment-scale sediment routing models used to study bedload pulse dynamics at decadal to centennial timescales (Nicholas *et al*., 1995; Benda and Dunne, 1997a; 1997b; Czuba and Foufoula-Georgiou, 2015; Gran and Czuba, 2017). The Glenelg River, Victoria, Australia is an ideal location to address this gap.

4.4 Why is the Glenelg River a good place to address these gaps?

The Glenelg River, Victoria, Australia has been impacted by a series of bedload pulses following land clearing in the mid to late 19th century (described in Chapter 3). The Glenelg River is an excellent place to address the gap in bedload pulse literature identified above for three main reasons:

1. The Glenelg River has been subjected to a series of bedload pulses that emanate from tributaries spaced along its length. The timing of pulse delivery and the calibre of sediment injected to the Glenelg River are also well-constrained. The tributary catchments feeding sand to the Glenelg River have largely adjusted to the land clearing of the 19th century: gully heads have stabilised, and the bed of several streams have begun to incise. This suggest the 'press' disturbance is waning and that pulse movement in the Glenelg River is driven by the redistribution of existing sediment stores.
2. The Glenelg River has been subject to a range of historic interventions. Examples include erosion control in headwater streams, removal of in-stream wood from the channel ('de-snagging'), piecemeal stock exclusion and re-vegetation, and earlier phases of sand extraction. The type, location and extent of these interventions is well-documented (see Chapter 3) which means their impact on the distribution of sediment stores can be accounted for.
3. Recent aerial imagery and LiDAR surveys of the entire catchment mean sediment stores and extrinsic controls such as valley width, tributary junctions and the location of constrictions can be easily mapped. Aerial imagery was flown during an historic drought (the Millennium drought (Bureau of Metorology, 2015)) which exposed much of the Glenelg River bed.

4.4.1 Extrinsic controls in the Glenelg River catchment

This section summarises the instances and distribution of extrinsic controls in the Glenelg River catchment. I include the pattern of sediment delivery feeding bedload pulses, tributary junctions, transport reaches, sedimentation zones and valley constrictions. I then use the review of how extrinsic controls impact pulse behaviour to predict the pattern of sediment storage in the Glenelg River. Following this section I propose hypotheses about how sand will move through the Glenelg, and then describe the methods I use to test those hypotheses.

4.4.1.1 Sediment Delivery

Overall, sediment was delivered to the Glenelg River as a decades long pulse, a 'press' disturbance that delivered at least six million m^3 of coarse sand to the Glenelg River between 1840 and 1946 (Erskine, 1994; Rutherfurd and Budahazy, 1996). Pulses were injected into the Glenelg River by seven different tributaries spaced along the river's length. Historical records show that increased sediment production coincided with land-clearing beginning in the 1840s, and then rapidly increasing until the mid-20th century (aided by a large flood in 1946) (Chapter 3). This was quickly followed by damming of the Glenelg River by Rocklands Reservoir, improved land practices aimed at reducing erosion, and gully stabilisation in tributary headwaters. Interventions were superimposed on the natural decline in sediment supply as the catchment adjusted to the new hydrologic regime and gullies stabilised. Declining sediment supply from the catchment means the lower reaches of some tributaries have begun to incise.

4.4.1.2 Junctions

There are seven major junctions with sand-bearing tributaries spaced along the Glenelg River. A tributary mouth fan has formed at the Mathers Creek - Glenelg River junction at the upstream end of the study area (termed tributary junction plugs by Rutherfurd and Budahazy (1996)). The sediment plug has generated a backwater that extends approximately 2.5 km upstream along the Glenelg River. Pulses of sand injected from Pigeon Ponds Creek and the Chetwynd River have also generated wide, low-angle tributary mouth fans that block the Glenelg River.

The combined delivery of sediment from tributaries and the trapping of sediment moving down the Glenelg River has caused a large junction-complex to form on the Glenelg River between Pigeon Ponds Creek and the Chetwynd River, filling this stretch of the Glenelg River valley with sediment (Figure 4.1) (Rutherfurd and Budahazy, 1996). This junction is complex, and the downstream end of the tributary valleys flowing into it now acts as a single, large sediment storage zone.

Tributary junction plugs have not formed at the mouth of Steep Bank Rivulet, the Wando River or the Wannon River. The Glenelg River does slightly aggrade immediately upstream and steepen downstream of these three tributaries, but this behaviour is common at tributary junctions not delivering bedload pulses (Benda *et al.*, 2004; Hanks and Webb, 2006; Rice, 2016).The lower reaches of these tributaries have wide, low-gradient floodplains that may act as buffers against pulsed sediment inputs during floods, preventing large, sudden injections of sediment depositing as fans across the Glenelg River.

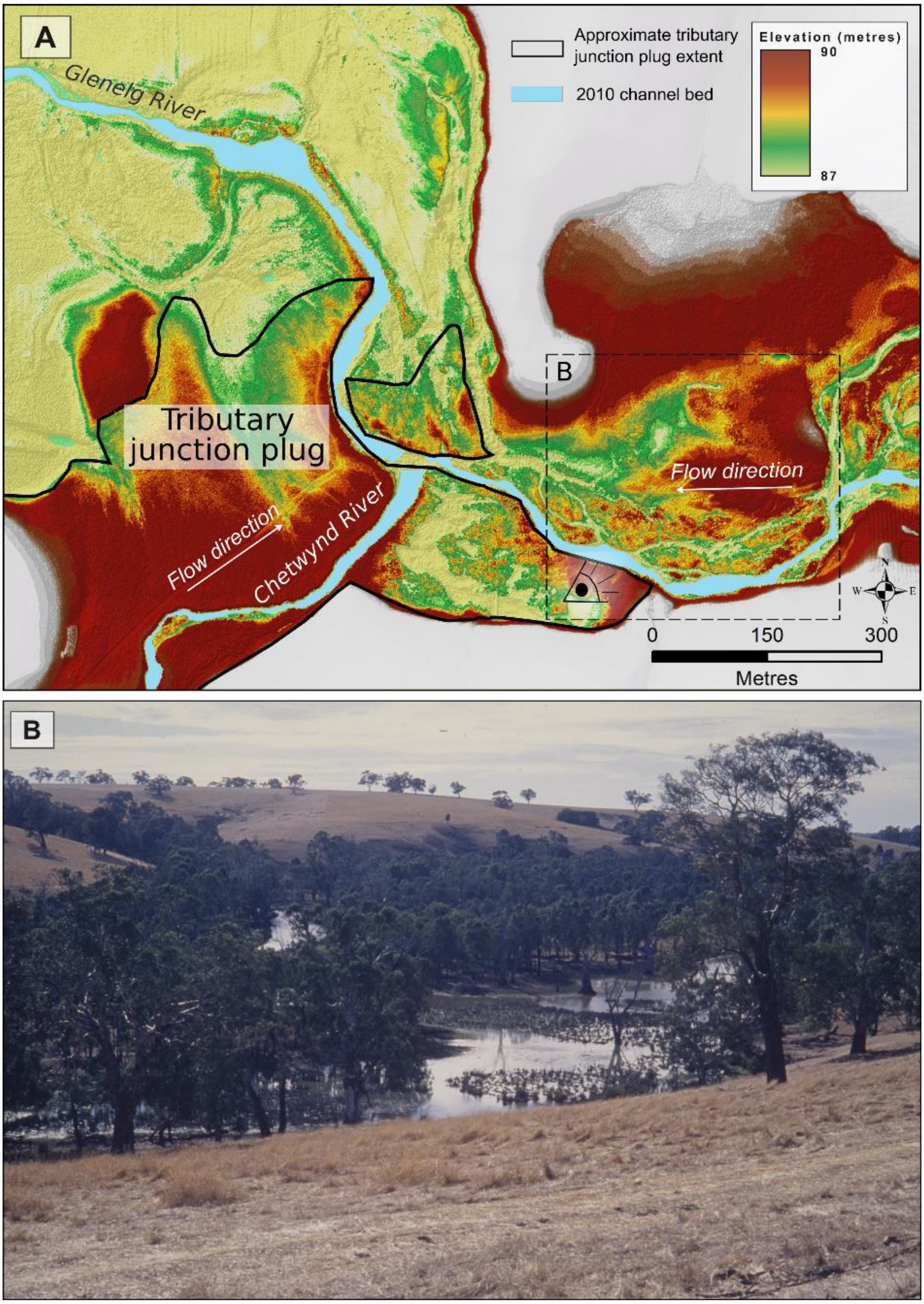


Figure 4.1: Example of a tributary junction plug that has formed across the Glenelg River at the Chetwynd River - Glenelg River confluence showing (A) the elevated portion of the junction plug emanating from the Chetwynd River valley. The Glenelg River has incised into the plug and the contemporary channel is shown in light blue, (B) the backwater swamp that has formed immediately upstream of the plug, view is looking upstream in 1994 and the icon in the corner of (a) shows the direction of view, looking towards the top right of the photo. Photo B courtesy of Ian Rutherfurd.

4.4.1.3 Transport reaches and sedimentation zones

Bedload pulses impact the entire study area but no information on the pre-pulse distribution of reach-scale slope is available. Contemporary elevation data only provides information on how river slope has since adjusted to increased sediment supply. Because slope adjustment is likely on-going, and will fluctuate as sediment cascades through the system, transport reaches and sedimentation zones are best identified using valley width, which serves as a surrogate for transport capacity (assuming narrow gorges constrain flow and increase sediment transport rates relative to the wide, flat valleys). I remind the reader that although valley/floodplain width is used as a surrogate for transport capacity here, the focus of this chapter is on sediment moving along the river bed (bed waves), not the floodplain (secular sediment waves).

The Glenelg River valley varies in width between 2 km to only 100 m in narrow gorges (Figure 4.2). Overall the gorge between Mathers Creek and Pigeon Ponds junction should funnel sediment downstream and into the sedimentation zone that has developed at the Pigeon Ponds and Chetwynd River junction plug complex. Similarly, this sedimentation zone should feed sediment into the narrow 16 km long gorge immediately downstream, which will funnel sediment downstream and supply another in-channel sedimentation zone at the gorge outlet, where the valley widens.

4.4.1.4 Constrictions

The Glenelg River floodplain is punctuated by abrupt decreases in valley width at several locations. These abrupt decreases in valley width occur at the head of gorges, and where bedrock ridges intrude across the floodplain. The difference between a gorge and a constriction is not sharp, and when a constriction persists downstream it becomes a gorge. I distinguish between a gorge and a constriction by their length and by the decrease in valley width they induce, compared to upstream reaches. Therefore, constrictions occur where ridgelines protrude into wide valleys, locally pinching the floodplain, but constrictions are also found *within* gorges, where a reach that is already narrow abruptly becomes even narrower at the constriction point (Figure 4.2).

For example, constrictions are nested within a narrow gorge upstream of Schofield Creek, while further upstream constrictions pinch off the floodplain in a much more abrupt manner, only for the valley to widen downstream again. I predict that constrictions interrupt sediment movement in transport reaches, and break secular sediment waves into smaller sections while allowing the bed wave to pass downstream.

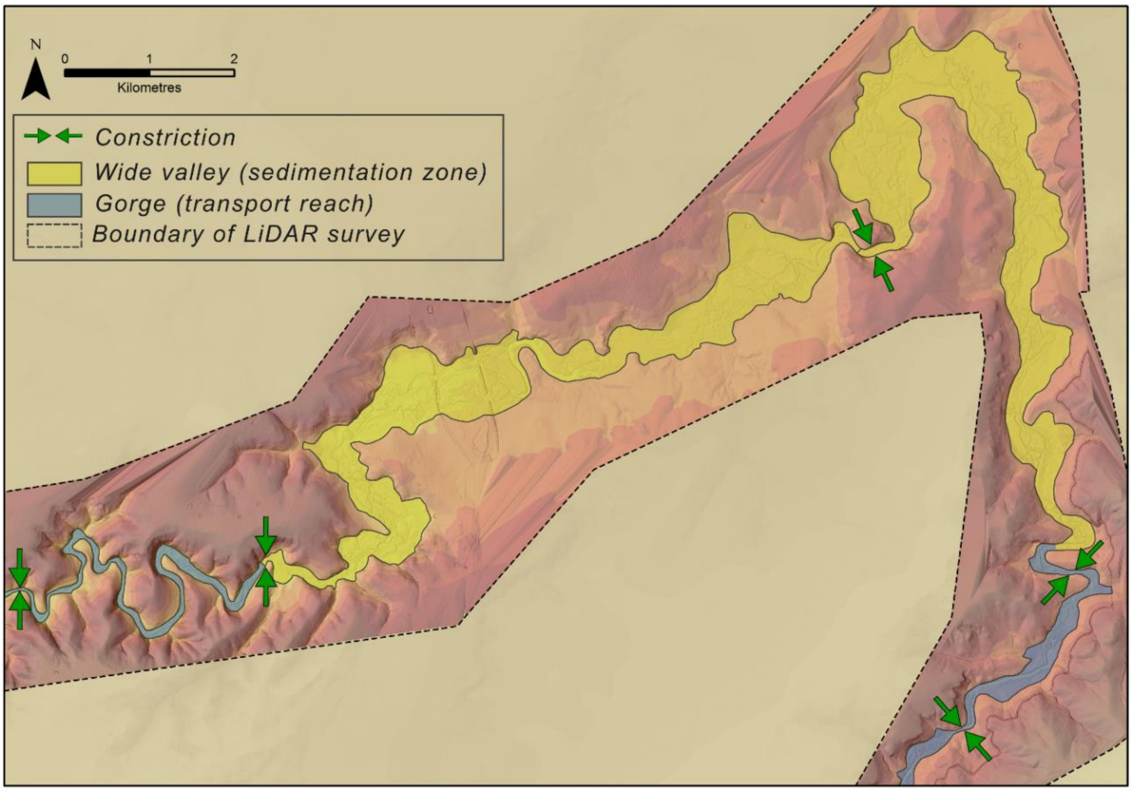


Figure 4.2: Successive transport and sedimentation reaches in the upper Glenelg River, 30 km downstream of the Mathers Creek junction. Green arrows mark the location of constrictions, which pinch wide valleys and are also embedded within the narrow gorges.

4.4.2 Predicted distribution of bedload pulses in the Glenelg River

On the basis of the literature review I expect the pattern of sediment storage in the Glenelg River to be expressed differently at smaller spatial scales vs. larger scales. At smaller scales (several kilometres to tens of kilometres) the Glenelg River will be divided into sedimentation zones and transport reaches. In sedimentation zones I predict that bed material will be characterised by a subtle rise and then fall of channel storage when viewed from upstream to downstream i.e. a stalled bed-wave that has migrated by a combination of dispersion and translation. Transport reaches will have markedly lower in-channel sediment stores that show little to no variation in sediment storage (a flat sheet of sand) with distance downstream.

At larger spatial scales (the section of the Glenelg River considered in this study is 238 km long) the pattern of sediment storage will be characterized by four distinct pulse behaviour zones. The pulse behaviour zones contain transport reaches and sedimentation zones within them. The four pulse behaviour zones that I predict will be found in the Glenelg River are:

1. *A dispersion zone between Mathers Creek and the Schofield Creek junction 64 km downstream* (Figure 4.3). Overall sand storage in this pulse behaviour zone is expected to decrease in a downstream direction, but narrow valleys and sedimentation zones will introduce variation about this trend. Pulse dispersion over tens of kilometres was observed downstream of a reservoir removal in the Elwha River, Washington, USA by East *et al*., (2015). Although the pulse dispersed, smaller-scale sediment storage zones did develop within the reach, mainly in pools and as newly formed bars. The more prolonged injection of sediment by Mathers Creek should amplify pulse dispersion and cause more sediment to accumulate in storage zones.

2. *A merging zone where pulses delivered by Schofield Creek, Pigeon Ponds Creek and the Chetwynd River merge together into a single, larger deposit.* The downstream limit of this zone is the upstream end of the narrow gorge which should act as a bottleneck and limit sediment movement (Figure 4.3). Several authors have noted that bedload pulses tend to merge in downstream, low-gradient reaches where sediment naturally accumulates (Fryirs and Brierley, 2001; Nelson and Dubé, 2016). Overall sand storage is expected to be consistently elevated in this zone, with variation introduced by channel constrictions that break pulses into smaller parts.

3. *A staggered dispersion zone between the entry to the gorge and the Steep Bank Rivulet junction.* Sand storage is expected to be low through the gorge (a transport reach), abruptly increase immediately downstream of the gorge (the associated sedimentation zone begins) and then steadily decline in a downstream direction as sediment is dispersed from the sedimentation zones (Figure 4.3). Valley constrictions will cause variation about this trend. The funnelling of sediment through higher transport reaches and its accumulation in downstream sections of the catchment was observed in the Bega River by Fryirs and Brierley (2001), in the Yuba River by James (2006) and on the White Salmon River by Wilcox *et al.* (2014).

4. *An accumulation zone between Steep Bank Rivulet and the end of the study reach.* Pulses from Steep Bank Rivulet, the Wando River and the Wannon River will cause successive dispersing pulses to be superimposed (Figure 4.3). The outcome should be a stepped increase in sand storage in a downstream direction. The merging of tributary pulses in the trunk stream, and the stacking of bedload pulses atop one-another, was documented by Knighton (1989; 1991) in the Ringarooma River, Tasmania and in the upper reaches of the Yuba River, California by Gilbert (1917) and James (2006).

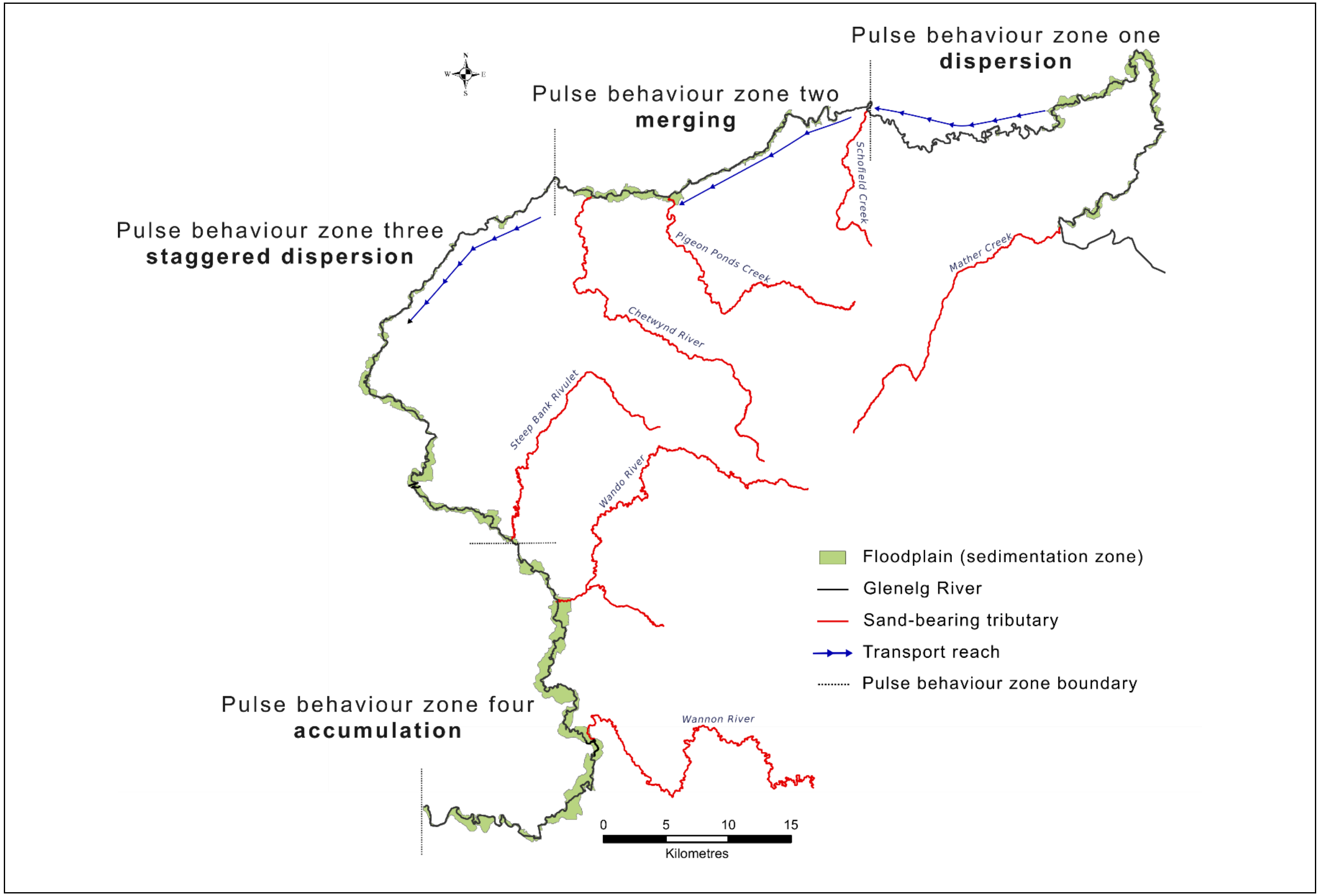


Figure 4.3: Predicted bedload pulse dynamics in the Glenelg River. With the four pulse behaviour zones identified, the location of sand-bearing tributaries in red, the mapped floodplain (sedimentation zones) in green and the location of the long, narrow gorges, which are predicted to act as transport reaches, shown in blue.

4.4.3 Approach of this chapter

The literature review undertaken for this chapter identified a clear gap: empirical data that quantifies the catchment-scale distribution of in-channel sediment storage in a hierarchical river network impacted by multiple bedload pulses. The challenge to closing this gap lies in the difficulty of mapping in-channel sediment stores over large distances (tens to hundreds of kilometres). The approach of this chapter is to avoid this difficulty by mapping the distribution of pools in the Glenelg River when water levels were exceptionally low.

4.4.3.1 Why the distribution of pools is a good proxy for sediment storage

Pools have been used as an indicator of fine (sand to fine gravel) sediment supply in gravel bed rivers before (Lisle and Hilton, 1992, 1999), but this approach has not been employed in sand-bed rivers experiencing bedload pulses. Furthermore, Lisle and Hilton (1992) measured the relative infill of pools (termed 'residual pool volume') and compared the particle size distribution of infill to that of the overall bed composition. Calculating residual pool volume requires surveying pool volume and measuring the distribution and grain size of fine sediment within that pool, which is not feasible at the catchment-scale.

Bedload pulses gradually fill pools and simplify the channel bed (Cao and Pender, 2004; Lintermans, 2004; Bartley and Rutherfurd, 2005b). This means that the size, number and distribution of (remaining) pools along a river impacted by a bedload pulse should reflect the relative sediment supply to the reach, and that the number and size of pools will be inversely related to the total volume of sediment stored in a reach. The inverse relationship between pool size/frequency and sediment supply can be used to map sediment storage. Areas devoid of pools (i.e. filled with sand) are sediment storage zones, and areas with a greater frequency of pools (or much longer pools) indicate less sediment storage. Some pools will be artificially drained by landholders for stock water, which will arterially reduce the number of pools mapped. However, the number of pools drained for stock water is expected to be much smaller than the total number of pools in the river, so the impact of artificial drainage will be small.

I use aerial imagery to map the distribution of pools and sediment in the bed of the Glenelg River. This method can be used at the catchment scale wherever aerial (or satellite) imagery is of high enough resolution that standing water can be distinguished from exposed streambed (such high-resolution imagery is becoming increasingly common). At the time of writing aerial imagery flown during extremely low flow is confined to a single survey from 2010.

4.5 Methods

4.5.1 Pool mapping method

This chapter leverages a suite of 0.5 m resolution aerial imagery flown over the Glenelg catchment in February 2010, during the later stages of the historic Millennium drought (DELWP, 2016). River flows were extremely low at the time of the survey and several sections of the Glenelg River and its tributaries had ceased to flow entirely. The remaining water in the system was mainly stored in pools spaced along the river's length. This storage pattern produced a remarkably clear pattern in the stream, which alternated between stretches of exposed sand and pools of water.

This pool mapping method quantifies the surface area of standing water in the Glenelg River at the time aerial imagery was captured. This pool mapping method has two main assumptions:

1. The distinction between pools and sand is binary. The streambed must be classified as sand *or* pool.
2. All pools have equal depth i.e. areas mapped as pool store no sand at all.

Pools, and the stretches of exposed sand between them, were manually mapped at a resolution of 1:2,000 for the Glenelg River between the Mathers Creek junction and the section of river above Dartmoor – a total length of 235 km (Figure 4.5). Mathers Creek junction was chosen as the upstream boundary for mapping because Mathers Creek is the first major sand-bearing tributary that meets the Glenelg River. Upstream of Mathers Creek junction the Glenelg River has a low-gradient, is anabranching and free of bedload pulses (i.e. not the focus of this study). The downstream limit of the mapping is the point where deeper flows begin to mask the streambed between pools, which makes distinguishing deep pools from the low-flow channel increasingly difficult.

Each pool or intervening stretch of sand was represented by a line feature that was paired with channel attributes (see below). Distinguishing pools from bare sand was straightforward as the two produced very different signatures on the aerial imagery (Figure 4.4A and B). The low-flow channel produced a signature that was noticeably different from the deeper pools (for example, reflective sand could be seen beneath the water) (Figure 4.4C). The low-flow channel was classified as sand, not pool because the purpose of the classification was to distinguish deep pools free of sand from the intervening sediment storage zones. In fact, partially-wetted stretches of streambed covered a small fraction of the survey (approximately 2 % of the total river length mapped).

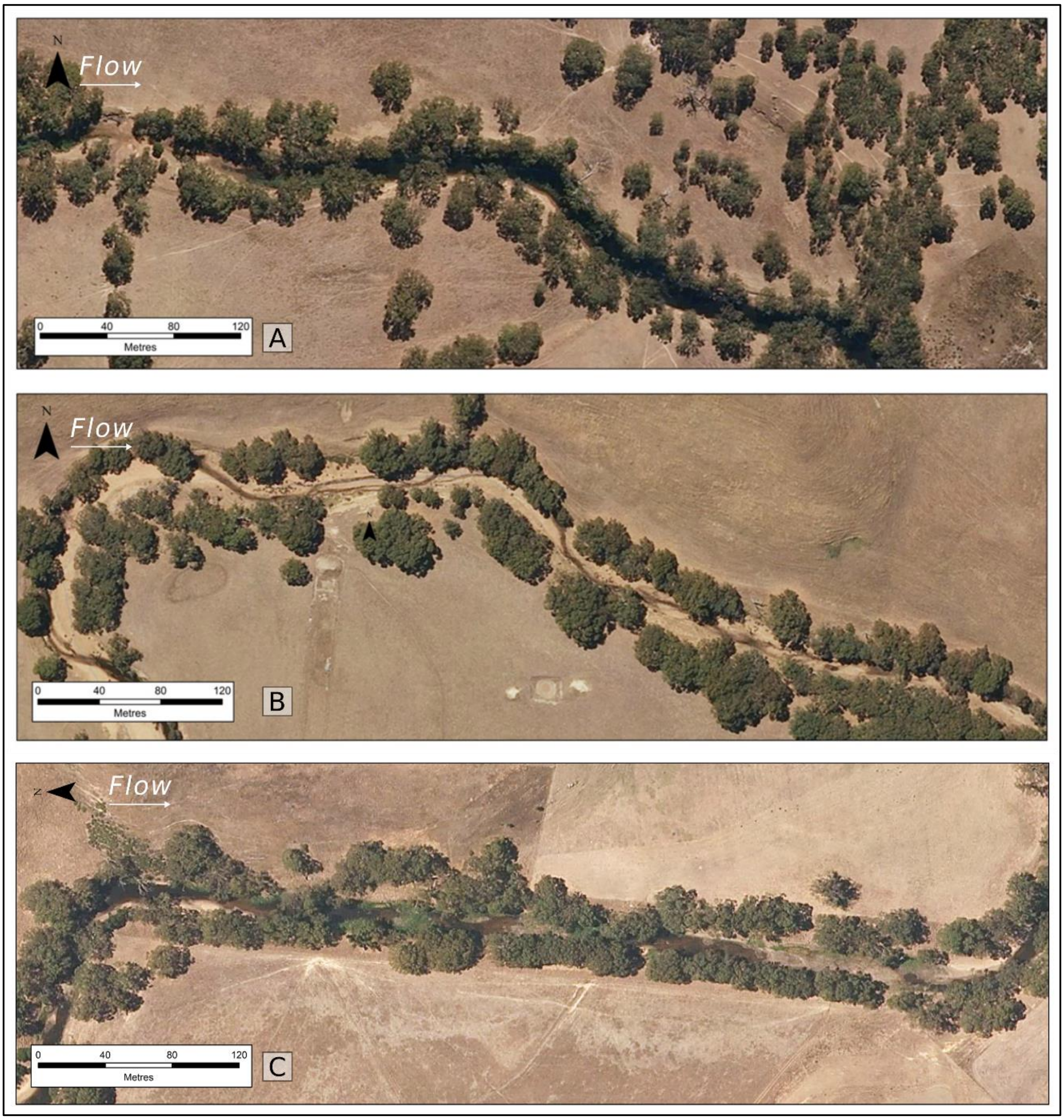


Figure 4.4: The 2010 aerial imagery used to map pools and sand, showing (A) a section of river mapped as pool, with the upstream boundary of the pool on the left of the image, (B) a section mapped as exposed sand and (C) a typical shallow run, where shallow water obscures some of the bed, but sand is still visible. While some water is present on the bed in these sections, shallow runs were classified as 'sand' using the binary pool-sand classification adopted for this method. Flow is from left to right in all images.

4.5.2 Analysis methods

The map of pools and sand was converted to a spatially-averaged metric (percent sand cover) for plotting. This section outlines the two steps used to calculate this metric.

4.5.2.1 Segment and reach definition

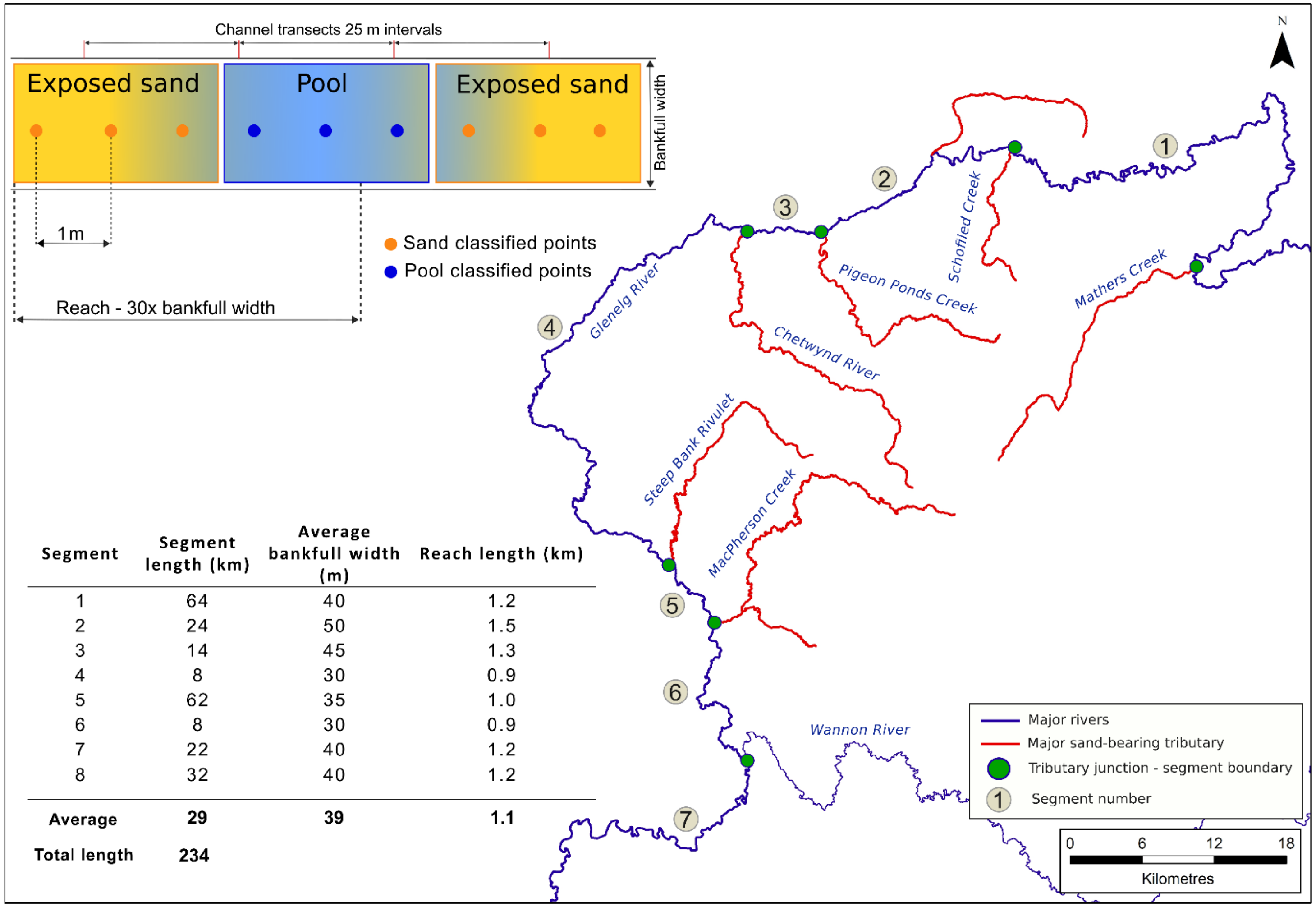
Using the nomenclature of Flotemersch *et al*. (2011) the Glenelg River was split into eight *segments* using junctions with major sand-bearing tributaries to define segment boundaries. Each segment was further divided into reaches so that a more detailed figure of sand distribution could be plotted (Figure 4.5). The segments relate to bankfull width and are not the same as the pulse behaviour zones identified in the conceptual model for the Glenelg River. The length of reaches within each segment was determined by multiplying the mean bankfull width for that segment by a factor of 30 (Flotemersch *et al*., 2011). The factor of 30 was chosen so that the length of reaches scaled with the size of the river. Segments could have been split into reaches of any length, but the factor of 30x bankfull width was chosen so that, in theory, each reach would capture several sets of pools (and accompanying 'riffles' – the intervening sand bed between pools), which are usually spaced between five and twelve channel widths apart (Keller, 1972). Mean bankfull width for each segment was obtained by calculating the average width of all LiDAR-derived channel cross-section transects, which were spaced every 25 m along the entire length of the Glenelg River, for each segment.

4.5.2.2 Calculating percentage sand cover

The percentage sand cover for each reach was determined by generating points at a spacing of 1 m along the entire length of the river centreline (Figure 4.5). Each point was classified as either pool *or* sand (but never both). The classified points were then used to calculate a sand cover metric (where sand coverage is just the percentage of a reach with exposed sand) using the formula:

$$P_{Sand,i} = \left(\frac{\sum Pts_{sand,i}}{\sum pts, i}\right) \times 100$$

Where $P_{Sand,i}$ is the percentage of reach *i* covered by sand, $\sum Pts_{sand,i}$ is the total number of points in reach *i* classified as sand, and $\sum pts, i$ is the total number of points in reach *i*. Percentage sand coverage is a proxy for sediment storage.



Segment	Segment length (km)	Average bankfull width (m)	Reach length (km)
1	64	40	1.2
2	24	50	1.5
3	14	45	1.3
4	8	30	0.9
5	62	35	1.0
6	8	30	0.9
7	22	40	1.2
8	32	40	1.2
Average	**29**	**39**	**1.1**
Total length	**234**		

Figure 4.5: Annotated map showing the major sand-bearing tributaries in the Glenelg catchment, the eight segments used for the pool mapping and to define the length of reaches. Top-left inset illustrates how points spaced every 1m along the length of the river were classified as pool or sand, bottom left inset summarises average length and width of reaches in each segment. Mathers Creek junction is the upstream limit of the study area for this chapter.

4.6 Results

4.6.1 Sand storage along the Glenelg River

The total number of pools, and the median length of those pools, varied considerably between the eight segments of the Glenelg River (Table 4.1). Pool size and spacing does not vary systematically in a downstream direction. The two longest segments; segment one and segment five, contain the longest (297 m) and shortest (64 m) median pool lengths, respectively. Median pool spacing ranges between four and fifteen channel widths. The most closely-spaced pools were in segment five (this segment also includes the narrow gorge below the Chetwynd River junction) (Figure 4.7). Importantly, the length of pools and spacing of pools does not vary systematically with segment length, i.e. the lack of clear patterns in pool length is not a function of sample size.

Table 4.1: Statistics for the eight segments of the Glenelg River for which pools and the intervening sand-bed were mapped, how they relate to the segments describing proposed pulse behaviour in the conceptual model. BFW is bankfull width.

Pulse behaviour zone	Segment	Segment length (km)	Number of pools	Median pool length (m)	Median pool spacing (m)
1 - Dispersion	1	64	61	297	325 (8 x BFW)
	2	24	24	78	425 (9 x BFW)
2 - Merging	3	14	18	104	270 (6 x BFW)
	4	8	5	78	346 (12 x BFW)
3 – Staggered dispersion	5	62	118	64	123 (4 x BFW)
4 - Accumulation	6	8	23	93	267 (9 x BFW)
	7	22	24	75	190 (5 x BFW)
	8	32	24	115	608 (15 x BFW)

The distribution of sand along the Glenelg River resembles a series of peaks and troughs; with peaks corresponding to a high percentage of sand coverage (high sand storage), and troughs corresponding to a low percentage of sand coverage (low sand storage) (Figure 4.6). Almost all peaks in sand coverage coincide with valley constrictions, which were mapped independently of in-channel sand stores. In the upper 60 km of the river (immediately downstream of Mathers Creek junction) percent sand coverage oscillates about a mean value of approximately 55 %. The volume of sand then sharply increases downstream of Schofield Creek junction. In each of the two gorges (annotated on Figure 4.6), and in the Pigeon Ponds-Chetwynd River junction complex, sand coverage steadily increases in a downstream direction. The downstream increase in sand coverage is unexpected. The conceptual model predicted that pulse dispersion would lead to the exact opposite pattern of sand distribution: high sediment storage near sediment sources (such as the junction complex where tributaries enter the Glenelg River) and a steady *decrease* in sand-storage in a downstream direction.

Downstream of the second gorge, sand coverage drops suddenly before another sharp peak at ~170 km downstream of Mathers Creek junction. This too is an unexpected pattern. The conceptual model predicted that the narrow gorge would funnel sediment downstream and that a sedimentation zone would form at the valley opening. A large sedimentation zone has not developed at the valley opening and instead sand coverage *declines* with distance from the gorge outlet (Figure 4.6 and Figure 4.7). This decline in sand storage was predicted to occur much further downstream.

In the lower 80 km of the study reach the long profile of sand coverage (Figure 4.6) shows a stepped increase, with each abrupt step-up in sand coverage coinciding with a constriction. The long profile of sand coverage in the lower 50 km of the Glenelg River resembles a u-shape, with sharp peaks in coverage that coincide with constrictions, superimposed on top of this u-shaped trough (Figure 4.6).

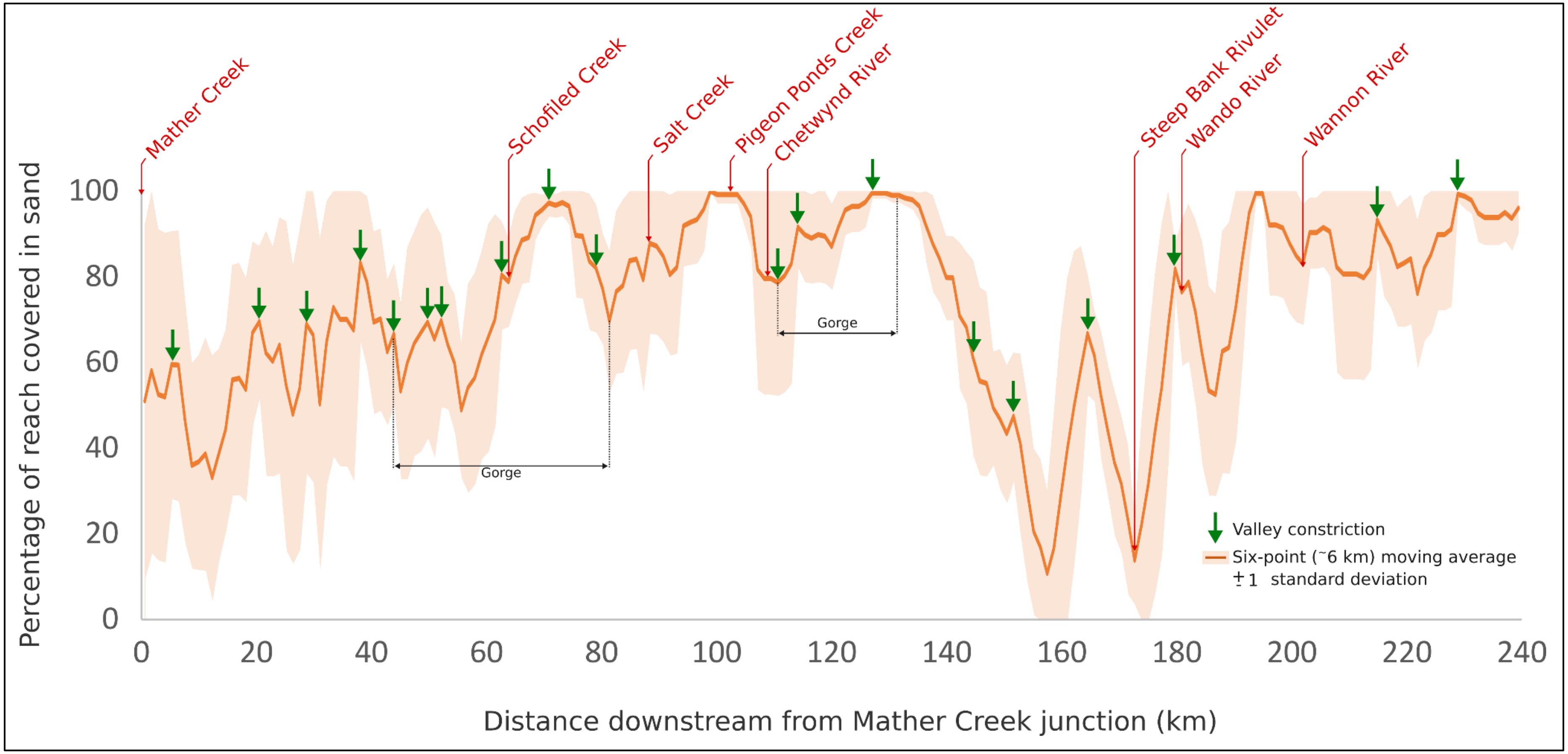


Figure 4.6: Six-point moving average (dark orange line) of the proportion of each reach covered in sand, variation about this average shown in orange (± 1 standard deviation) superimposed. Red arrows indicate where major sand-bearing tributaries enter the Glenelg River and green arrows denote constrictions, where the valley abruptly narrows. Constrictions were mapped independently. The two narrow gorges are also annotated.

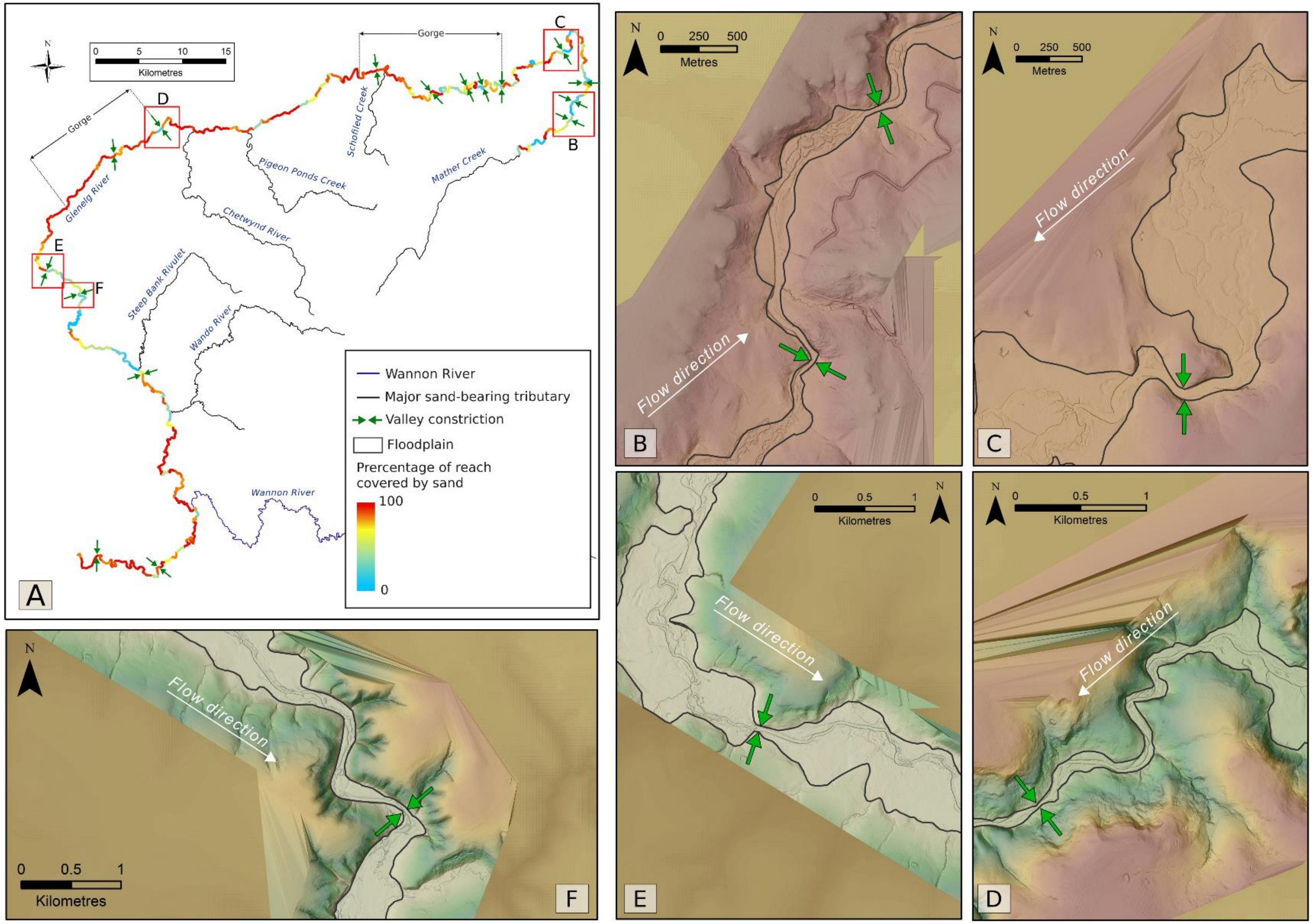


Figure 4.7: (A) The proportion of each reach covered in pools (serving as a proxy for in-channel sand storage) along the Glenelg River. The two narrow gorges annotated in Figure 4.6 are also marked, black lines are sand-bearing tributaries that also serve as the boundaries between segments, labelled red boxes refer to inserts B-F which are examples of constrictions.

4.6.2 Results summary

Sand storage (measured by its proxy – percentage sand coverage) varies significantly across the catchment. In particular, the downstream portion of segment five, below the narrow gorge, shows a marked decrease in sand storage. This is the exact opposite of what the conceptual model predicted. Sand coverage varies across other segments too, but segment one, immediately downstream of Mathers Creek, has the lowest sand coverage of all segments. The behaviour in each of the four pulse behaviour zones identified in the conceptual model is summarised in Table 4.2.

Table 4.2: The predicted and observed pattern of sand storage for each of the four pulse behaviour zones described in the conceptual model.

Pulse behaviour zone	Predicted pattern of sand storage	Observed pattern of sand storage
1 Dispersion	Decreasing sediment storage with distance downstream of Mathers Creek junction, local variations imposed by transport reaches and sedimentation zones	Sand storage is highly variable and increases with distance downstream from Mathers Creek
2 Merging	A relatively flat, even profile of sand stored as pulses from the Schofield Creek, Pigeon Ponds Creek and Chetwynd River merge	Relatively flat, even profile of sand storage, with peaks in sand storage superimposed at constrictions
3 Staggered Dispersion	Low sand storage through gorge, high sediment storage immediately downstream of gorge (where sedimentation zone forms) and then a steady decrease in sand storage with distance downstream	Sand coverage steadily increased with distance down the gorge, before rapidly dropping: a sedimentation zone did not develop. Downstream of the gorge sand has accumulated as a wedge against valley constrictions
4 Accumulation	Sand coverage would increase in a stepwise fashion with distance downstream in this reach, with each step coinciding with a tributary input	Predicted trend was observed. However, drops in sand coverage are larger than expected and sand coverage in the lower 50 km of the study area follows a ‘u-shape’

4.7 Discussion

In this chapter I have reviewed the controls on catchment-scale bedload pulse dynamics by classifying each control as either intrinsic or extrinsic. I used an understanding of these controls to develop a conceptual model for bedload pulse dynamics in the Glenelg River, and to predict the pattern of sand storage that would arise.

A core element of the conceptual model was that when sediment is delivered to a sand-bed river with cohesive banks as a sustained ‘press’ disturbance, dispersion would dominate pulse behaviour at the segment scale (tens of kilometres). This type of response should be expressed in the mapping as a gradual decline in sand storage downstream from inputs, with local perturbations superimposed on transport reaches, sedimentation zones, tributary junctions and channel constrictions (the extrinsic controls). The distribution of sand storage within individual sedimentation zones should reflect a stalled wave, i.e. sand storage should show some combination of dispersion (a decrease in sand storage with distance downstream) with a localised peaks in storage superimposed if translation has taken place. This is not the pattern observed in the Glenelg River.

Instead, in-channel sediment storage does not systematically decrease downstream from tributary inputs. Sand storage *increases* with distance from tributary inputs (or in some cases remains elevated). Valley constrictions, rather than proximity to sediment sources, floodplain width or tributary junctions, are the dominant control on the catchment-scale pattern of sediment storage in the Glenelg River. Constrictions have broken the Glenelg River into a series of smaller compartments. Within the smaller compartments sand has accumulated as a wedge against the downstream constrictions. Sand storage abruptly declines immediately downstream of the constrictions before building steadily against the next constriction downstream.

I argue here that, by limiting sediment movement during floods, constrictions are the dominant control on bedload pulse dynamics in the Glenelg River. When sediment accumulates upstream of constrictions, the jerky, stochastic movement of sediment between compartments during floods resolves to a series of standing waves when viewed at the catchment scale, with the peak of waves coinciding with the channel constrictions.

I now consider the mechanism by which valley constrictions limit sediment movement, how floods control in-channel sediment stores within each of the compartments that the constrictions define, and the implications for the Glenelg River and conceptual models of bedload pulse dynamics more broadly

4.7.1 Valley constrictions and pulse dynamics

James (2006) identified that bed waves, which move along the channel, and sediment waves, which include floodplain storage and recruitment, are out-of-phase in most catchment-scale pulses. Bed waves pass more rapidly and are usually symmetrical in shape, while the larger sediment waves pass more slowly and exhibit long tails by recruiting stored sediment from floodplain storage (i.e. they are asymmetrical, positively skewed to the right with respect to time (James, 1989b)). Given that only in-channel sediment stores were mapped in this chapter, it is surprising that valley-scale constrictions, which dictate the accommodation space available for floodplain storage, have exerted such a strong influence on the pattern of sand accumulation in the Glenelg River. Most of the valley constrictions along the Glenelg River pinch off floodplain width abruptly, but only some constrict the bankfull width of the channel. At most constrictions the channel is not appreciably wider upstream or downstream (Figure 4.7).

The fact that floodplain constrictions are associated with in-channel sediment accumulation suggests that floods large enough to interact with valley topography drive bed wave movement in the Glenelg River. When floodwaters are forced through constrictions, the greater area of valley walls in contact with floodwaters exert more drag on the flow, which decreases flow velocity, which increases flow depth upstream of the constriction. The resulting backwater promotes deposition in the channel and on the adjacent floodplain.

This is surprising since floods are usually associated with the slower movement of the secular sediment waves, which include interaction with the floodplain. Deposition behind constriction-controlled backwaters have been documented within channels (Pasternack and Wyrick, 2017) and across floodplains (Thompson *et al.,* 2011). A similar phenomenon was modelled, but not mapped, by Czuba *et al.* (2017) who found that narrow reaches in the Greater Blue Earth River Basin in Minnesota acted as 'bottlenecks' to sand movement within the channel.

Flow regulation in the Glenelg River has decreased the frequency of smaller flows (bankfull and below) that re-work sediment deposited in-channel during the previous flood (Figure 4.8). The frequency of flows at or above 35 $m^3 s^{-1}$, approximately half of bankfull flow at Casterton and the discharge at which sand transport rate sharply increases (see Chapter 5 for details of the sediment transport modelling used to calculate this value), decreased ten-fold after regulation commenced in 1953 (from a 4 % exceedance to 0.4 % exceedance). Similarly, bankfull flow frequency (70 $m^3 s^{-1}$ at Casterton) decreased ten-fold following regulation (from 0.4 % exceedance to 0.05 % exceedance) (Figure 4.8).

These bankfull flows would usually slowly disperse bed waves downstream, and their absence means that the impact of the most recent flood is recorded in the pattern of in-channel sediment storage mapped in this chapter. Regulation has increased the dominance of floods on pulse dynamics by reducing lower flows. By significantly reducing the flows that modify the bed wave only, regulation ties the bed wave signal to that of the larger secular sediment wave. This suggests that floods are the dominant control of pulse dynamics in regulated rivers, in rivers with high discharge variability and in rivers where only floods generate bed shear stress sufficient to mobilise the median grain size of the migrating pulse.

Figure 4.8: Flow duration curve for the Glenelg River before and after regulation by Rocklands Reservoir, showing the decrease in sub-bankfull flows caused by the dam. The Fulham Bridge gauge (gauge number 238224) is 35 km downstream of the Balmoral gauge (gauge number 238201), which no longer operates. Data courtesy of Department of Land Water and Planning, Victorian State Government.

4.7.2 Pulse movement within uniform compartments

Sand coverage gradually declines downstream of constrictions. Examples include decreasing bed storage downstream of the constrictions in pulse behaviour zone one, and the steep decline in sand coverage downstream of constrictions within the second gorge (pulse behaviour zone 3 (Figure 4.3). The smooth downstream profile may be generated by the steady shedding from the downstream face of upstream deposits. This steady dispersion of sediment can be accomplished by bankfull flows, but will be most pronounced during floods when Froude numbers are high but sediment supply is limited by the constriction (Lisle *et al*., 2001; Humphries *et al.*, 2012).

Because floods drive most bed wave movement, the longitudinal pattern of sediment storage within a 'uniform' segment does not resemble a stalled wave. Instead, sediment storage increases in a downstream direction, forming a wedge against downstream valley constrictions. I propose that in addition to limiting sediment movement between compartments, floods rapidly shunt what sediment does enter a compartment downstream, where it accumulates behind the downstream constriction. In this manner sediment migrates within a pulse behaviour zone not as a slow-moving wave but as a rapid injection that builds sediment stores from downstream to upstream, like the filling of a bucket. This theory contrasts with the idea that sediment moves *within* uniform reaches as a migrating wave, adopting a characteristic period and amplitude according to reach morphology (Nicholas *et al.*, 1995; Benda and Dunne, 1997a; Gran and Czuba, 2017).

The increase in sand coverage upstream of constrictions also occurs within narrow gorges, which are transport reaches not storage zones. The narrow gorges may indeed be acting as transport reaches, storing little to no sediment on their small, intermittent floodplains, but what sediment does enter the gorges accumulates upstream of the constrictions nested within them. This trapping dynamic produces the increase in coverage (i.e. storage) when viewed from upstream to downstream.

4.7.3 The relative importance of extrinsic controls on bedload pulse dynamics

The arrangement of extrinsic controls along the Glenelg River, and valley constrictions in particular, is the dominant control on bedload pulse dynamics. Proximity to sediment sources (tributaries) and the arrangement of transport reaches and sedimentation zones, play a secondary role. This stands in contrast to the findings of Phillips (2010) who attributed only a third of all entropy in a fluvial system to extrinsic controls (where entropy is the total length of river impacted by a control), a third to intrinsic factors and a third to anthropogenic influences.

The importance of local-scale controls (constrictions directly impact tens to hundreds of metres of river) to larger scale patterns of sediment movement has been established in a number of rivers spanning a variety of sediment regimes (Ferguson *et al*., 2006; Fryirs, 2013; Rice, 2016; Czuba *et al.*, 2017; Gran and Czuba, 2017). The key difference here is that rather than producing a fractured and chaotic distribution of sediment at the catchment scale, extrinsic factors have given rise to a more periodic pattern of sediment storage that resembles a series of standing waves, their crests resting at valley constrictions.

4.7.4 Implications for how bedload pulses are conceptualised

Nicholas *et al.* (1995) conceptualised catchment-scale sediment pulse movement as the interaction of successive transport reaches and sedimentation zones. The two types of reach are coupled: transport through one reach drives sedimentation in the next (Church, 1983; Macklin and Lewin, 1989; Benda and Dunne, 1997a). In the Glenelg River the opposite appears to be true. Sand coverage increases within the narrow gorges (due to the constrictions) and then *falls* immediately downstream, right where sediment storage should increase. Overall the superposition of constrictions on reaches with high transport capacity restricts the sediment transport rate during floods, which starves downstream reaches and prevents sedimentation zones from developing.

The larger point here is that envisioning bedload pulse dynamics as a migrating wave, or a series of waves, may not be useful above the reach-scale. The 'jerky conveyor belt' analogy employed by Ferguson (1981) is more appropriate for scales larger than a single, uniform reach free of extrinsic controls. The intermittent movement of sediment through a network described by the 'jerky conveyor belt' analogy is now commonly explored using the language and concepts of sediment connectivity (Hooke, 2003; Fryirs *et al*., 2007; Croke *et al*., 2013; Fryirs, 2013; Thompson *et al.*, 2016; James, 2018). The Glenelg River exhibits longitudinal disconnection, but because floods drive most sediment transport, the system also exhibits a temporal element to disconnection. Using this language, the regulation of the Glenelg River by Rocklands Reservoir has diminished the kinds of in-channel flows that re-establish connectivity between catchment compartments (Thompson *et al.*, 2016), while increasing the relative importance of floods in driving pulse dynamics.

However, I propose that the wave analogy is a useful way to visualise the *distribution* of sediment that emerges at the catchment-scale. The peak and trough pattern that emerges from stochastic sediment movement, which occurs in a series of steps, resolves into a series of standing waves that are distributed along the Glenelg River: the peak of the waves lies upstream of the constrictions and the trough lies immediately downstream of the constrictions. Sediment supply (determined by the transport capacity at upstream constrictions) controls the amplitude and the period of the standing waves. The waves described here arise in a similar manner to standing waves on a mobile streambed: sediment is exchanged across the surface but the profile of the bedform is static. In the Glenelg River, local-scale valley constrictions combine with stochastic sediment movement (most of which occurs during floods) to produce a series of standing waves that exchange sediment through the catchment.

4.7.5 How the standing wave conceptualisation relates to other perspectives of bedload pulses

A key contribution of James (1989; 1999; 2006; 2010) was to carefully de-construct the wave analogy, and in doing so identify two types of bed waves at the catchment scale:

1. Gilbert waves, which are discontinuous along a river and are separate from the much larger sediment wave, which interacts with the floodplain; and
2. a wave-like signal generated by adjustment of channel grade as the river responds to an increase and then decrease in sediment supply.

The important distinction is between wave-like *movement* of coherent packets of sediment, originally implied by Gilbert (1917) (a phenomenon commonly observed at the reach scale (Andrews, 1979; Pickup *et al.*, 1983; Lisle *et al.*, 2001; Sutherland *et al.*, 2002; Venditti *et al.*, 2010; Morgan and Nelson, 2019)), and emergence of wave-like *signal* due to stochastic movement of sediment and the adoption of an at-a-station reference frame.

A wide body of work has since taken the concept of bed waves refined by James and applied either a Lagrangian or Euclidian reference frame. These studies have examined bed wave dynamics at increasing levels of complexity. In order of increasing complexity and spatial scale, examples include: how discrete inputs migrate through a reach (Lisle *et al.*, 2001; Sutherland *et al.*, 2002; Cui *et al.*, 2003b; Venditti *et al.*, 2010), how discrete inputs migrate through a network (Nicholas *et al.*, 1995; Benda and Dunne, 1997a; Rutherfurd, 2001; Gran and Czuba, 2017), prolonged inputs through a 'simple river' (Bartley and Rutherfurd, 2005b; Wilkinson *et al.*, 2006; Major *et al.*, 2012), prolonged inputs through a more complex river (Macklin and Lewin, 1989) or multiple inputs through a complex river (Knighton, 1989; 1991). The increase in complexity is matched with an increase in timescale from years to decades to centuries.

Each part of this wider body of research has viewed pulses in a slightly different way, and each has revealed important controls on pulse dynamics. For example, how reach structure influences pulse dispersion, how the arrangement of channels link controls, how long a discrete pulse takes to exit a catchment, and where in a catchment a bed wave is most likely to form. An important difference has emerged in the way pulses are conceptualised at different scales. At the reach scale wave analogies are most appropriate, whereas at the catchment scale pulses are thought of. These pulses are not so much discrete identities that migrate, but diffuse inputs that generate aggradational responses in some reaches and an elevated sediment flux in others.

The standing bed waves described in this chapter are an additional way of conceptualising bed waves at the catchment scale, where extrinsic controls are the dominant control on pulse dynamics. The standing wave analogy takes the insight that different reaches respond to bedload pulses with varying degrees of aggradation or increased sediment flux, incorporates the kinds of extrinsic controls that shape this response, and then borrows the concepts from the wave analogy to describe the pattern of sediment storage and sediment flux that arises.

Clearly not all bedload pulses will generate standing waves. The insight provided by the standing wave model is that when viewed at the catchment scale, bed waves can be considered not as a migrating entity that changes shape (or is destroyed entirely in gorges), but as the topographic expression of multiple interacting bed waves moving through a complex catchment. This standing wave pattern will be most pronounced in rivers with a high flow variability, where sediment is delivered as a prolonged press disturbance, and where structural elements of a catchment, such as gorges, constrictions or sharp breaks in slope, are abundant.

4.7.6 Implications for the management of bedload pulses in the Glenelg River

One motivation for exploring bedload pulse dynamics in the Glenelg River was that management interventions on this river were planned on the assumption that the pulses injected into the Glenelg River at tributary junctions migrate downstream as waves (Erskine, 1994; Rutherfurd, 2001; Brizga *et al.*, 2003; Bartley and Rutherfurd, 2005a; Clark *et al.*, 2013). Extracting sediment from the peak of the wave was predicted to flatten the wave by decreasing wave size and starving the leading edge of sediment. Manipulating the wave in this manner was predicted to accelerate the recovery of reaches at the wave peak and trailing edge, and to protect downstream reaches from sand ingress. The standing wave model proposed here suggests that the migrating wave model used to select sand extraction sites was inappropriate.

The standing wave model suggests that the peak of the wave is stationary and remains jammed against valley constrictions. In-stream extraction should therefore be concentrated immediately upstream of constrictions (at the ‘crest’ of the standing waves), rather than areas within the compartments where sediment stores are not replenished. Focusing extraction at constrictions has two main advantages: a) the sites will be regularly replenished with sediment during floods, and b) the downstream extent of extraction (bed and bank erosion) will be limited by the constrictions, which act as sediment bottlenecks. The standing wave model also suggests that the area immediately downstream of constrictions, which are relatively starved of sediment, are an inefficient place to extract sediment, due to lower sediment supply and greater potential for erosion by floodwaters starved of sediment by the upstream constriction.

The migrating wave paradigm was used to predict how bedload pulses will migrate through the Glenelg catchment in the coming decades. Assuming pulses behaved as migrating waves, should see a prolonged but steady decline in sediment stores from upstream to downstream. The pattern of persistent erosion would be interrupted by another pulse migrating into the recovering reaches, perhaps triggered by tributary reactivation when the bed of the trunk stream lowered (Erskine, 1994; Rutherfurd and Budahazy, 1996). The standing wave model proposed here predicts that pulse evacuation will instead occur in a series of steps, with the upstream wave crests. Like the migrating wave model, the decline in sediment supply from the catchment sets this stepped removal of sediment in motion. The difference is that unlike the gradual decline in sediment stores over a long distance (the trailing edge of the wave) upstream deposits must be depleted almost entirely, so little to no sediment recharges the next compartment downstream, before the next wave peak will begin to erode. The speed of this removal of sediment peaks is determined by flood frequency, the driver of bedload pulse dynamics in the Glenelg River.

Future research should focus on quantifying the size of backwaters induced by constrictions, the discharge at which backwaters begin to form, and the volume of sediment deposition they induce upstream of constrictions (both within the channel and as sediment is lost to floodplain storage). Post-flood LiDAR surveys and high-resolution dating of floodplain sediments coupled with hydraulic and sediment transport modelling are the most promising techniques available to pursue this avenue of research.

4.8 Conclusion

This chapter has presented a conceptual model for bedload pulse dynamics in the Glenelg River and a pool-mapping method that can be used to evaluate that model. The pool mapping method provides a catchment-wide view of in-channel sediment stores at a single point in time, several decades after sediment pulses first entered the Glenelg River. I categorised controls on pulse dynamics as either intrinsic, controls that are internal to the pulse itself, such as grain size and initial volume, or extrinsic, controls external to the pulse that influence pulse dynamics, such as tributary junctions, valley constrictions and interaction between reaches. The conceptual model predicted that the Glenelg River could be split into four pulse behaviour zones and that bedload pulses would disperse, merge, or accumulate within these zones, depending on the extrinsic controls present in each zone.

Both extrinsic controls and in-channel sediment storage were mapped along 234 km of the Glenelg River. The distribution of sand in the Glenelg River does not support the predictions of the conceptual model. Instead, sand storage is compartmentalised, and the compartments are at a much smaller scale than the four pulse behaviour zones proposed by the model. Compartments were bounded by constrictions, several of which abruptly narrowed the floodplain but not the channel.

The constrictions limit sediment movement during floods by generating backwater deposition zones immediately upstream. As a result of this mechanism, peaks in sand storage occur immediately upstream of constrictions, and troughs in sand storage occur immediately downstream of constrictions. Flow regulation has exacerbated the impact of floods by decreasing flows at or below bankfull by a factor of ten. Channel deposits are not dispersed downstream by sub-bankfull flows between floods. Within compartments sand accumulates against the downstream constriction, a pattern I argue arises when floodwaters quickly shunt available sediment to the downstream end of compartments. The accumulation of sand at the downstream end of compartments arises because the ratio of sediment supply to discharge drops dramatically at the upstream, supply-limited end of the compartment and pulse dispersion is promoted.

I propose that when viewed at the catchment scale, the stochastic movement of sediment between compartments of the Glenelg River resolve to a series of standing waves. Wave crests are static and lie immediately upstream of constrictions. Sediment is exchanged between wave crests during floods, so that the leading edge of the most downstream bedload pulse advances downstream. The standing wave analogy can be employed in catchments were extrinsic controls and a high discharge variability generate a variable pattern of sediment storage that persists over time, even as sediment flux remains elevated.

The standing wave model has two important implications for management of bedload pulses in the Glenelg River: 1) sand extraction should be focused on the wave crests upstream of constrictions, where extraction pits are readily replenished and the downstream consequences of extraction are limited by the constriction, and 2) upstream wave deposits must be depleted almost entirely before erosion proceeds to downstream reaches, unlike the gradual decline over a larger length of river predicted by the migrating wave model.

Chapter 5: In-stream extraction concepts and methods

5.1 Introduction

Chapter 2 identified the four ways managers can respond to pulses of bedload sediment in rivers. The most appropriate intervention (if any) will depend on the goals of managers, but this thesis focuses on interventions that aim to accelerate recovery. This chapter, and those that follow, considers whether in-stream extraction could be used to accelerate the recovery of rivers impacted by pulses of bedload sediment.

This chapter moves from the general case of bedload pulses in rivers, to that of in-stream extraction as an intervention that accelerates the recovery of sand-bed rivers impacted by those pulses. This chapter lays the groundwork for chapters 6 and 7 in three ways: by developing a conceptual model of in-stream extraction, describing the field site where the conceptual model will be evaluated and, finally, outlining the methods used to evaluate this conceptual model.

5.1.1 In-stream extraction as a tool to manage bedload pulses

Extraction of sand and gravel from streambeds is usually driven by commercial imperatives: extracted material is sold as an input to cement production or as aggregate for roads (Torres *et al*., 2017). Between 1900 and 2010 worldwide demand for sand increased twenty-three fold (Krausmann *et al*., 2017). Historically this demand was met by sand extraction from river beds, where clean, well-sorted sand that is better suited to concrete production than terrestrial sources, was easily accessible and its removal unregulated (Edwards, 2015). This led to the widespread over-extraction from rivers which has generated a suite of negative social consequences (Padmalal *et al*., 2014; Torres *et al*., 2017). These adverse impacts include increased social harm by criminal syndicates running illegal mining operations (Rege, 2016; Rege and Lavorgna, 2017), widespread ecological destruction and habitat loss (Sutherland *et al*., 2017) and a sharp decrease in sand supply to coasts, which has exacerbated erosion and susceptibility to rising sea levels (Anthony *et al*., 2015; Luo *et al*., 2007). Although sand is increasingly viewed as a global, common-pool resource, most sand is still extracted by small, independent operations that vary in sophistication.

Most studies documenting the geomorphic impacts of in-stream extraction have also focused on historic commercial over-extraction, usually in gravel bed rivers (Kondolf, 1994; Rinaldi *et al*., 2005; Padmalal *et al*., 2008b). In-stream extraction is also used as a management tool: to remove contaminated sediment (Melbourne Water (2019)), to mitigate aggradation when bedload pulses are delivered to the channel (for example to promote bed-degradation and maintain channel depths for navigation (Parker *et al*., 1996; James and Singer, 2008), to reduce the frequency and magnitude of overbank floods (Gob *et al*., 2005; Zinger *et al*., 2011; USACE, 2014) or to mitigate the impacts of sediment released from tailings dam failures (Hudson-Edwards *et al*., 2003; Garcia *et al*., 2016a).

In-stream extraction has also been identified as a way to accelerate the recovery of rivers impacted by a bedload pulse (by removing the cause of aggradation: excess sediment) (Wilkinson *et al*., 2006; Sims and Rutherfurd, 2017). When sediment supply declines (such as at the tail of a bedload pulse), sediment stored on the channel bed erodes, filled pools re-scour and channel recovery begins. The basic premise is that extraction reduces sediment supply, which drives bed degradation, pool scour and increased channel complexity, i.e. recovery.

Does in-stream extraction accelerate recovery? The answer depends on several related, but more specific questions: do sand-bed rivers respond to extraction differently than gravel bed rivers? How much sediment must be extracted? Where in a river should extraction take place? How, exactly, should sediment be removed from the channel? These are the questions stream managers face when deciding on whether to intervene by way of in-stream extraction, and they highlight a clear gap in our understanding of what management interventions can be used to accelerate recovery in rivers impacted by pulses of bedload sediment.

5.1.2 How is in-stream extraction approached in this thesis?

This thesis contributes to filling these gaps by examining how in-stream sand extraction impacts a sand-bed river experiencing bedload pulses in western Victoria, Australia, by way of three closely related chapters: Concepts and methods (this chapter), pit-scale results and discussion (Chapter 6) and reach-scale results and discussion (Chapter 7). Together the three extraction chapters consider whether extraction pits prevent sediment from moving into downstream reaches, how extraction pits impact channel morphology in the reaches they are extracted from, and how a series of extraction pits impact reaches upstream and downstream of the extraction site. The extraction chapters gradually increase in the scale they consider, from individual pits (tens to hundreds of metres), to several interacting pits (hundreds of metres to kilometres) to reaches downstream of extraction sites (up to tens of kilometres). By removing sediment from storage at the rate it is replenished in-stream extraction should function in a similar manner to sediment retention structures: sediment is trapped but discharge is unaffected.

This first task of this chapter is to use the literature to build a conceptual model that predicts how in-stream extraction could impact sand-bed rivers. Existing conceptual models describe the impacts of in-stream extraction in terms of the river's longitudinal profile only. The conceptual model I present in this chapter expands on existing two-dimensional models by including the complexity introduced by natural channels. Examples of complexity in sand bed rivers subject to pulses of bedload sediment include:

- sediment travelling in suspension which will either fill or bypass an extraction pit

- the repeated filling and re-excavation of different extraction pits in the sequence
- order-of-magnitude variation in flow and sediment supply during floods and droughts
- whether stock can access the river bed
- the impact of in-stream vegetation on sediment movement and channel morphology
- how these changes affect the overall movement of a bedload pulse.

The two results-oriented chapters that follow this chapter each consider a different spatial scale: a single extraction pit, and series of interacting extraction pits which impact the reaches downstream of extraction sites. This increase in spatial scale is mirrored by an increasing temporal scale: from years to decades. Each chapter begins with an evaluation of the pre-existing models (i.e. thalweg change) and then progressively adds the complexity found in a natural setting.

The extraction pits studied in these chapters are two to four metres deep, tens to hundreds of metres long and have been excavated in straight sections and from point bars. I have organised the extraction literature around three spatial scales; an individual extraction pit, a sequence of extraction pits and, the reaches upstream and downstream of extracted areas. The literature described herein comes from both the geomorphology and engineering approaches. It covers annual to decadal timescales and draws on three types of studies: flume studies, modelling studies and field studies.

5.2 In-stream extraction literature review

5.2.1 Filling of a single extraction pit

Three approaches have been used to study the evolution of a single extraction pit: flume experiments (Lee *et al*., 1993; Lee and Chen, 1996; Neyshabouri *et al*., 2002; Barman *et al*., 2018a), numerical modelling (Cao and Pender, 2004; Chen, 2005; Gill, 1994) and more recently, field studies in natural channels (Owen *et al*., 2012; Yuill *et al*., 2016). Each of these approaches is considered in more detail below.

5.2.1.1 Flume studies

The behaviour of single extraction pits has been investigated by monitoring the filling of pits excavated in straight channels of experimental flumes. The data generated by these flume studies was then used to derive empirical equations that describe pit behaviour under a steady flow. Engineers use these models to predict how quickly a pit of given dimensions, subject to steady flow, will re-fill, and whether the resulting scour poses a risk to downstream infrastructure.

Overall, extraction pits excavated in uniform sediment progressively fill from their upstream end. At the same time, pits erode at their downstream ends, which develop a characteristic scour profile (Lee *et al*., 1993). The filling process occurs in two periods: a convective period where the upstream end of the pit translates downstream to meet the original tail of the pit and then a diffusive stage, where the pit begins to shallow and migrate downstream. During both stages the bed immediately downstream of the pit erodes (Figure 5.1).

Bed degradation immediately upstream of the extraction pit was observed by Lee *et al*. (1993) and Neyshabouri *et al*. (2002), but did not occur when sediment supply was held constant at the upstream end of the flume experiments of Barman *et al*. (2018a). In all flume experiments (and the modelling studies that use them for calibration) flow was sub-critical, sediment was uniform in size and pits were not big enough to alter the overall energy slope of the reach the pit was excavated from. While different equations have been derived to describe this behaviour, the filling sequence and overall pit behaviour is consistent between studies.

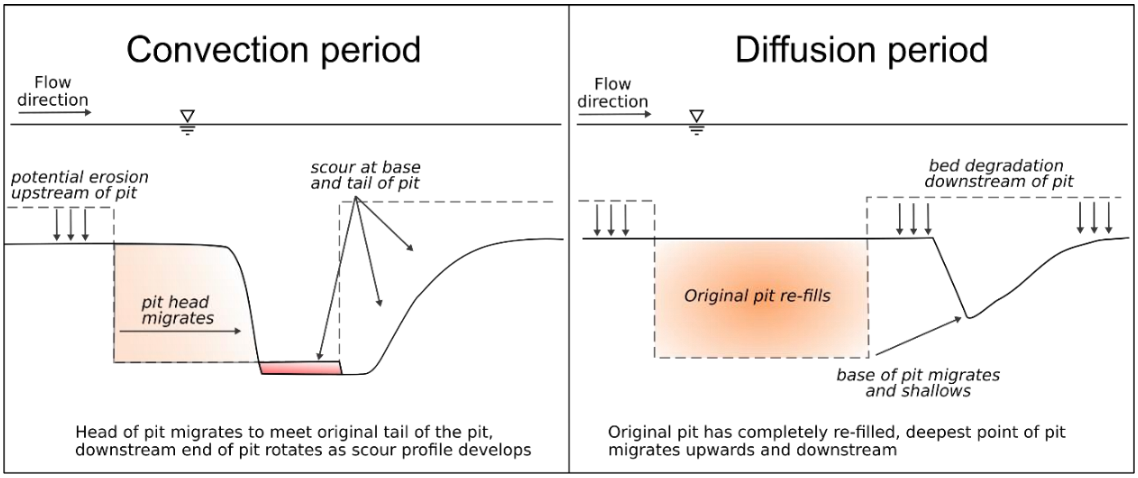


Figure 5.1: A summary of the pit evolution model proposed by Lee *et al.* (1993) illustrating the convection and diffusion periods.

More recent experiments (Barman *et al*., 2017; Barman *et al*., 2018a; Barman *et al*., 2018b; Barman *et al*., 2019) have focused on measuring the hydraulic processes responsible for driving sediment movement in and around extraction pits. These flume studies document velocity reversal at the base of the pit, and increased turbulence driving increased bedload transport rates in, and downstream of, rectangular pits. Barman *et al*. (2018a) used cross-sections across the width of the experimental pits to show that the walls of the pit quickly collapse, but that the entire width of the bed is re-buried as the upstream end of the pit advances. These more recent experiments help explain why flume pits evolve as they do, but do not alter the overall conceptual model describing how the pits migrate and change shape (Figure 5.1).

5.2.1.2 Modelling studies

The empirical models used to explain flume experiments are one-dimensional: they do not consider how bed scour and sediment deposition are distributed across the width of the river, or how an extracted point bar (either alone or as part of a larger extraction pit) recovers with time.

Gill (1994) derived a purely theoretical solution to describe how trapezoidal mining pits migrate in a flume. But the model ignored suspended load, held discharge constant, assumed an infinitely long channel and predicts essentially the same behaviour for a single pit as earlier experiments.

Barman *et al*. (2018b) modelled the evolution of a single extraction pit by coupling several different bedload-only sediment transport equations to the Exner equation. The Exner (1925) equation describes sediment mass balance and relates changes in bed elevation per unit time to sediment flux. The simplest form of the equation can be written as:

$$\frac{\partial \eta}{\partial t} = -A\frac{\partial U}{\partial x}$$

Where η is bed elevation relative to some fixed datum, t is time, A is a coefficient, U is average flow velocity but is commonly replaced with sediment flux term, and x is downstream distance (Paola and Voller, 2005).

Model performance was evaluated by comparing the predicted pattern of erosion and deposition at different timesteps with that measured in a flume. The van Rijn (1986) transport formula showed closest agreement with measured bed profiles, but modelled profiles were more sensitive to the transport formula chosen than to the size of the pit. Although this model was implemented in two-dimensions, only longitudinal profiles were presented and there was no mention of the cross-channel deposition or erosion.

Chen *et al*. (2010) used the data of Lee *et al*. (1993) to undertake a sensitivity analysis for the non-equilibrium adaptation length, L (the distance over the streambed that flow transitions from below full sediment transport capacity to full sediment transport capacity) and α (the ratio between near bed and depth averaged sediment concentration). Sediment transport, deposition and erosion were simulated using the CCHE2D a two-dimensional, depth-averaged hydrodynamic and sediment transport model (Wu, 2001).

The key findings of this research were that larger values of L and α (a ‘super-non-equilibrium model’ where the sediment transport is very slow to adjust to changes in the flow field) generates a pit head that slopes too gently in the convection period, and a base that migrates upwards too slowly in the diffusion period. Very low values of L and α (essentially an equilibrium model) over-estimated scour at the base of the pit but made little difference to bed scour upstream and downstream of the pit. No equations to scale these adaptation parameters to natural rivers (where the value of L and α vary by several orders of magnitude and are not constant with time) were provided. Given that equilibrium models still capture the essential behaviour of extraction pits (Lee *et al*., 1993; Lee and Chen, 1996; Barman *et al*., 2018b), introducing non-equilibrium parameters may be needlessly complicating modelling of natural channels.

The above studies all consider pit evolution in flumes. Chen (2005) implemented CCHE2D using the non-equilibrium sediment transport formula of Yang (1984) (where L

was set to 1000 m and α was set to 1) to evaluate whether a large extraction pit excavated from a gravel bed river in Phoenix, Arizona would reduce flood levels. The pits had little impact on the overall depth and extent of flood flows. Although the model predicted most sediment would deposit in the upstream end of the extraction pit, and that erosion downstream of the pit would be the dominant channel response, it only simulated a single flow (a 500 year flood event). A more detailed analysis of the advantages of using a non-equilibrium model was not provided, and the results were essentially hydrodynamic, not morphodynamic, in focus.

The modelling studies described above re-produce flume results well, and two-dimensional depth-averaged modelling across a large area has been shown to be feasible. The challenge lies in relating the very detailed, single-pit models, which are mostly empirical, to the much larger scale, and more complex natural channels that this thesis is investigating. The modelling work reviewed here has shown that for sand-bed rivers, van Rijn's (1984) physics-based sediment transport formulations coupled with a depth-averaged two-dimensional model should be capable of capturing enough channel complexity to be realistic, but simple enough to implement over several kilometres. I now turn to studies that have considered the more complicated example of a single extraction pit in natural channels.

5.2.1.3 Natural channel case studies

Most 'real world' pit-monitoring studies concentrate on oceanic mining pits and how they affect the surrounding seabed (van Rijn, 1987). Within the more limited literature on extraction pits in natural river channels, the common practice of point bar removal, or point bar skimming (removing the surface layer but leaving the core of the point bar intact) has received even less attention. The published studies based on natural channels document a more complicated pattern of infill and pit migration than the simple laboratory experiments suggest.

Yuill *et al*. (2016) monitored the evolution of a large (1400 m long, 200 m wide) borrow pit excavated from a lateral bar in the in the lower Mississippi River over a two-and-a-half-year period. The pit extended over less than a third of the total channel width. The upstream end of the pit migrated downstream as models predict, but sediment accumulation on the bed of the pit was much more variable and included sets of migrating dunes. Importantly, not all incoming sediment was trapped in the borrow pit. As much as 70 % of the sediment was routed around the true-left of the pit, via the channel thalweg, and the trap efficiency of the pit decreased as it filled (from eleven percent of total sediment transport through the reach in the first six months post-dredging, to five percent in the final six months of monitoring). Hydraulic modelling found that a twenty percent reduction in velocity post-extraction, and reductions in bed shear stress (with deeper sections showing a greater shear stress reduction), explained the pattern of infill. They also found the rate and pattern of infill to be strongly dependent on local sediment supply and flow regime. For example, the pit scoured during a high flow event with a steep rising limb but showed little fill during an event with a more subdued hydrograph.

Gob *et al*. (2005) monitored an 800 m long dredge pit excavated from the bedrock-confined channel of the Semois River, Belgium. Repeat cross-section surveys revealed that after four years (which included five floods large enough to fully mobilise the median bed grain size) pit infill was incomplete. The pit did not migrate downstream, instead filling vertically from the base of the pit upwards, with deep sections between bedrock outcrops aggrading the most. Moreover, material was laterally re-distributed within the pit (from elevated benches into the deeper, dredged thalweg).

Owen *et al*. (2012) studied excavation of sand and gravel from behind a low-water dam and skimming of a nearby point bar in the Big River, Missouri, nine months following extraction. The pool behind the sediment retention dam filled from the upstream end, but the point bar failed to aggrade to its pre-skimming level. Importantly, both reaches that contain the extraction sites showed net sediment export during a 10-year flood event. The downstream portion of the point bar also scoured. In this case, the type and magnitude of deposition and/or scour triggered by extraction depends where in the channel extraction occurs. On straight sections scour is distributed according thalweg path, which often meanders across the channel bed and deepens a low-flow channel. When sediment is removed from the surface of a point bar scour is concentrated at the downstream end of the point bar – where the decrease in sediment exchange across the point bar is most acute.

Rempel and Church (2009) studied the impact of skimming 69,000 m^3 of sand and gravel from a large bar in the Fraser River, Canada. They found that thirty percent of the extracted gravel was replenished during a single above-average flood, and no material was replenished by two below-average floods. However, the volume of material excavated was an order of magnitude lower than that estimated to make any appreciable impact on water gradient or sediment transfer through the reach. Changes in the upstream and downstream reaches were not evaluated.

These studies show that several assumptions about how extraction pits behave, as discussed in the conceptual model outlined in section 5.2.1.1, do not hold true in these natural channels. Re-filling of an extraction pit or aggradation across a point bar is irregular and depends on local sediment supply (which is unsteady). Extraction pits and point bars do not always trap all incoming sediment - some material either by-passes the pit or bar, and some material is temporarily stored in the pit or on the bar surface, before being re-scoured and flushed downstream. The mechanism responsible for incomplete filling will differ between straight channel sections and curved channel segments. Overall, variation in the style and rate of infill arise when extraction is superimposed on the existing pattern of sediment transport in natural channels.

5.2.1.4 Next steps to advance understanding of pit behaviour

Many of the natural channel case studies are from large rivers (tens to hundreds of metres wide, tens of metres deep) or gravel bed rivers with mixed grain sizes and surface armouring. There is a distinct gap in studies that consider extraction from discrete pits and point bars in 'medium' sized (tens of metres wide) sand-bed rivers, and especially in sand-bed rivers experiencing a pulse of bedload sediment. These studies do not address if and how a stochastic flow series and intermittent sediment delivery have on the pattern or rate of pit infill. Furthermore, the studies only consider the behaviour of a single pit excavated once. How, for example, would a series of extraction pits, which re-fill and are then then re-excavated multiple times, interact with one-another and with the surrounding streambed? What effect would these interactions have on the morphology of the river, and the stability of the channel and their suitability as a tool to accelerate recovery form bedload pulses? I now draw from the wider literature examining how sediment deficit drive geomorphic change to consider these questions.

5.3 Theory of the interaction of extraction pits

If extraction pits trap 100 percent of incoming sediment, then the most useful way of conceptualising the filling of a series of pits is as a series of check dams placed along a river. Like extraction pits that are excavated, re-filled and then are re-excavated, check dams usually trap most, if not all, of the sediment supplied to them. Extraction pits pass sediment downstream once they have re-filled (or have almost re-filled) and check dams pass sediment downstream during floods that swamp them (Boix-Fayos *et al.*, 2007; Fortugno *et al*., 2017).

Unlike a check dam, single-pit experiments illustrate that the geometry and location of a filling pit is not static. As a pit fills, migrates and changes shape the downstream bed adjusts. This adjustment means the erosion caused by one pit can alter the boundary conditions of the next pit downstream. Gill (1994) developed an analytical model to predict how two pits would interact. Ignoring the role of suspended sediment, and holding discharge and sediment supply constant, the modelling predicted that both pits begin to fill and migrate *at the same time*. While upstream pits may prevent incoming bedload from reaching downstream pits, sediment scoured from the intervening streambed begins to fill the downstream pit, and initiate pit migration.

The intervening bed between the two extraction pits is an adjustment zone (as described in the non-equilibrium transport model of Phillips and Sutherland (1989)), where the river entrains sediment to overcome the deficit induced by the upstream pit. When the length of this adjustment zone is greater than the spacing between pits, the two pits are coupled and interact. When the length of the adjustment zone is much shorter than the spacing between pits, flow returns to full capacity before meeting the next pit downstream and the two pits behave independently.

When additional pits are added to the river, they increase the magnitude of the sediment deficit passed downstream. As a result, the sediment deficit imposed on downstream reaches grows with the number of extracting pits excavated. As the magnitude of the sediment deficit grows in a downstream direction, so does the intensity of bed scour and channel adjustment. From the standpoint of downstream reaches, a sequence of extraction pits behaves as if they were a single, large extraction pit. The more pits in a sequence, and the closer they are spaced together, the greater the 'size' of this single, hypothetical pit.

I now consider what the impact of this sequence of extraction pits will have on downstream reaches.

5.3.1 Reach-scale impacts of in-stream extraction

The pattern of bed scour downstream of a sediment deficit has been examined in several contexts. For example, in reaches downstream of check dams in Mediterranean streams (Bombino *et al*., 2006; Boix-Fayos *et al*., 2007; Preciso *et al*., 2012), downstream of gravel mining in large gravel bed rivers (Galay, 1983; Kondolf, 1994; Martin-Vide *et al*., 2010; Rinaldi *et al*., 2005; Rovira *et al*., 2005) and in reaches downstream of hydroelectric dams (Petts, 1979b; Galay, 1983; Benn and Erskine, 1994). As well as the increased spatial scale of these studies (entire reaches cf. individual pits) there is also a step-change in timescale. These studies consider reaches that have been wholly or partially starved of sediment by repeat phases of extraction in upstream areas, often over several decades. Reach-scale impacts of extraction have been documented both upstream and downstream of extraction sites.

Studies conceptualising how extraction impacts natural channels have traditionally been two-dimensional and emphasise change in longitudinal profile. I build upon these more simplistic models by developing a conceptual model for the upstream and downstream reaches that considers how extraction will impact channel morphology (pool and riffle sequences, channel benches and bars), cross-section shape and overall river planform. This increased level of detail is appropriate for the scale of in-stream habitat, such as pools and riffles, which are regularly targeted for restoration.

5.3.2 Downstream impacts of extraction

Sediment-starved reaches tend to erode their bed and banks. The larger the sediment deficit, the greater the erosional response. This erosion can significantly change the morphology of reaches downstream of extraction sites. Modelling studies have found that if sediment supply remains elevated, aggradation will resume once extraction ceases (Cao and Pender, 2004).

5.3.2.1 Change in longitudinal profile

Analysis of repeat channel cross sections and specific gauge records (Rinaldi, 2003) downstream of extraction sites shows that the rate and magnitude of incision is greatest immediately below extraction reaches and that incision progresses in a downstream direction, gradually diminishing in intensity (Cao and Pender, 2004; Davis *et al.*, 2000; Galay, 1983; Martin-Vide *et al*., 2010). This longitudinal scour profile is well described by a simple diffusion model, where degradation decreases exponentially with distance from extraction sites (Simon, 1989; Martin-Vide *et al*., 2010; Li and Qi, 2015). As incision progresses downstream it triggers adjustments in channel morphology: erosion at the toe of banks drives slumping (Kondolf, 1994; Rinaldi *et al*., 2005), channel contraction (Erskine, 1996; Hoyle *et al*., 2008), increased abundance of vegetated bars (Calle *et al*., 2017) armouring in gravel bed rivers (Kondolf, 1997), and nickpoint migration in adjoining tributaries (Kondolf, 1994).

Incision caused by extraction can initiate feedbacks between morphology and sediment transport. Martin-Vide *et al.* (2010) documented up to five metres of extraction-driven incision following 26 years of gravel extraction in the Gállego River, Spain. The deepening and widening of the low flow-channel meant that it contained much larger flows, which increased bed shear stress and sediment transport capacity. This higher-capacity channel eroded over 2 million m^3 of sediment, more than twice the original volume of gravel extracted.

Most of the studies considering the impacts of extraction in aggrading reaches have been undertaken in large, gravel bed rivers where dredging is used to maintain navigable water depths over several kilometres (OTML, 2014; USACE, 2014). Cao and Pender (2004) used a one-dimensional hydraulic and sediment transport model to predict how extraction in an aggrading river would perturb a river's longitudinal profile over hundreds of kilometres downstream of a large extraction site. This study predicted that bed profile would recover smoothly, with scour decreasing at an exponential rate with distance downstream from the extraction site. In this sense, the scour profile resembles that of the much smaller-scale erosion immediately downstream of an extraction pit. Whether this larger-scale exponential scour-profile develops in downstream reaches depends on whether sediment supply is restored between phases of extraction, or whether successive phases of extraction are more rapid, and the downstream impacts compound.

5.3.2.2 Impact on channel form

How will channel forms such as pool and riffle sequences, bars and benches respond to the decrease in sediment supply caused by extraction? Most research considering how bed structure responds to a decrease in sediment supply after an initial aggradation phase considers gravel bed rivers, where bed armouring and grain-size effects exert a dominant control on riffle elevation (Lisle, 1982; Lisle and Hilton, 1992; Kelsey *et al*., 1993; Madej *et al*., 2009) or bedrock constrictions drive pool scour (Wohl and Cenderelli, 2000; Cui *et al*., 2008). Of the research considering how ephemeral, mixed sand and gravel bed streams have responded to a decrease in sediment supply, most have focused on larger scale changes such as channel contraction and incision over several kilometres (Surian and Rinaldi, 2003; Boix-Fayos *et al*., 2007; Boix-Fayos *et al.*, 2008; Calle *et al*., 2017), or consider the tail of a bedload pulse where the decline in sediment supply is much more gradual (for examples see Fryirs and Brierley, 2016).

Sand-bed channels with cohesive banks, such as the Glenelg River, preferentially adjust bed elevation in response to a change in sediment supply (Simon and Darby, 1997). The greater the sediment deficit, the greater the decrease in overall slope (Mackin, 1948). I argue that how this decrease in slope manifests downstream of extraction sites depends on the two axes of adjustment:

1. The relative dominance of low-flows – which eliminate bed relief and smooth the channel, vs. high-flows, which promote channel-scale flow patterns that organise sediment into rhythmic features and promote bed relief.

2. The cumulative sediment deficit imposed. Pits sequenced along a river will progressively increase the sediment deficit from upstream to downstream

5.3.2.3 Flow regime

During low-flows (well below bankfull) unconsolidated sand is easily stripped from riffles and deposited in pools (Lisle, 1982; Thompson, 2006). This pushes the low-flow channel towards a plane bed configuration with little relief. This featureless low-flow channel will gradually incise and begin to meander. During high-flows (bankfull) secondary circulation cells are strong enough to scour new pools on meander bends and at channel constrictions. Sand entrained from these depressions will either re-fill pools on the falling arm of the hydrograph or be organised into migrating bars on the streambed. If these bars have low relief, they will be re-worked by subsequent low-flows and the process repeats. If the bars are high relief, low-flows will divert around them, causing the low-flow channel to meander.

The excess flow energy at bankfull flow exacerbates scour on elevated parts of the channel such as bar heads, bar tails and cut-off channels (Bridge, 1993). Where pools have persisted in the bed (they were not originally filled by the bedload pulse) they may elongate or simply be maintained.

The prevalence of pool and riffle sequences, and the stability of bars and benches is the net outcome of the interaction between these two class of flows. Low flows generating a flat, featureless bed and high flows promoting pool scour and deposition on bar tops, which increases bed relief over time. The longer the sediment deficit persists, the longer the downstream reach that is impacted.

5.3.2.4 Magnitude of sediment deficit

Adding additional extraction pits to a sequence of pits along a river will progressively increase the magnitude of the sediment deficit. This is synonymous with increasing the size of the hypothetical ‘single upstream pit’. The impact is an increase in the incision rate from upstream to downstream. I argue that as this sediment deficit grows, the role of flow variation, which can re-work bed sediment and smooth the bed, is overwhelmed by the increasing tendency for the river to incise downstream of extraction pits. This larger (more prolonged) deficit will also promote scour on bars and benches. The result of this accelerated incision is an increase in bed relief from upstream to downstream as a low-flow channel cuts a path between bars and benches that are being rapidly abandoned.

5.3.2.5 Additional complexity

The above model assumes flows re-work well-sorted sand that is easily mobilised. However, superimposed on this overall pattern of adjustment are roughness elements that resist scour and initiate riffles in the channel. For example, when coarse bed material was exposed by erosion downstream of sediment control weirs in the Widden Brook, NSW a pool and riffle sequence formed (Keene *et al.*, 2008). Other features that either increase roughness, such as in-stream wood, or promote aggradation, such as local zones of cohesive sediment or in-stream vegetation, may also be enough to initiate pool-riffle sequences. These elements introduce local perturbations to the overall trend described above. I now consider how in-stream vegetation complicates a rivers response to extraction.

5.3.2.6 Role of vegetation

So far, this model has considered how pool-riffle units will respond to flows in reaches downstream of extraction, and how these changes are expressed in cross-section. In-stream vegetation introduces additional complexity to this pattern of channel response. As the low-flow channel incises, bars and benches are progressively abandoned and colonised by vegetation (Calle *et al.*, 2017; Erskine *et al.*, 2012; Kondolf *et al.*, 2002; Rinaldi *et al*., 2005; Surian and Rinaldi, 2003). As vegetation encroaches into the channel it does three things: increases roughness on vegetated features which promotes deposition (Steiger *et al*., 2001; Corenblit *et al*., 2007; Gurnell, 2014), shields vegetated surfaces from scour which locks sediment into storage (Corenblit *et al.*, 2007), and diverts flow, which shifts the pattern of velocity and turbulence in the channel (Follett and Nepf, 2012; Meire *et al*., 2014; Ortiz *et al.*, 2013; Yang *et al.*, 2016).

Trapping and storing sediment along the margins of the channel means that sediment-starved flows are unable to entrain the sediment and close the sediment deficit. By limiting the volume of sediment eroded per river metre, vegetation increases the length of river adjusting to upstream extraction, and therefore the total length of river impacted by extraction.

Many studies have described how vegetation promotes channel contraction in sediment-starved reaches, or how vegetation stabilises islands and builds new floodplains (Gurnell *et al.*, 2001). However, the interaction between in-stream vegetation and extraction pit themselves has not been studied. The lack of information regarding how in-stream vegetation will influence pit evolution is a clear gap in the extraction literature. Two related questions need to be addressed to fill this gap:

1. Can vegetation establish and persist upstream of extraction sites, on the margins of extraction pits and immediately downstream of extraction pits?
2. If vegetation can establish, how will the stands alter flow hydraulics, sediment movement and pit infill?

So far, this review has focused on the downstream impacts of extraction. I now turn to the upstream impacts of extraction.

5.3.3 Upstream impacts of extraction

Extraction can cause bed degradation in reaches upstream of the extraction site. Several studies have identified migrating nickpoints immediately upstream of extraction sites, which rotate into broader ‘nickzones’ in non-cohesive sediment (Kondolf, 1997, 1994; Wishart *et al*., 2008). While a similar process occurs at the collapsing head of single extraction pits, at the larger scale the nickpoint is generated by an increase in the overall bed slope. This increase in overall bed slope is caused by either a large extraction zone that alters the overlying water slope, or as a feedback mechanism when downstream-progressing erosion lowers the streambed enough to increase the bed energy slope in upstream reaches. These reaches then adjust their profile by way of an upstream-progressing nickpoint (Martin-Vide *et al*., 2010).

In-stream extraction almost always generates a migrating nickpoint, but some studies find no evidence for migrating nickpoints upstream of extraction sites. Wishart *et al.* (2008) found no evidence of upstream-progressing erosion above extraction pits in a wandering gravel bed river in England (but did document a nickpoint at another extraction site). This study attributed the lack of nickpoint development to the extraction technique used, which left a carefully graded river bed after excavation. This also suggests that the technique of extraction could influence erosion patterns (Wishart *et al.*, 2008).

Migrating nickpoints are similar to downstream impact of extraction in that they drive incision, albeit in a more episodic manner- nickpoints often remain stationary during low flows then migrate long distances in a short period of time during higher flows (Germanoski and Ritter, 1988; Erskine, 1996). The episodic movement of nickpoint generates a pulsing of sediment supply to downstream reaches (Schumm *et al*., 1984).

Overall, the number of studies that document nickpoint migration upstream of extraction sites far outnumbers those which document no nickpoint, or only consider downstream impacts. However, most studies that document upstream progressing incision have been in large rivers with wide, deep, extraction zones repeatedly excavated over decades. There is still uncertainty as to whether extraction from smaller, discrete extraction pits in medium sized rivers generates upstream-progressing incision.

Regardless of whether incision progresses upstream or downstream, bed level lowering will drive adjustment in tributaries.

5.3.3.1 Tributary interaction

As nickpoints migrate upstream, they lower the local base level of adjoining tributaries, which respond by generating their own nickpoints that migrate up the tributary (Schumm, 1973; Smith *et al*., 2009). Tributary nickpoints may be clearly expressed in long-profile (Bressan *et al*., 2014), rotate into broad nickzones (Rutherfurd and Budahazy, 1996) or develop at natural grade controls such as tree roots (Germanoski and Ritter, 1988) or bedrock ledges. Whether nickpoints develop, then migrate and flush additional sediment into the trunk stream depends on the substrate of the tributary channel (armoured vs exposed, and the stream power available to drive incision (i.e. tributary catchment area).

5.3.4 Conceptual model summary

From the above review I develop two conceptual models of channel change following extraction. The proposed conceptual models relate to two scenarios: a single pit, and multiple pits at the reach scale (Figure 5.2). The scenarios build in complexity, increasing in scale and duration. The jump in scale, between a single pit and multiple pits, is also a conceptual leap. The single pit case is a single 'fill-cycle', which may be repeated, the multiple-pit scale assumes repeated phases of in-stream extraction and predicts the cumulative change in surrounding reaches. Each scenario is summarised below.

This conceptual model represents the current state of the literature. It brings together studies at multiple scales, undertaken in different types of rivers (or flumes), with varying degrees of human interventions superimposed. The model also adds a new element not previously considered in the literature: the interaction of a sequence of extraction pits.

5.3.4.1 How a single pit will behave

A single extraction pit spanning the width of the channel traps all incoming bed sediment, filling from its upstream end. The fill-rate is proportional to the sediment supplied to the pit, which will vary with discharge. The re-filling causes the pit to change shape and migrate downstream in two periods: the convection period, where the pit head migrates and the downstream end rotates; and the diffusion period, where the remaining pit migrates downstream and shallows.

When a single pit is extracted multiple times, and the flows that supply sediment are stochastic, pit re-fill will not be steady and uniform. This is the biggest difference between the flume studies and natural channels. Once the extraction pit has completely re-filled, and assuming it is not extracted again, the bed discontinuity is smoothed from the river's longitudinal profile and the sediment deficit is closed (Figure 5.1). If the pit is extracted immediately after filling, then the downstream scour profile will continue to develop, generating a deeper, longer scour profile that has the same overall shape as the 'single-phase' scenario.

5.3.4.2 Interacting extraction pits at the reach scale

A sequence of closely spaced pits will interact, with the scour downstream of one pit filling the next pit downstream. When several extraction pits are excavated from the bed at the same time they interact. Each pit re-fills just as a single pit would, but the streambed between the pits erodes, coupling the two pits. The closer the pits, or the less stored sediment available between the two pits, the stronger the coupling of the two pits. When pits are excavated a long way apart (intervening bed >> adjustment distance) they behave as independent pits. This interaction means at the reach scale, a sequence of extraction pits behaves as a single, larger pit. The impact of a sequence of extraction pits is cumulative: the more pits excavated in a sequence the greater the sediment deficit imposed on downstream reaches. Repeated phases of extraction, from a single pit or a sequence of pits also prolong the sediment deficit.

A complicated space for time substitution can be used to predict the recovery pattern along the reach. The streambed immediately downstream of a single extraction site, where the sediment deficit is greatest and scour is concentrated, is destabilised and may not move along its recovery trajectory until extraction ceases. At the same time, a sequence of pits causes the sediment deficit to accumulate in a downstream direction. In the case of several pits spaced along a reach, downstream reaches will be further along the recovery trajectory than upstream segments, since they have been starved of the most sediment for the longest period. The net result is a trend of increasing 'recovery' in a downstream direction, with localised decreases in recovery superimposed at the tail of extraction pits.

This pattern of recovery also assumes all pits are extracted at once. In reality, re-fill is stochastic, pits are repeatedly extracted and the specific sequence of extraction (i.e. which pits are extracted in what order) will dictate how pits interact. This adds an additional layer of complexity but the basic principles of the multi-pit model (pit coupling, accumulating sediment deficit) hold no matter the specific order of extraction.

5.3.4.3 How extraction impacts upstream and downstream reaches

The downstream bed erodes, and the morphology that develops depends on the frequency of low-flows that smooth the bed, and bankfull and above flows that mobilise sediment, promote scour and generate bed relief. The erosion also drives channel contraction and bank erosion. In-stream vegetation colonises bars and benches, which aids channel contraction and locks sediment into storage. The net effect of vegetation is to decrease the availability of sediment along the river, which increases the length of river in sediment deficit. It is in this downstream area of adjustment that stream managers hope to accelerate channel recovery.

Extraction can cause a nickpoint to migrate upstream. Whether or not a nickpoint is generated depends on the methods of extraction and whether extraction increases the overall energy slope of the river. Upstream-progressing incision becomes more likely over time, as downstream bed degradation increases overall energy slope.

The changes in reach morphology are complicated by the pre-existing pattern of sediment transport, which includes the movement of sediment between bars, around bends, interactions with tributaries, and the role of in-stream vegetation.

5.3.4.3.1 Sinuous channels

Point bars, lateral bars and mid-channel bars are sites of deposition, and sediment is transferred between these stores by stochastic flows. Extraction drives erosion which is expressed as scour at the head and tail of point bars, or the development of cut-off channels against the bank side of point bars and benches. Areas of flow concentration, such as the outside of meander bends or at channel constrictions, will deepen and if the decrease in sediment supply is prolonged, pools may develop at these sites. The tendency for scour zones to deepen can be counteracted by the tendency for low flows to deposit sediment in depressions, smoothing the bed. Like all aspects of channel adjustment, the stochastic nature of flows will determine how exactly bed relief evolves in response to extraction.

5.3.4.3.2 Extraction and vegetation

Vegetation promotes channel contraction by stabilising bars, islands and benches. The tendency for vegetation to lock sediment into storage also increases the length of river over which channel adjustments take place. Vegetation increases the length of river impacted by reducing the availability of sediment to close the deficit caused by extraction. In cross-section, vegetation should lead to greater bed relief

5.3.4.3.3 Tributary interactions

When tributaries intersect an extraction reach, bed degradation in the trunk stream can promote incision in the tributaries. Tributary incision may occur as a migrating nickpoint, a smooth increase in slope, or if the channel bed is highly resistant, little incision may occur at all (a ‘hanging’ tributary). Tributary incision may also increase sediment delivery to the extraction reach. Sediment delivery may be delivered as a series of pulses (each pulse driven by a period of rapid nickpoint migration). The net effect of tributary incision is to increase sediment supply, which decreases the sediment deficit caused by extraction. The spacing of tributaries in relation to extraction pits will have a strong impact on how sediment injections affect bed level.

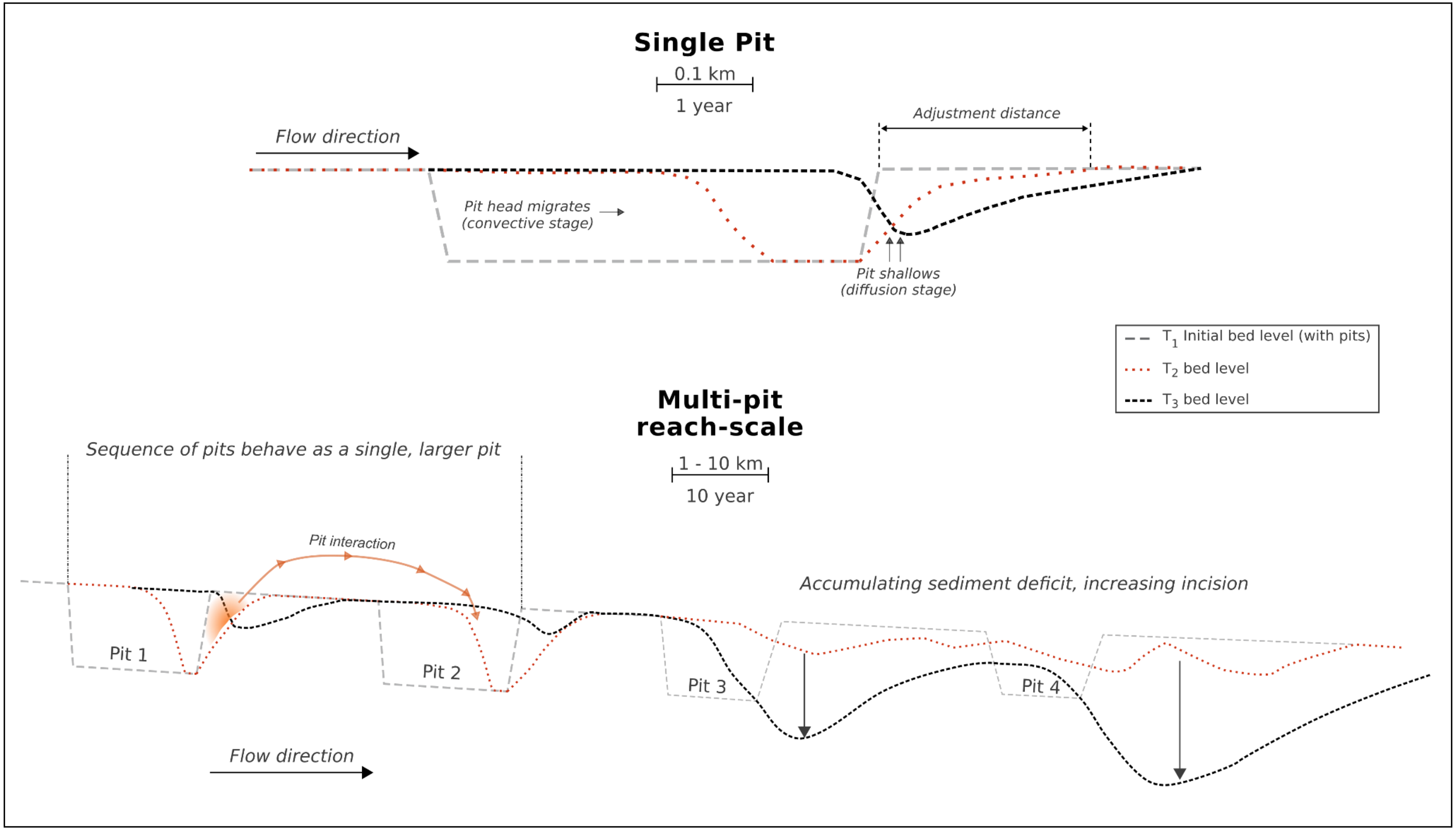


Figure 5.2: Summary of the proposed conceptual model for the evolution of a single extraction pit and the interaction of multiple pits at the reach-scale when pits are repeatedly extracted. T_1 T_2 and T_3 represent sequential time steps.

5.3.4.4 How recovery is defined in this chapter

How do the channel changes predicted by the conceptual model relate to channel recovery? Answering this question requires a clear definition of recovery, which I now provide.

The focus of this thesis is on the physical, abiotic aspects of recovery: the structure of the channel, the physical processes maintaining stability and, over time, the development of a more complex channel. The desired state of the river is a channel with more pools that remain sediment-free, increased bed relief, and a heterogeneous mix of stable landforms that support vegetation (Bartley and Rutherfurd, 2005a; Brierley and Fryirs, 2009; Fryirs and Brierley, 2016). This improved state is not synonymous with a return to the pre-disturbance channel morphology, which is seldom possible in rivers transformed by bedload pulses (Fryirs and Brierley, 2000; Dufour and Piegay, 2009).

In theory, in-stream extraction reduces sediment supply which causes a more complex channel structure to develop faster than it would without intervention. If too much sediment is extracted too quickly, erosion will be severe and extraction will actually inhibit recovery by decreasing channel stability, undermining vegetation, and replacing one source of degradation (excess sediment) with another (excess flow energy). Ideally, extraction should remove sediment at or below the rate it is replenished (annual bedload flux) to minimise the risk of degrading the channel.

The streambed is destabilised by a migrating extraction pit, so whether the area immediately downstream of extraction exhibits recovery depends on the how the pit evolves. Overall, improvements in channel structure should track the accumulating sediment deficit in a downstream direction, with perturbations in channel structure superimposed immediately downstream of extraction pits. Eventually, assuming no more extraction pits are added to a reach, and as the sediment deficit is closed by erosion, channel improvement will begin to diminish in a downstream direction. In the short term, the instability in one section (where the pits are excavated) is traded against improved channel condition in downstream reaches. If extraction is to generate a net improvement in stream condition, the length of the 'improved reach' should be much longer than the length of the disturbed reach.

5.3.4.5 Summary of gaps in the extraction literature

To assess whether in-stream extraction can accelerate the recovery of rivers impacted by a bedload pulse, we must understand how extraction alters sand-bed channels. The conceptual model above summarises what is known about how a channel will respond to extraction, but this literature review has identified that there are still gaps in this understanding. The four main gaps relevant to the recovery of bedload pulses in sand bed rivers are:

1. In what circumstances extraction pits trigger the upstream migration of a nickpoint. It is collective wisdom that in-stream extraction causes nickpoints to migrate into upstream reaches. Nickpoints have been observed upstream of very large extraction sites in large gravel bed rivers, but they are usually absent from flume studies, numerical modelling and sand-bed rivers. The fact that nickpoints are absent from

many of the single-pit studies, but are present in many other larger-scale extraction studies, means the conditions that promote nickpoint development in sand-bed rivers needs verifying.

2. Studies of extraction in natural channels have not included sand-bed rivers that are tens of metres wide, or sand-bed rivers experiencing a bedload pulse even though this kind of river is a very common source of sediment for extraction.

3. How multiple in-stream extraction pits excavated in a sequence interact in a natural channel.

4. The two-dimensional pattern of scour downstream of extraction pits, and how this pattern of scour interacts with the pre-existing channel form and sediment transport processes. Most studies emphasise long profile adjustment, or changes in planform over decades. Few studies consider the two-dimensional aspect of channel change caused by extraction.

5. Whether in-stream vegetation interacts with extraction pits, and if so, whether vegetation affects pit re-fill, pit evolution and the two-dimensional pattern of channel adjustment downstream of extraction sites.

6. Does in-stream extraction accelerate recovery? The link between post-extraction morphology and the desired channel state (described above) has not been established. Whether extraction pushes a reach along a trajectory towards this desired state determines whether extraction is an effective means to accelerate reach-scale recovery from a bedload pulse.

So far, this chapter has reviewed the conceptual model describing how an extraction pit re-fills with sediment and the impact an extraction pit has on upstream and downstream reaches. The review then synthesised a body of literature to develop a new theory of how a sequence of extraction pits will interact, and the impacts a series of interacting pits will have on upstream and downstream reaches. The rest of this chapter outlines the methods that will be used to test both the existing singe-pit models, and the newly developed multi-pit models in a sand-bed river. This study addresses these gaps in the Glenelg River, SE Australia.

5.4 Study reach

This section outlines the field site where the conceptual model of in-stream extraction will be evaluated in the following chapters. The field site is an 8 km long reach of the Glenelg River, western Victoria, Australia (Figure 5.3). Chapter 3 provides a full description of the catchment-wide context and only the relevant details of the study reach are described here.

Easy access to the riverbed and proximity to point of sale mean sand has been extracted from the study reach since the 1990s, but at a varying rate. The focus of this chapter is on extraction from a series of discrete extraction pits excavated as long, deep pools. This extraction technique is currently being used in several reaches of the Glenelg River and its tributaries, including two sites 5 km upstream of the study reach. The study reach (Corndale Road) was chosen to assess the impacts of in-stream extraction because:

1. Easy site access meant detailed channel surveys were possible and straightforward.
2. Several flood-studies have been completed for the reach, which aided the development of the hydraulic model used in this study.
3. Good extraction records have been kept for the sites in the reach since 2010 (the site has been regularly extracted since the 1990s but pre-2010 records are unavailable).

Pits were excavated on straight segments, on point bars, or in a larger pit that encompassed straight sections *and* the downstream point bar (Figure 5.3). Pits were excavated during low-flow and are on an average three metres deep (see results section for detail on the extraction techniques used). The pits were designed to act as sediment traps that would slowly fill from their upstream end. The commercial target for extraction was the clean, quartz, well-sorted sand. The river management target was to lower bed levels in the reach and to prevent sand moving into downstream habitat pools.

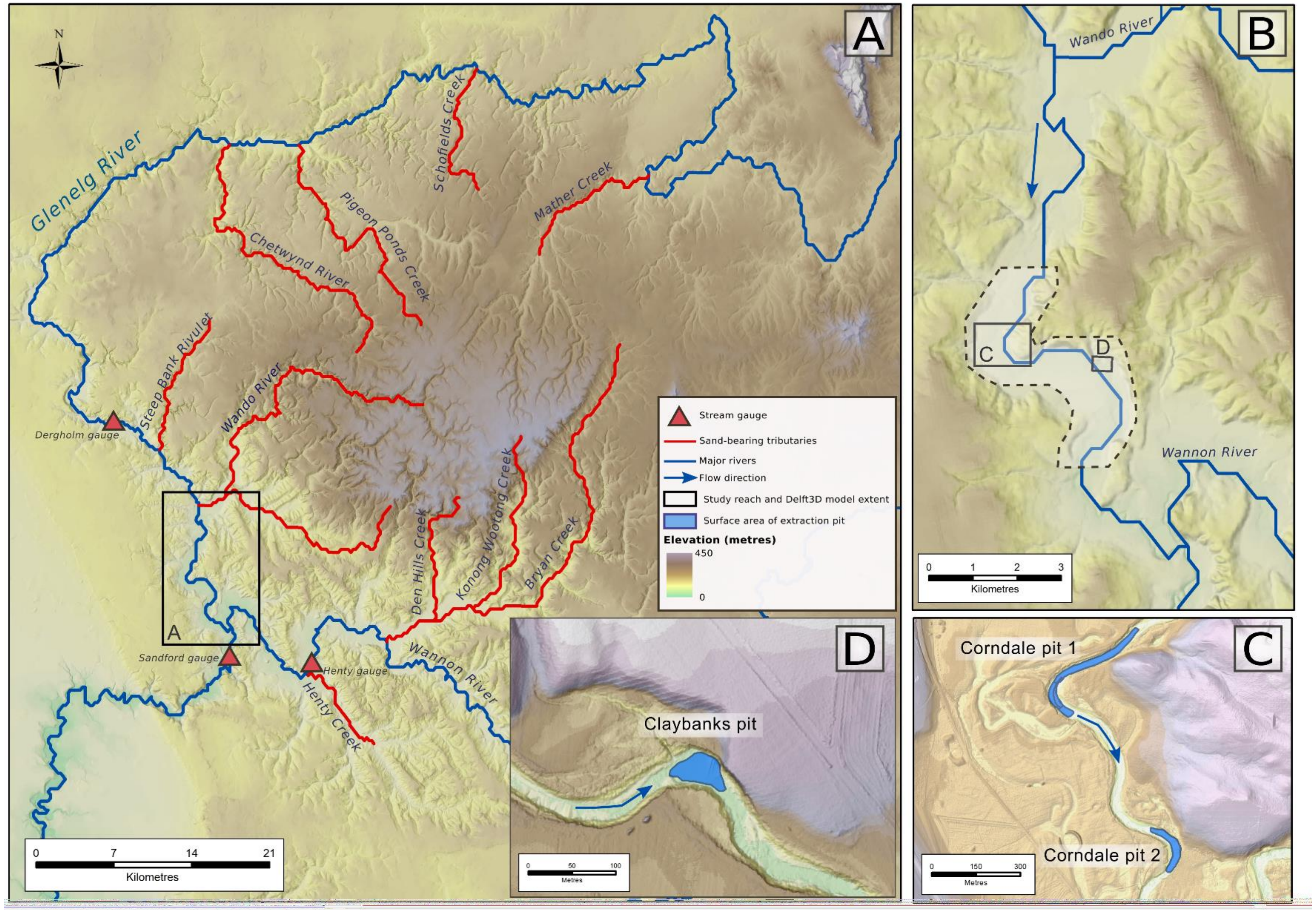


Figure 5.3: The extraction study reach within the wider Glenelg River catchment showing the extent of the Delft3D model, and the location of the thee extraction pits modelled. The extent box labelled A corresponds to the area in Figure 5.4.

5.5 Methods

The conceptual model defined the spatial scale and the timeframe that must be investigated. This section outlines the methods used to do so. The two chapters that follow use a combination of methods to evaluate the single-pit and multi-pit reach-scale conceptual models developed for the study site, namely: interviews with extractors, two-dimensional (2D) depth-averaged hydraulic and sediment transport modelling, repeat channel surveys, a reach-scale sediment budget and channel observations.

5.5.1 Why this approach?

Overall the approach of this chapter is to reconstruct past change and then compare this change to those predicted by a conceptual model. A common alternative is to compare changes in a treated reach with some reference reach not subject to intervention. Unfortunately, no baseline survey data was collected for any control reaches in the Glenelg River, so channel change can only be quantified in reaches subject to extraction. This is a limitation of this study. Without a control reach, the contribution of extraction to observed channel change can only be inferred form conceptual models, not quantified. However, this is a common scenario faced by managers who must nevertheless make decisions about where and when to intervene in a river.

The *strength* of this approach is that pit-infill and channel change documented by repeat channel surveys can be used to calibrate the hydraulic and sediment transport modelling. At the same time, the modelling relates sediment transport processes to observed channel change. Coupling the two methods generates a more robust sediment transport model, greater insight into the processes shaping pit-infill, and drives the inputs to the reach-scale sediment budget.

In combination, the Delft3D modelling and the repeat channel surveys explain the past: why the pits filled the way they did and what past extraction has done to the surrounding reach. In doing so, the results can be used to refine the conceptual model: how extraction of a given amount impacts the overall sediment budget of a river, and how this impacts downstream reaches.

The literature review at the start of this chapter identified that the extraction technique and the size and shape of the extraction pit in the streambed can have an important impact on how a channel responds to extraction. Furthermore, the timing of extraction relative to seasonal flows influences the flow forces that an empty pit is subject to, and the total energy of sediment-starved water downstream. I use interviews with extractors (along with extraction reports submitted to local government) to establish three things: the timing of extraction, the extraction technique used, and the volumes of sand extracted from the Glenelg River.

5.5.2 Interviews with extractors

Interviews with extractors and compilation of extraction reports submitted to local government were used to determine the method of extraction (how pits were excavated) and sequencing of extraction (which pits were excavated at what time). How pits are excavated in the channel bed determines how pits are re-filled, and the sequencing of extraction determines the magnitude of the sediment deficit imposed on the study reach, and whether extraction pits will interact. Although the descriptions offered by extractors are anecdotal, when used in conjunction with aerial imagery and channel surveys, they provide insight into how in-stream extraction is implemented in sand-bed rivers, and how the river responds.

Records of royalties paid to state government are another frequently used means of calculating extraction volumes, but these records were unavailable for the entire study period, and extractors have a financial incentive to under-report extracted volumes. The implication of this is that where extraction returns are available, they would constitute a minimum volume. Because the agency granting waterway work permits in the Glenelg River (the Glenelg Hopkins Catchment Management Authority - the recipient of the extraction reports used as a data source in this thesis) is separate from the agency collecting extraction royalties, the incentive to under-report extraction volumes is somewhat reduced. However, reported extraction volumes used in this thesis must be regarded as a minimum.

5.5.3 Channel surveys

5.5.3.1 Baseline channel survey

LiDAR data, which was flown in 2010 and included the channel banks and some of the bed was used to build a baseline elevation model. The detailed total station surveys (described in the next section) were compared with this baseline data to assess channel change. The 2010 LiDAR survey was flown during summer low flows. Exposed sections of the channel bed generated accurate LiDAR pulse returns but standing water did not. The gaps in the 2010 LiDAR were dispersed along the streambed. The gaps in LiDAR coverage were filled by interpolating values from the surrounding LiDAR elevation points. Interpolated points were generated with an average density of 0.1 pts/m^2 (compared to an average density of 2 pts/m^2 for the LiDAR points captured during the original survey). Because the low-flow channel, which was covered in water, was slightly lower than the surrounding streambed, a uniform value of 0.8 m (approximate water depth) was subtracted from the elevation of the interpolated points. The area of bed covered with the low-density interpolated points was small compared to the total area of the streambed captured by the 2010 LiDAR survey.

To ensure the baseline dataset was representative of bed elevation at the start of the study period (2005), the 2005 cross-section elevations were compared with the baseline dataset at overlapping points. This was only relevant for the streambed between extraction pits, because the dimensions of the excavated pits were known.

5.5.3.2 Post-extraction surveys

Channel cross-sections were surveyed along the entire study reach in 2005 by consulting firm Earth Tech to establishing baseline bed levels in possible extraction sites (Figure 5.4A). I re-surveyed 34 of these cross-sections in the study reach in 2018 to document changes in thalweg elevation and cross-section shape. Both sets of cross-section surveys were completed using a combination of theodolite and RTK GPS measurements.

In addition to the re-surveying of cross-sections in 2018, I also undertook a more detailed two-dimensional survey of both the re-filling extraction pits and the surrounding streambed in April 2019 – one year after the pits were last excavated and before the winter flow season began. A Sokkia iX-1000 robotic total station was used to complete the detailed survey (Figure 5.4B). The total station survey was tied to a series of geo-located control points arranged along the channel banks. The cross-sections and total station survey were tied to Australian Height Datum (AHD) 91 (Geoscience Australia, 2019) for comparison between years. The absolute horizontal and vertical error of all RTK GPS measurements was ± 0.02 m.

To summarise, the total station surveys document where in the pit sediment settles (how the pit fills) after twelve months of flow, while the repeat cross-section surveys document the magnitude and pattern of bed scour across the entire reach over a 14-year period.

The absolute difference in minimum bed elevation (the thalweg) between 2005 and 2018 was calculated by subtracting the 2018 elevations from the 2005 elevations. A positive difference indicates aggradation, a negative value indicates erosion. A similar calculation was made for the entire width of each cross-section and the methods used to do so are described in section 5.5.5 (sediment budgeting).

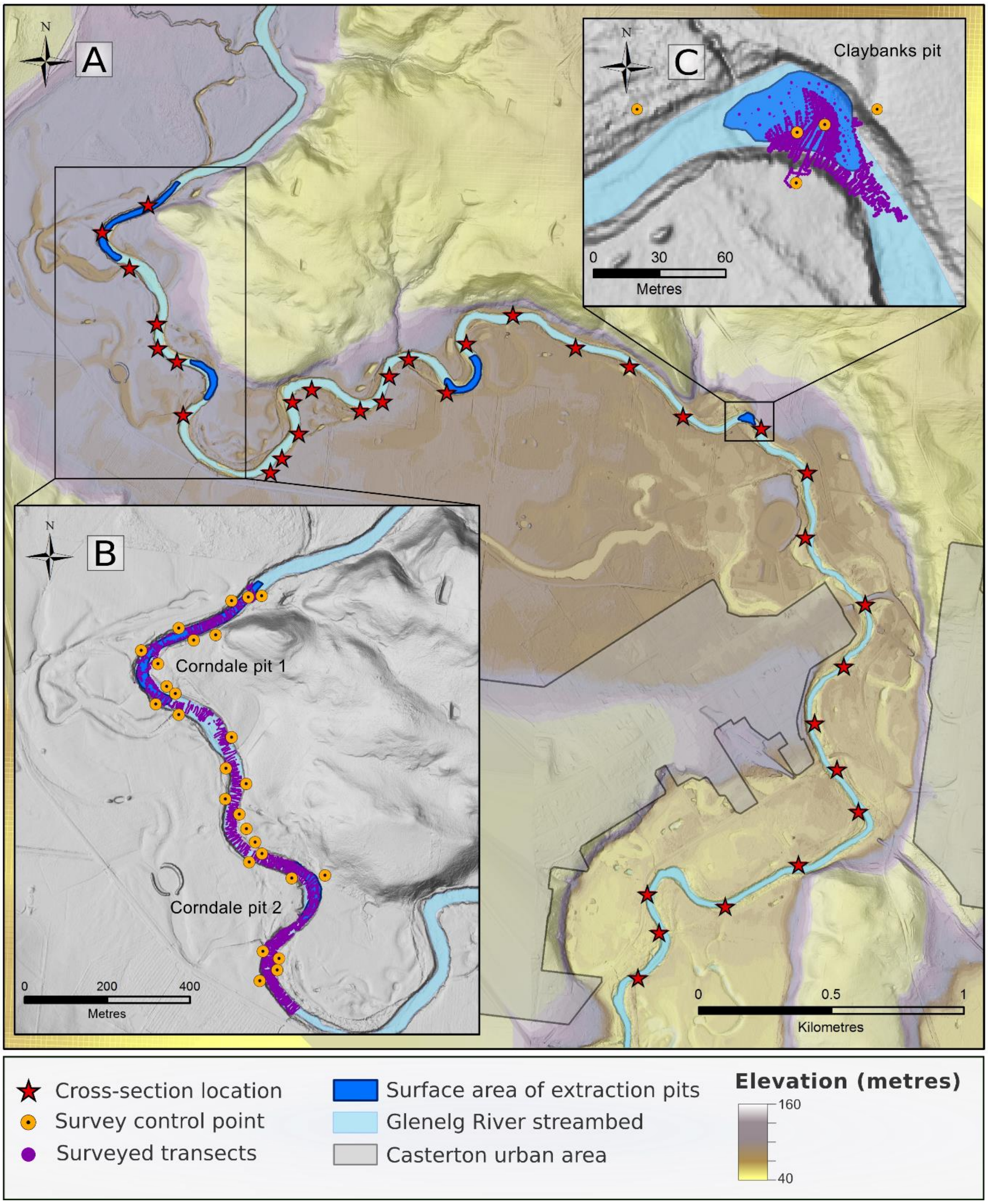


Figure 5.4: The distribution of surveys in the study reach, showing (A) the location of the 34 cross-sections that were surveyed in 2005 and again in 2018, (B) the more detailed survey of the Corndale extraction site pits one and two (surveyed in 2019), with GPS control points positioned along the bank and, (C) the detailed survey of the Claybanks extraction site which was completed in 2018 and again in 2019.

5.5.3.3 Channel mapping and observations

In addition to the channel surveys a small UAV was used to capture high-resolution aerial imagery of the channel bed and banks. Imagery was collected using a 12MP camera attached to a DJI Phantom 4 UAV at a flight altitude of 35 m. Images were captured as a uniform grid over the study reach using front overlap of 85 % and side overlap of 65 %. The width of the flight path was set by including a 30 m buffer either side of the channel banks. The flight altitude, front-lap and side-lap values ensured that all points of interest (the river bed and banks) were captured from several angles (Carrivick *et al*., 2016). Standing water obscured some sections of the bed, which can introduce errors from surface reflections (Tamminga *et al*., 2015). However the imagery was not used to generate accurate Digital Elevation Models (only orthorectified imagery), and the abundance of points captured on the adjacent floodplain more than compensated for any distortions introduced by poor point-matching over water (James and Robson, 2014). Imagery was imported into the commercially available structure from motion software Pix4D™ to generate orthorectified imagery with a final resolution of 0.1 m.

Image resolution is sufficient to identify: the type and distribution of vegetation in the channel and on the banks, the location and size of scour features on channel bars and benches, and the pattern of sand transport at the time of the survey (a low-flow of approximately 1.5 m^3 s^{-1} with a mean water depth of 0.5 m). Oblique photographs were used to supplement the aerial imagery.

5.5.4 Hydraulic modelling

The two-dimensional hydraulic and sediment transport model is used to predict the pattern of deposition within the pit during a single re-fill cycle, but not the *rate* of infill, which is stochastic. The hydraulic model is also used to quantify how an extraction pit alters hydraulic properties of the reach (the distribution of velocity, shear stress and the intensity of secondary circulation). The latter is quantified by running two scenarios with identical discharge, but different bathymetries: one without extraction pits (the bed is assumed to be a flat sheet of sand, interpolated between LiDAR returns on the channel margin), and one with the extraction pits 'burnt' into the streambed. The difference in hydraulic variables could then be compared on a cell-by-cell basis.

The modelling suite Delft3D (Deltares, 2014) was used to build a 2D depth-averaged hydrodynamic and sediment transport model of the entire study reach. Delft3D solves the Navier-Stokes equations for an unsteady flow in an incompressible fluid by implementing a numerical scheme across an orthogonal, curvilinear grid (Deltares, 2014). The relevant boundary conditions, and parameters used to represent physical processes, are outlined below. For a complete description of the numerical scheme employed by Delft3D, and all other aspects of the Delft3D modelling suite, see the Delft3D FLOW user-manual.

5.5.4.1 Computational mesh and model bathymetry

An orthogonal computational mesh was generated for the entire length of the study reach and its floodplain, resulting in a total of 342,000 computational cells with an average cell-size of 4 m^2. Flow boundaries were defined at the upstream end of the model domain (across the width of the flow-flow channel, 1 km upstream from extraction pit one) to ensure boundary conditions did not unduly impact the area of interest.

Model bathymetry was derived from LiDAR surveys flown in 2010 with an average point density of 2 pts/m^2. The computational mesh was used to undertake a nearest-neighbour interpolation of the LiDAR points and generate a bathymetric DEM for the model. This resulted in an average of 4 elevation point per model cell, more than enough to prevent step-changes in elevation and artefacts in subsequent model runs (Babister *et al.*, 2012). In areas without LiDAR returns (the wetted low-flow channel) the elevation of adjacent cells was projected across the channel, generating a flat sand sheet in the bathymetry. This bathymetry was used for all model runs without extraction pits. Assuming a flat bathymetry in the low-flow channel was appropriate given that cross-sections in the study reach were largely trapezoid in shape.

To model extraction pits, aerial imagery flown immediately after extraction was used to generate polygons of the surface area of extraction pits. The polygons were used to 'burn' 3 m deep (the average depth of extraction pits) holes in the DEM.

5.5.4.2 Turbulence

Flow turbulence − the generation, growth, migration and destruction of rotating eddies in the flow − redistributes energy within the channel and can significantly alter the magnitude and direction of flow velocity vectors (Buffin-Bélanger *et al.*, 2013). However, the grid scale of hydraulic models is too coarse, and the model timestep too large, to resolve the turbulent scales of fluid motion (Deltares, 2014). Like most two-dimensional, depth-averaged hydraulic modelling suites Delft3D calculates *averaged* values of turbulent energy using a closure model. For all simulations completed in this thesis, the K- □ closure model was used (the explicit, numerical implantation of these equations in Delft3D can be found in the Delft3D manual, (Deltares, 2014)). The K- □ closure model, which relates depth-averaged fluid motion to the turbulence they generate, requires two input parameters: eddy viscosity and eddy diffusivity. Eddy viscosity determines how energy is transferred through a fluid via small (sub-grid) turbulent flow structures, Eddy diffusivity describes how this turbulent energy is dissipated through the wider flow field. Values for both parameters are usually in the order of 0.1 – 5 $m^2 s^{-1}$ for natural rivers (Williams *et al.*, 2016).

5.5.4.3 Secondary circulation

Secondary circulation generated by helical flow cells in open channels play an important role in the formation of point bars and the distribution of momentum. Modelling helical flow cells explicitly would require a fully three-dimensional model domain to capture vertical fluid motions. This approach is computationally intensive and the field measurements to calibrate the model rarely exist. Three-dimensional simulations are therefore much less common than depth-averaged approaches. A major advantage of the Delft3D modelling suite is that it is able to model spiral motion intensity by calculating the velocity of flow normal to depth-averaged main flow (Deltares, 2014).

Delft3D accounts for the effect of secondary flow by extending the depth-averaged shallow water equations with (Deltares, 2014):

- an additional advection-diffusion equation to account for the generation and adaptation of the spiral motion intensity
- additional terms in the momentum equations to account for the horizontal effective shear stresses originating from the secondary flow. This allows for the more realistic bedload movement on the channel bed.

The adapted shallow water equations are described in detail in the Delft3D user manual (Deltares, 2014). Secondary flow was enabled for all simulations completed in this thesis to better capture the hydraulic and sediment transport processes on meander bends in the study reach.

5.5.4.4 Model calibration

The hydraulic model was calibrated by adjusting the single uniform channel roughness value, as is common practice for 1D and 2D hydraulic models. Hydraulic model calibration requires a pair of known water depths and discharges - a rating table. The Casterton gauge (gauge number 238212) has operated intermittently, and several different rating tables have been used to convert recorded stage to discharge estimates over the monitoring periods. Therefore, a single, representative rating table was used to calculate stage heights for given discharges. The stage predicted by the hydraulic model at the gauge site was compared to these measured stage heights.

Model roughness values (Manning's *n*) were adjusted so that for a given discharge (for example bankfull discharge of 70 $m^3 s^{-1}$) model stage was within 5 % of the observed stage at Casterton. Eddy viscosity was held at a constant value of 0.1 $m^2 s^{-1}$, and eddy diffusivity was held constant at a value of 2 $m^2 s^{-1}$. Adjusting these values by an order of magnitude made little difference to the modelled stage at Casterton, so they were held constant.

A single channel roughness of *n*= 0.05 was used for all subsequent model runs (this value is lower than the channel roughness values of earlier 1D and 2D hydraulic models of the Casterton area, which averaged *n*= 0.07 - 0.1 (Cardno Victoria, 2011; Water Technology, 2014) (Table 5.1). Earlier values are considered high for sand bed channels (Hicks and Mason, 1998) and were calibrated against much larger discharges than those used for this study.

Table 5.1: Parameter values used for the 2D hydraulic model and the sediment transport modelling.

Hydraulic model			
Parameter	Value	Unit	
Manning's n	0.05	none	Determined via calibration
Eddie viscosity	0.1	m^2/s	Determined by calibration
Eddie diffusivity	2	m^2/s	Determined by calibration
Water density	1000	kg/m^3	The density of water at 20 ºC
Sediment transport model			
Parameter	Value	Unit	
Median grain size (D50)	1000	µm	The median grain size of sand in the study reach, taken from measurements made by Rutherfurd & Budahazy (1996)
Specific density	2500	kg/m^3	The specific density of sand
Dry bed density	1600	kg/m^3	The density of well-sorted sand on the streambed accounting for porosity effects
Sediment layer thickness	5	m	The initial thickness of the sediment on the bed of the river at the start of all model runs
Threshold sediment thickness	0.05	m	The minimum water depth of a cell required to perform sediment transport calculations

5.5.4.5 Sediment transport modelling

Delft3D incorporates several common sediment transport formulas that simulate sediment transport processes and drive morphodynamic changes during model runs. Sediment transport formulas are only valid across the range of flows and sediment types from which they were derived. In the case of the Glenelg River this means only formulas derived for sand-bed rivers are appropriate. Several different *total* transport formulas (formulas that do not distinguish between bedload and suspended load components) meet this criteria, for example: Einstein (1950), Myer-Peter and Muller (1948) or Engelund and Hansen (1967), but it is more useful to distinguish between bedload and suspended load when assessing how extraction pits perturb sediment transport. Therefore, this study uses the sediment transport formula of van Rijn (1984). This formula was selected for four reasons:

1. it was developed specifically for sand-bed rivers
2. it distinguishes between bedload and suspended load components of sediment transport
3. it allows for dynamic bed form development and includes the impact of bedforms on channel roughness
4. the formula is easily implemented in the Delft3D modelling suite.

The van Rijn (1984) formulation used in this study was originally presented in three companion articles, each corresponding to different aspects of sediment transport: bed load transport (van Rijn, 1984a), suspended load transport (van Rijn, 1984b) and the development of bedforms and alluvial roughness (van Rijn, 1984c). The full-derivation is not presented here, just the relevant equations as they are implemented in Delft3D.

5.5.4.5.1 Bedload Transport

Bedload sediment transport, as presented in the Delft3D manual (Deltares, 2014) is given by:

$$\begin{cases} 0.053\sqrt{\Delta g\, D_{50}^{3}}\, D_{*}^{-0.3}\, T^{2.1}\, for\; T < 3.0 \\ 0.1\sqrt{\Delta g\, D_{50}^{3}}\, D_{*}^{-0.3}\, T^{1.5}\, for\; T \geq 3.0 \end{cases}$$

Where g is gravity (m s^{-2}), D_{50} is the median grain diameter, D_* is the dimensionless particle diameter and T is a dimensionless bed shear parameter, written as:

$$T = \frac{\mu_c \tau_{bc} - \tau_{bcr}}{\tau_{bcr}}$$

The dimensionless bed shear parameter is normalised with respect to critical bed shear (τ_{bcr}), according to Shields (1936), and the term $\mu_c \tau_{bc}$ is the effective shear stress. The formulas for shear stresses are:

$$\tau_{bc} = \frac{1}{8}\rho_w f_{cb} q^2$$

$$f_{cb} = \frac{0.24}{(log_{10}(12h/\xi_c))^2}$$

$$\mu_c = \left(\frac{18\, log_{10}(12h/\xi_c)}{C_{g,90}}\right)^2$$

Where ρ_w is water density, h is water depth, q is depth-averaged velocity, ξ_c is the reference level or roughness height (which is interpreted as the bedload layer thickness, or the active layer), and $C_{g,90}$ is the grain related Chézy coefficient, defined as:

$$C_{g,90} = 18\, log_{10}\left(\frac{12h}{3D_{90}}\right)$$

Where D_{90} is the grain diameter at the 90th percentile.

The critical shear stress is written according to Shields (1936):

$$\tau_{bcr} = \rho_w\, \Delta g\, D_{50}\, \theta_{cr}$$

Where θ_{cr} is the shields parameter which is a function of the dimensionless particle parameter D_*:

$$D_* = D_{50}\left(\frac{\Delta g}{v^2}\right)^{\frac{1}{3}}$$

Where D50 is the median grain diameter, Δg is acceleration due to gravity and v is velocity.

5.5.4.5.2 Suspended load

The formula for the suspended sediment transport is:

$$f_{cs} = \begin{cases} f_0\,(z_c) & if\ z_c \neq 1.2 \\ f_1\,(z_c) & if z_c = 1.2 \end{cases}$$

Where:

$$f_0\,(z_c) = \frac{(\xi_c/h)^{z_c} - (\xi_c/h)^{1.2}}{(1-\xi_c/h)^{z_c}\,(1.2 - z_c)}$$

$$f_1 = \left(\frac{\xi_c/h}{1-\xi_c/h}\right)^{1.2} \ln(\xi_c/h)$$

Where ξ_c is the reference level or roughness height (which is interpreted as the bedload layer thickness, or the active layer) and Z_c is the suspension number, defined by:

$$z_c = \min\left(20, \frac{w_s}{\beta k \mu_*} + \phi\right)$$

Where:

$$\mu_* = q\sqrt{\frac{f_{cb}}{8}}$$

$$\beta = \min\left(1.5, 1 + 2\left(\frac{w_s}{\mu_*}\right)^2\right)$$

$$\phi = 2.5\left(\frac{w_s}{\mu_*}\right)^{0.8}\left(\frac{c_a}{0.65}\right)^{0.4}$$

Where w_s is the settling velocity of the median particle dimeter. The reference concentration is written as:

$$C_a = 0.015\alpha_1\frac{D_{50}}{\xi_c}\frac{T^{1.5}}{D_*^{0.3}}$$

Where α_1 is a calibration coefficient (with a default value of 1). The computed suspended sediment load, C_a, is converted into a reference concentration equal to $f_{cs}C_a$.

Flow velocity, flow direction, shear stress and the magnitude of turbulence are calculated at each cell at each timestep and fed into the sediment transport formula. These values vary across the model domain and with time. The bedload and suspended load sediment transport rates (and direction) are then computed for each model cell, at each timestep. Settling velocity (w_s) was defined as 0.15 m s^{-1} and was held constant for all calculations. Bedload layer thickness (roughness height, ξ_c) set equal to 0.15 m (the approximate height of active transport layer determined for the Glenelg River by Rutherfurd and Budahazy, 1996), and was constant for all calculations.

5.5.4.6 Sediment supply calculations

5.5.4.6.1 Casterton daily flow series

The Casterton flow gauge was not operational between 2005 and 2018, but several nearby gauges were: Glenelg River at Dergholm (2004-2019), the Wando River (which enters the Glenelg River below Dergholm but above Casterton (1974-2019), and the Glenelg River at Sandford, which is 8 km downstream from Casterton, below the Glenelg River-Wannon River junction (2004-2016). Together, the upstream and downstream gauge sets were used to derive a mean daily discharge record for the Glenelg River at Casterton between 2004 and 2018.

The Glenelg River gauge at Sandford includes inflow from the Wannon River, a major tributary of the Glenelg River (Figure 5.3). To correct for this additional discharge, mean daily discharge measured from the Henty gauge on the Wannon River (18 km upstream from the junction (Figure 5.3)) was subtracted from the Sandford record.

Upstream of Casterton, mean daily discharge was extracted from the Dergholm and Wando gauges and then summed. Steep Bank Rivul*et al*so enters the Glenelg River downstream of Dergholm but upstream of Casterton, but the river is un-gauged.

The upstream and downstream discharge estimates were then calibrated against the limited flow records from the Casterton gauge, for the twelve months between September 2018 and September 2019. The Sandford (downstream) data showed the closest match to the Casterton calibration data, with mean daily flow records typically within 5 % of those measured at Casterton. Therefore, mean daily discharge at Casterton derived using the Sandford gauge predictions.

5.5.4.6.2 Daily sediment supply

The van Rijn (1984) sediment transport formula was coupled to the 2D hydraulic model to estimate the sediment transport rate at the upstream end of the study reach associated with discharges between 10 m^3 s^{-1} and 200 m^3 s^{-1} (the range of daily mean flows in the Glenelg River between 2005 and 2018). A two-part sediment rating curve was then generated by plotting the calculated sediment transport rate as a function of discharge and fitting two linear trend lines to the data: discharge ≤ 100 m^3 s^{-1} and another for discharges > 10 m^3 s^{-1} (Figure 5.5). A single exponential or logarithmic model is often fit to such data, but analysis revealed these models seriously under or over-estimated sediment transport rates at discharges >100 m^3s^{-1}. Fitting two separate trendlines to different sections of the same transport data is not common, but the aim of the model was to characterise sediment supplied to the study reach between 2005 and 2018, not provide a single, generalised function for all flows.

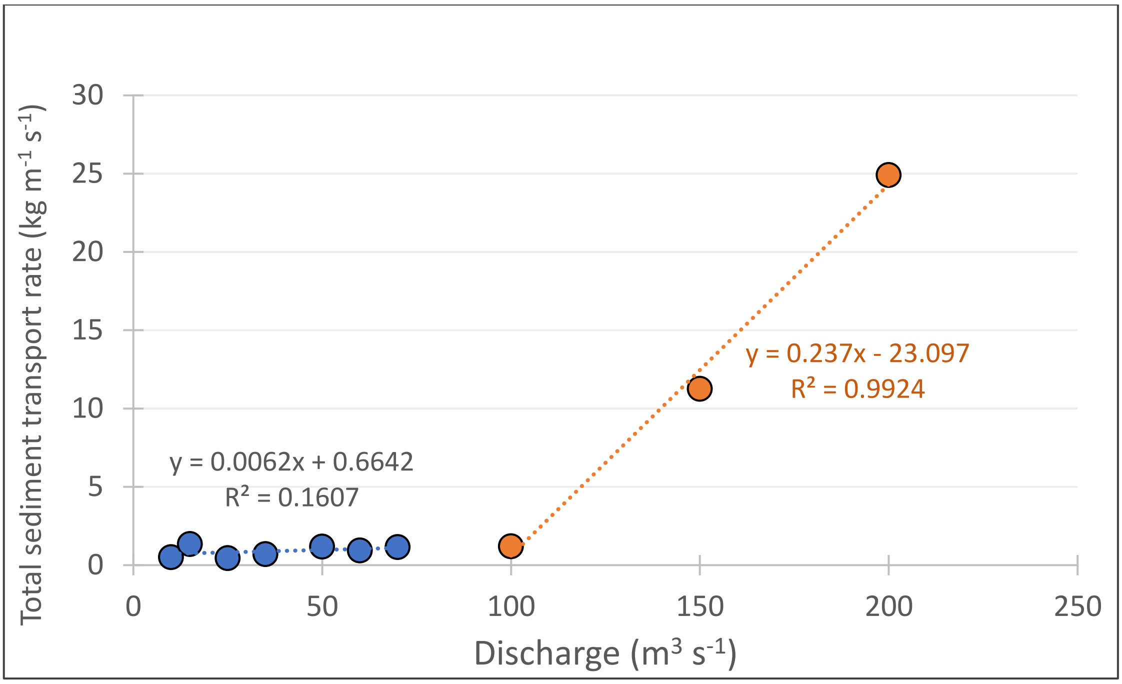


Figure 5.5: Discharge vs. the total sediment transport rate modelled for the Casterton study reach using Delft3D, with the two rating curves shown.

The two linear equations describing the sediment rating curve were used to estimate the sediment transport rate generated by any discharge value in the Casterton flow series.

Finally, the volume of sediment supplied to the extraction reach was calculated. The key assumptions employed in this calculation are:

- Flow entering the study reach is at capacity and is never supply-limited. This assumption was considered valid because tens of kilometres of streambed upstream of the study reach was covered in unconsolidated sand. This large store of sand could be readily mobilised and supplied to the study reach, especially during the bankfull flows modelled in this thesis.
- The simple relationship between the Sandford River gauge and the Casterton gauge is a reasonable approximation of daily flow at Casterton

Casterton mean daily discharge, and the associated sediment transport rate, was converted to a *total* daily sediment supply using the equation:

$$SS_D = \overline{STR_D} \times 86{,}400$$

Where SS_D is the total daily sediment supplied to the study reach (kg day^{-1}), $\overline{STR_D}$ is sediment transport rate associated with the mean daily discharge value (kg s^{-1}) and the constant 86,400 is the number of seconds in a day.

The total maximum volume of sediment supplied to the study reach each year was then calculated using the equation:

$$SS_A = \frac{\sum_{i=1}^{i=365} SS_D}{2650}$$

Where SS_A is the volume of sediment supplied to the study reach each year of the record (m^3), SS_D is the daily sediment supplied to the reach (kg day^{-1}), as calculated above, and the constant 2650 is the density of sandstone, the default output units of sediment fractions in Delft3D (kg m^{-3}).

5.5.4.7 Sediment transport model calibration

Sediment transport rate was not measured in the study reach between 2005 and 2018. However, by using the extraction pits as a surrogate for a large, in-stream sediment trap, the sediment transport model can be calibrated. Using the extraction pits to measure sediment supply has two advantages:

1. Pits take months to fill, and are subject to stochastic, varying discharges. This means uncertainty in the transport rate 'measured' the pits is evenly distributed across a range of discharges.
2. Pit re-fill period incorporates discharges that would be difficult or impossible to sample otherwise (discharges at bankfull or greater).

However, using pit re-fill to calibrate sediment supply has two disadvantages:

1. Pit re-fill integrates the stochastic variation in sediment supply, so cannot be used to calibrate the predicted transport rate of specific discharges. Instead, this method is limited to calibrating the volume supplied to a pit, *on average*, across a *range* of flows.
2. The pits may not trap all incoming sediment. Some sediment may by-pass the pit. The calibrated sediment supply (and the corrected transport rates) are therefore a minimum.

A calibration coefficient was calculated for each pit re-fill phase using the equation:

$$\alpha = \frac{SED_{EXT}}{SED_{SUP}}$$

Where α is the calibration coefficient, SED_{EXT} is the volume of the extracted pit (m^3) and SED_{EXT} is the predicted volume of sediment supplied to the reach during the re-fill period (m^3). Table 5.2 outlines the calibration coefficients for eight re-fill phases of pits excavated at the Corndale extraction site, including the two partial re-fills which were surveyed in 2018.

Comparing the volume of the extracted pits (which when re-filled measure the actual sediment supply) with the sediment supply predicted by the transport model reveals that the transport model under-estimates the volume of sediment supplied to the reach. The mean calibration coefficient, α (excluding the partial re-fills) of 5 was adopted as the calibration coefficient for all sediment transport and morphodynamic modelling. This was applied by multiplying both the reference concentration (and hence suspended sediment load) and the magnitude of the bedload transport vector in the Delft3D model, by a factor of 5.

Table 5.2: Extraction pit volume (actual, minimum sediment supply), time for each pit to re-fill, the sediment supply predicted by the van Rinj (1984) transport model and the ratio of extracted volume to modelled supply (calibration coefficient).

Extraction pit	Pit volume (m^3)	Re-fill period (days)	Modelled sediment supply (m^3)	Extracted volume: modelled supply ratio (calibration coefficient, α)
1A	19,860	273	2,021	9.8
1	29,682	275	2,976	10.0
2	8,672	275	2,976	2.9
Point bar 1	976	244	2,778	0.4
1A	19,860	1,035	6,763	2.9
2	8,672	1,035	6,763	1.3
1	29,682	438 (partial re-fill)	661	44.9
2	8,672	438 (partial re-fill)	661	13.1
Mean (with partial re-fill)		501	3,200	11
Mean (without partial re-fill)		522	4,046	5

5.5.4.8 Morphodynamic modelling

Deposition and erosion of sediment alters channel bathymetry, which alters the overlying flow field. This feedback is important whenever erosional and depositional fluxes are large relative to the depth of the flow field (for example deposition in an extraction pit). The impact of extraction on the study reach was modelled by including morphodynamic feedback in the Delft3D model runs.

The calibrated sediment fluxes (see above) calculated using the van Rijn (1984) transport formula were coupled with the hydraulic simulations. The morphodynamic module of Delft3D conserves mass and calculates erosion and deposition fluxes in and out of each model cell, at each timestep. Bathymetry is updated at each timestep by integrating the sediment flux across the model timestep, and calculating change in sediment volume per cell. Delft3D changes the quantity of bottom sediments (which are spread across the cell area to give a bed elevation) using the expression:

$$\Delta_{SED}^{(\mathrm{m,n})} = \frac{\Delta t\, f_{MORFAC}}{A^{(m,n)}} \left(S_{b_{uu}}^{(m-1,n)}\, \Delta y^{(m-1,n)} - S_{b,uu}^{(m,n)}\, \Delta y^{(m,n)} + S_{b,vw}^{(m,n-1)}\, \Delta x^{(m,n-1)} - S_{b,vw}^{(m,n)}\, \Delta x^{(m,n)} \right)$$

Where:

$\Delta_{SED}^{(\mathrm{m,n})}$ = change in quantity of sediment on the bed at coordinates (m,n) (kg m^{-2})

Δt = computational timestep

f_{MORFAC} = morphological acceleration factor

$A^{(m,n)}$ = area of grid cell at location (*m,n*) (m^2)

$S_{b,uu}^{(m,n)}$ = computed bedload sediment transport vector in *u* direction, held at *u* point of the computational cell located at (*m,n*) (kg m^{-1} s^{-1})

$\Delta x^{(m,n)}$ = cell width in *x* direction (m)

$\Delta y^{(m,n)}$ = cell width in *y* direction (m)

The grid-cell layout and nomenclature describing transport vectors is shown in Figure 5.6.

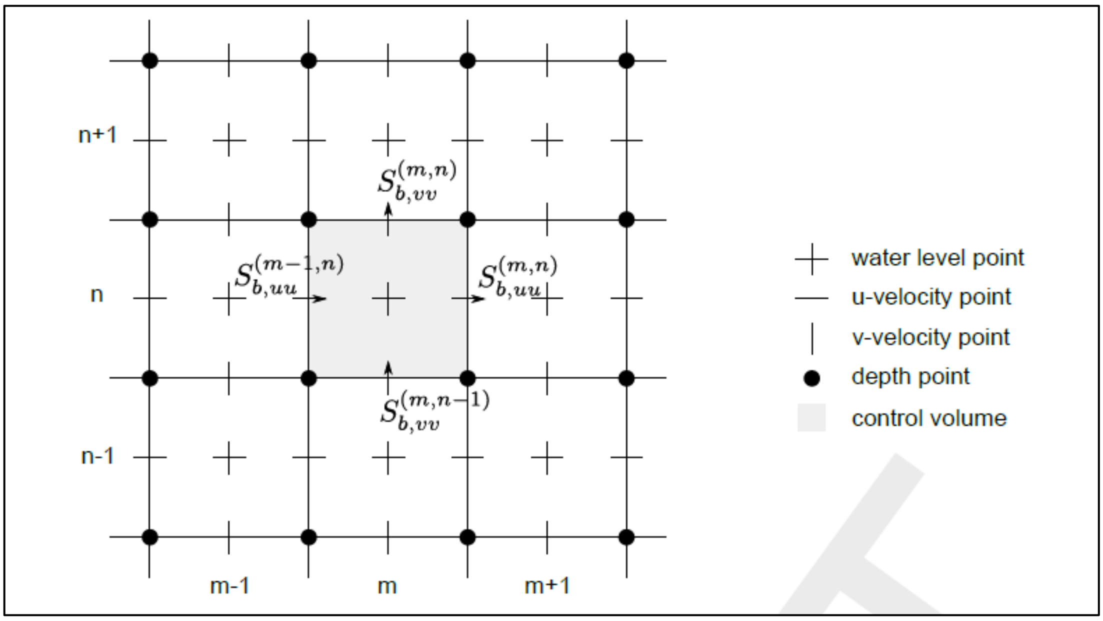


Figure 5.6: Grid cell layout and nomenclature showing the bedload transport vectors used to update model bathymetry during morphodynamic simulation Delft3D (Deltares, 2014).

5.5.5 Sediment budgeting

At the same time the sediment transport model was built and calibrated, a sediment budget was constructed for the study reach. The sediment budget was calculated using the calibrated sediment transport model, flow records, the extraction records, and changes in the volume of sediment stored in the study reach.

A sediment budget describes the input, transport, storage, and export of sediment from a geomorphic system (Reid and Dunne, 2005), and takes the form:

$$I - \Delta S = O$$

where *I* is sediment input, *ΔS* is the change in sediment storage and *O* is the sediment output. The sediment budget has multiple purposes:

- It explains the past by situating the magnitude and sequencing of extraction within the morphological boundary conditions of the river. Is extraction removing all, a fraction of, or much less than, the sediment supplied to the reach each year?
- It informs the future by quantifying the magnitude and distribution of erosion triggered by a given volume of extraction (either total volume or percentage of annual sediment supply). This allows managers to better plan if, how, where, when and how much sediment to extract from a river to accelerate recovery.

5.5.5.1 Sediment input (I)

The two-part sediment rating curve fitted to the calibrated sediment transport model (section 5.5.4.5) was coupled with the mean daily flow series derived for Casterton flow series (section 5.5.4.6.1) to calculate the volume of sediment supplied to the study reach between 2005 and 2018. The mean daily flow for each day of the study period was multiplied by the associated total sediment transport rate calculated for that flow. This value was then multiplied by 86,400 (the number of seconds in a day) to generate a record of the total daily sediment supplied to the study reach, for each day, between 2005 and 2018.

5.5.5.2 Change in bed storage (ΔS)

Changes in the volume of sediment stored on the bed of the study reach was calculated using the entire width of each cross-section, rather than just the channel thalweg. Using the entire width of each cross-section allowed changes in low-flow channel storage to be delineated from changes in storage on bars and benches.

The 2005 and 2018 cross-sections were surveyed at different resolutions, and the 2018 cross-sections spanned a greater width. So that cross-sections could be easily compared, each cross-section was set to a constant point-spacing of 1 m. To compensate for wider spacing between successive survey points within some cross-sections, points of known elevation were interpolated. Kriging, a tool that has been shown to produce accurate results when elevation varies systematically in space (i.e. a cross-section), was used to interpolate the surveyed elevation points (for both the 2005 and 2018 surveys) into a raster with a constant cell size of 1 m x 1 m (Environmental Systems Research Institute, 2016). All 2018 elevation rasters were then clipped to match the extent of the 2005 rasters.

Each raster (one for 2005 and one for 2018 at each cross-section) was one metre 'long' (in the streamwise direction). The 2005 values were then subtracted, on a cell-by-cell basis, from the 2018 values. The outcome of this rasterization and then simple subtraction was a DEM of difference (DEMoD) for each of the thirty-five cross-sections: negative values represent erosion and positive values represent deposition.

The study reach was broken into smaller sub-reaches, so that each cross section lay at the centre of a sub-reach. Cross section spacing varied between 150 m and 350 m, producing sub-reaches of different lengths. The cross-section DEMoDs for each sub-section were then combined with the mapped channel features (low flow channel, bars, benches, banks) to calculate a more detailed sediment budget than would have been possible without feature mapping.

Cross-section DEMoDs were broken into segments according to the mapped features they overlapped. Each cross-section could potentially have a bank, bench, bar and low-flow segment. The area of each mapped feature was multiplied by the net change in storage in the corresponding cross-section segment. Using the combination of feature mapping and cross-section DEMoDs accounts for the area of a sub-reach covered in different landforms and is therefore more accurate than simply multiplying net cross-section change by reach length. The DEMoD and mapping method employed here assumes that the volume change calculated for features that intersect the cross-sections are representative of the volume change in other features in the sub-reach with the same classification. When multiple instances of the same feature type were intersected in a single cross-section (for example a bench on each channel margin), volume change values were calculated for each: one for the true-right features, and one for the true-left feature.

The net change in storage at each cross-section was assumed to be representative of change in storage between cross-sections, so that each cross-section represented a smaller section of the study reach. Cross-section storage change was converted to sub-reach volume change by:

$$\Delta S_{SR_i} = \Delta S_{XS_i} \times L_{SR_i}$$

Where ΔS_{SR_i} is the total change in sediment stored in sub reach *i* (m^3), ΔS_{XS_i} is the change in sediment stored at cross-section *i* calculated using the DEMoD technique (Wheaton *et al*., 2010) in m^3, and L_{SR_i} is the streamwise length of sub-reach *i* (m). The changes in storage for each sub-reach was summed to estimate the overall change in storage for the entire study reach.

5.5.5.3 Sediment extracted (ΔS)

Extraction removes sediment from storage. The volume of material removed from extraction pits in the study reach was compiled from annual extraction reports, which were written each year between 2010 and 2018. Extraction reports document which pits were excavated at what time. The surface area of the pits (which are excavated to the same size each time they are extracted) was measured from aerial photos taken immediately after extraction (for example a single extraction of pit one has a surface area of 9,893 m^2). The depth of the pits was read from the extraction reports. Depth varied slightly along the pit, (for example from two to four metres in pit one), so a single, average depth (for example three metres in pit one) was assumed for each pit. The volume of sand extracted from each pit was calculated by multiplying the pit surface area by the average depth value (for example 29,682 m^3 from pit 1).

The method used to estimate the volume of sand extracted was considered reliable. Uncertainty in the volume estimates are comparable with (or are likely much less than) the uncertainty in the volumes associated with the other sediment budget components (sediment supply estimates, and the change in storage computed from cross-sections).

Pits are excavated during the low-flow season between December and April (although not every pit was extracted each year), in anticipation that pits will re-fill in the next high-flow season, between May and September.

5.5.5.4 Sediment output (O)

The sediment output from the study reach (O) is calculated once the supply and storage terms have ben quantified. The sign and magnitude of the output term has important implications for the supply of sediment to downstream reaches, and the overall movement of the bedload pulse. If output is equal to input (O = I), then the extraction has no impact on the volume of sediment supplied to downstream reaches. If output exceeds input (O > I), then the erosion triggered by extraction has increased the supply of sediment to downstream reaches. If output is less than input (O < I) the extraction reach is sequestering sediment and decreasing supply to downstream reaches.

Chapter 6: Pit-scale results

6.1 Introduction

In the previous chapter I developed a conceptual model that predicted how a single extraction pit would re-fill with sediment, how a single extraction pit would migrate downstream, and how a sequence of pits would interact. The conceptual model also predicted how a sequence of extraction pits would impact upstream and downstream reaches. The previous chapter also outlined the field site where the conceptual model was evaluated, and the methods used to evaluate the model. This chapter tests the pit-scale predictions of that model. The next chapter (Chapter 7) presents the reach-scale results.

How sand extraction pits re-fill and migrate has implications for channel stability, nearby infrastructure such as bridges and bank protection, any habitat the pits provide, and the commercial viability of in-stream extraction. Moreover, the infill process determines the pit's trap efficiency (the proportion of incoming sediment trapped and stored in the pit), which in turn controls how pits impact downstream reaches. Pit infill and migration has been investigated in laboratory flumes and in very large rivers, but not in small to medium sized sand-bed rivers. This chapter addresses the behaviour of extraction pits in a medium sized sand-bed river experiencing a bedload pulse, using a combination of repeat channel surveys, hydraulic modelling and sediment transport modelling. All analysis was undertaken in an 8 km long study reach of the Glenelg River, which is described in Chapter 5.

First, the results of interviews with extractors are presented. These interviews were used to determine how sand was extracted from the Glenelg River (which has been demonstrated to influence how a reach responds to extraction). The interviews also investigated when sand was extracted from the Glenelg River so pit excavation could be related to flow season and as a means of cross-checking extraction reports used to compute pit re-fill time. Secondly, the detailed surveys of pit re-fill are presented, which document how sediment settled in the pit and how the surrounding streambed responded. Thirdly, the results of the hydraulic and sediment transport model are presented. These results are organised by extraction pit, as each pit differs in geometry and position in the river (straight vs. meander bends). Finally, the implications for models of extraction pit evolution are discussed.

These results provide the context for the sediment budget and reach-scale analysis presented in the next chapter. The next chapter also covers the upstream and downstream impacts of extraction.

6.2 Pit-scale results

6.2.1 Interviews with extractors

This section summarises the insights from interviews with the commercial extractors removing sand from the Glenelg River. The clean, well-sorted sand from the Glenelg River is used as an aggregate for concrete and is sold to wholesalers in western Victoria. Extractors pay a royalty to the Victorian state government (currently AUD \$1.43/ m^3) and provide an annual report summarising extraction activities to the statutory authority overseeing in-stream works – the Glenelg Hopkins Catchment Management Authority (Department of Jobs, Precincts and Regions).

6.2.1.1 Extraction method

Historically a combination of bucket excavators, drag-line excavators and front-end loaders have been used to remove sand from the bed of the Glenelg River. The resulting extraction 'pits' varied in depth and width, and often disturbed large areas of the stream bed. Since the mid-2000s the Glenelg Hopkins Catchment Management Authority has worked with extractors to minimise disturbance to the river bed and protect the channel banks from being undermined during extraction. These more 'environmentally sensitive' techniques are driven by a shift in how the Glenelg Hopkins Catchment Management Authority manage in-stream extraction in the Glenelg River: from a passive role that focused on coordinating removal of a commercial resource, to the use of extraction as a management tool that is funded through the sale of extracted sand.

Extraction pits are now excavated using a bucket excavator (as opposed to a drag-line or front-end loaders) (Figure 6.1A-C). In straight channel-segments machinery (excavators and haul trucks) accesses the streambed via the gently sloping point bars at the downstream end of the target reaches, which minimises bank disturbance. Pit excavation proceeds from upstream to downstream. As excavators 'back out' of the extraction site, they leave a well-defined, deep pit that does not undermine the adjacent banks. In extraction pits that include a straight channel segment, and the toe of a point bar at the downstream end, the technique is the same. The excavator simply maintains the existing width of the pit and extends the pit around the toe of the point bar (Figure 6.2).

Where extraction pits are excavated from the toe of a point bar they use a similar technique, except excavators work from a bench that extends from the point bar and into the pit being excavated (Figure 6.1C). As the upstream and downstream ends of the pit are excavated, the excavator progressively 'backs-out' towards the centre of the pit. The narrow bench left in the channel is then removed, leaving a deep, discrete pit that arcs around the toe of the point bar (Figure 6.1F). A 1 m buffer of streambed is left along the margins of the pit.

6.2.1.2 Extraction sequencing and observations

Extraction occurs at the end of the summer low-flow 'season' (between February and March), when the Glenelg River ceases to flow. Pits are only re-excavated once they have completely re-filled with sand. Extractors monitor each pit at the beginning of each low-flow season to determine whether enough sand has accumulated for the pit to be re-excavated. The response of the pits to flow events is also noted by extractors, who have observed sand entering the upstream end of pits during small environmental water releases (~2 $m^3 s^{-1}$), and empty pits completely re-filling during large flood events (> 200 $m^3 s^{-1}$). Extractors have observed that floods also deposit sheets of sand (approximately 200 mm in depth) across the entire reach between the two extraction pits at the Corndale site. This sand re-buries exposed wood, but subsequent observations suggest that subsequent flows re-work this sand to re-expose wood in the streambed.

While floods completely fill extraction pits, on both straight section and point bars, they are rare, and most re-filling takes place during winter flows below bankfull (bankfull discharge is 70 $m^3 s^{-1}$). The seasonal flow pattern is the major determinant of whether a pit re-fills, and consecutive dry years have meant some pits remained only partially filled for several consecutive years. Extractors also note that when an extraction site includes two pits, both pits tend to re-fill at the same time (although at slightly varying rates). Because the pattern of flow is irregular, and the seasonal sediment yield variable, not every pit is re-filled (and therefore re-excavated) each year. For example, the Corndale site may be extracted once a year for three consecutive years, but the Claybanks site may only be extracted once over the same period. However, where an extraction site contains multiple discrete pits, pits tend to be excavated together: the pit that re-fills the slowest determines the extraction schedule for all pits at the site.

In summary, the extraction reports and interviews with extractors has led to four main conclusions:

1. The deep, discrete extraction pits excavated in the Glenelg River do not disturb the channel banks, they have been excavated in straight sections and at the toe of point bars. Not every pit at every extraction site is excavated each year.
2. Extraction pits are excavated in an upstream direction, as excavators ‘back-out’ of the channel. On meander bends, excavation starts from a temporary sand platform on the streambed and the outside of the meander is removed first. The temporary platform is removed last, leaving a discrete pit. The extraction technique leaves a pit that resembles extraction pits modelled in flume studies.
3. When two pits are excavated at the same extraction site, both pits begin to re-fill at the same time. Each pit fills at a different rate.
4. The rate pits re-fill depends on the magnitude and frequency of winter flows, which are stochastic. Pits completely re-fill during floods and sheets of sand are deposited on the streambed between pits.

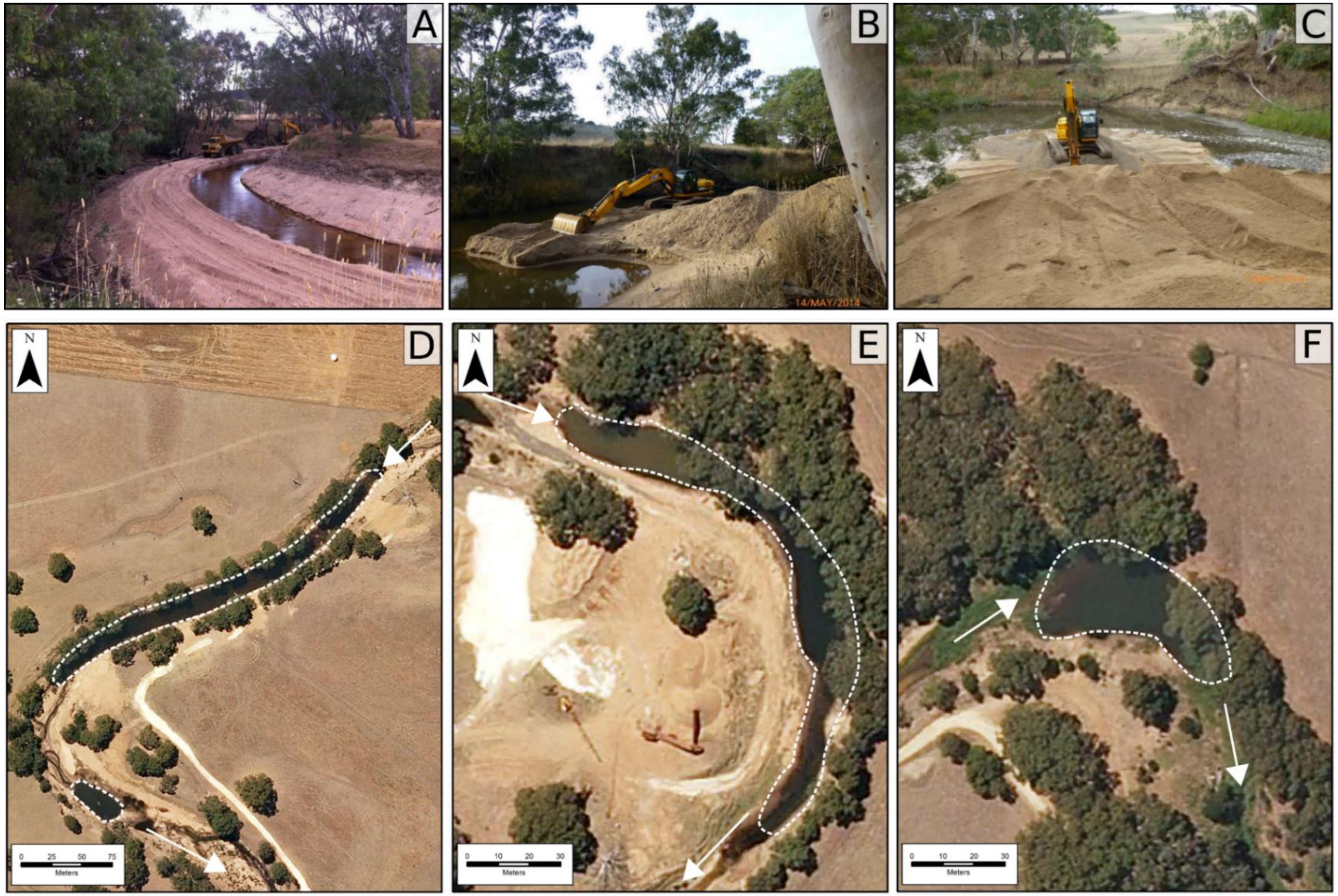


Figure 6.1: The extraction technique used in the Glenelg River (A) looking upstream at an extraction access ramp on the bend of the river with an excavator and haul truck removing material at the upstream end, (B) an excavator in the final stages of 'backing-out' from an extraction pit in the bed of the river, (C) an excavator on the remainder of a platform during point bar removal on a sharp meander bend, (D) plan view of two pits immediately after excavation at the Corndale extraction site – same pit as photo (A) but after the ridge used as an access track has been removed, (E) plan view of freshly excavated extraction pit at the toe of a point bar at the downstream end of the Corndale extraction site, and (F) plan view of the Claybanks extraction pit following excavation – the same site as photo (C) but once the sand platform used for extraction has also been removed. Photos A-C supplied by Vickery Bros, aerial photos D-F were captured in 2010, as part of the Victorian Index of Stream Condition program, white arrows show flow direction.

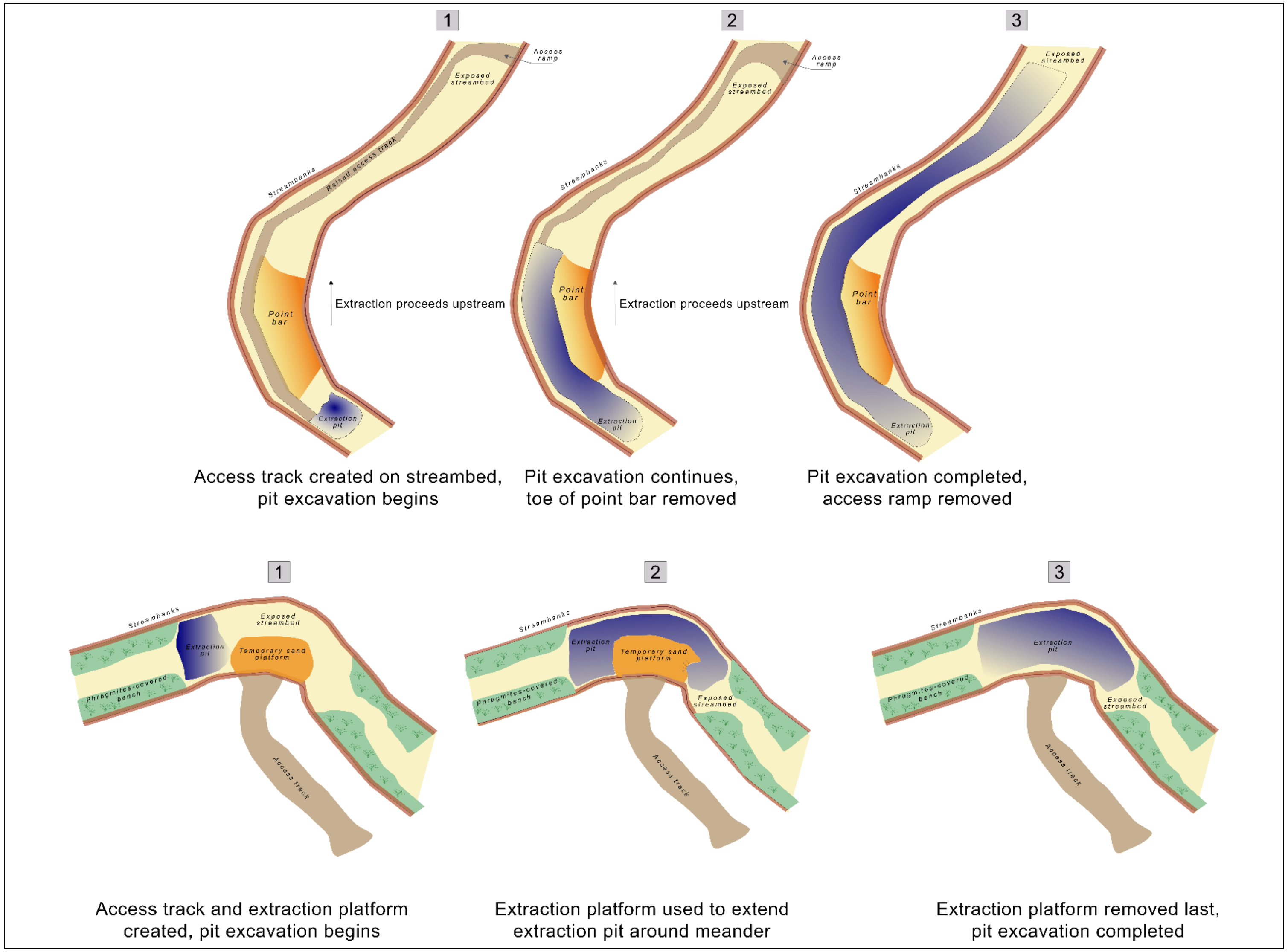


Figure 6.2: Schematic illustrating the three stages pit excavation on (top) long extraction pits that include straight segments and the toe of point bars and (bottom) pit excavation on sharp meander bends.

6.2.2 Channel surveys

This section presents the results of the detailed two-dimensional channel surveys completed in April 2019 (the end of the summer low flow season). Recall that the baseline survey the 2019 survey was compared against was generated by burning 3 m deep extraction pits into the 2010 LiDAR DEM of the Glenelg River. The results of the repeat surveys are presented first, and the results of the hydraulic modelling follow. This is because the repeat surveys reveal how the extraction pits re-filled, and the hydraulic model sheds light on how and why they filled.

6.2.2.1 Pit infill

The extraction pits were excavated to a constant depth of approximately 3 m (Figure 6.3A, Figure 6.4A and Figure 6.5A). At the downstream end of pit 1 the pit was excavated around two small 'islands' of sand that support large pieces of instream wood. These islands were approximately 2 m in diameter, so make little difference to the overall volume of the pit.

The upstream end of pit 1 migrates downstream by 210 metres over the twelve months between surveys, but also fills from the channel margins towards the centre of the pit at the same time (Figure 6.3B). Although the upstream end of the pit migrated, it did not fill to the same elevation as the upstream bed, and there is a small step in the longitudinal bed profile over the pit (Figure 6.3D). At the downstream end of pit 1, where the two small islands were left untouched, the infill pattern is irregular, and some minor erosion of the bed has occurred. Sand has also accumulated against the downstream end of the pit as a large wedge (Figure 6.3D). The simultaneous filling of pit 1 from upstream, from the channel margins and against the downstream end of the pit has left a narrow, intermittent trough in the centre of the pit (Figure 6.3B). The upstream margin of the partially-filled pit is steep, but the downstream margin is gently sloping. In total, 16,450 m^3 of sand has accumulated in pit 1, 55 % of the total volume of the excavated pit.

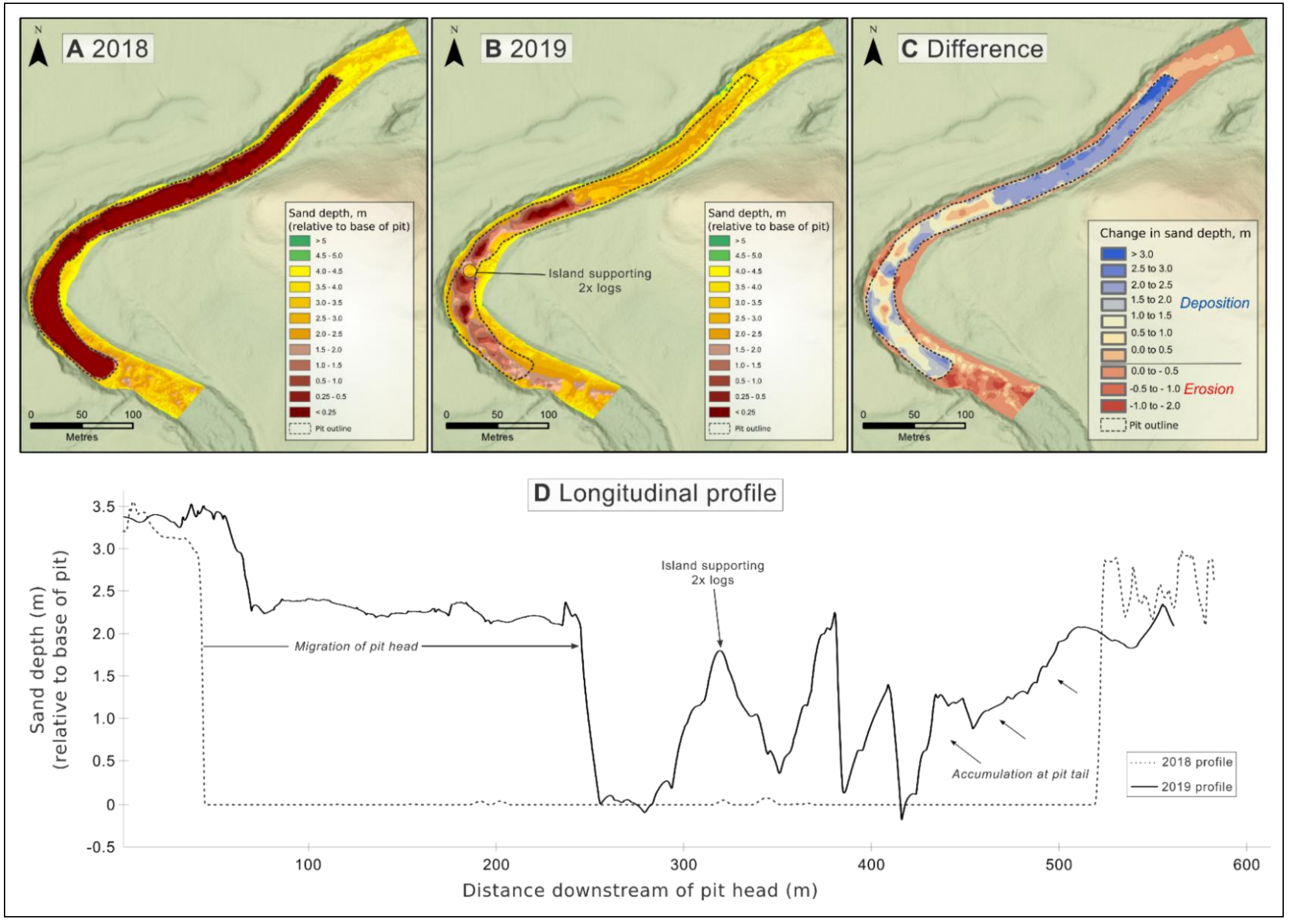


Figure 6.3: Channel surveys documenting the infill of pit 1 at the Corndale extraction site in (A) 2018 right after extraction, (B) 2019 and (C) DEM of difference showing the pattern of infill between 2018 and 2019, (D) an annotated longitudinal profile of the pit illustrating migration of the pit head and accumulation at the pit tail. Flow in A-C is from top to bottom, flow in D is from left to right. Sand depth is the depth (m) of sand above the elevation of the base of the extraction pit right after excavation, before in-fill begins.

The head of pit 2 has migrated downstream to reach the apex of the point bar (Figure 6.4). At the same time, sand has accumulated against the point bar, and the zone of maximum lateral accumulation shifted towards the downstream end of the original pit (Figure 6.4B and C). Infill has left a deep, narrow channel on the outside of the meander bend that extends beyond the downstream end of the original pit. Unlike pit 1, the downstream end of pit 2 has migrated downstream by extending a narrow, deep channel along the channel centreline (Figure 6.4D). In total, 9,000 m^3 of sand has accumulated in pit 2, 70 % of the volume of the empty pit.

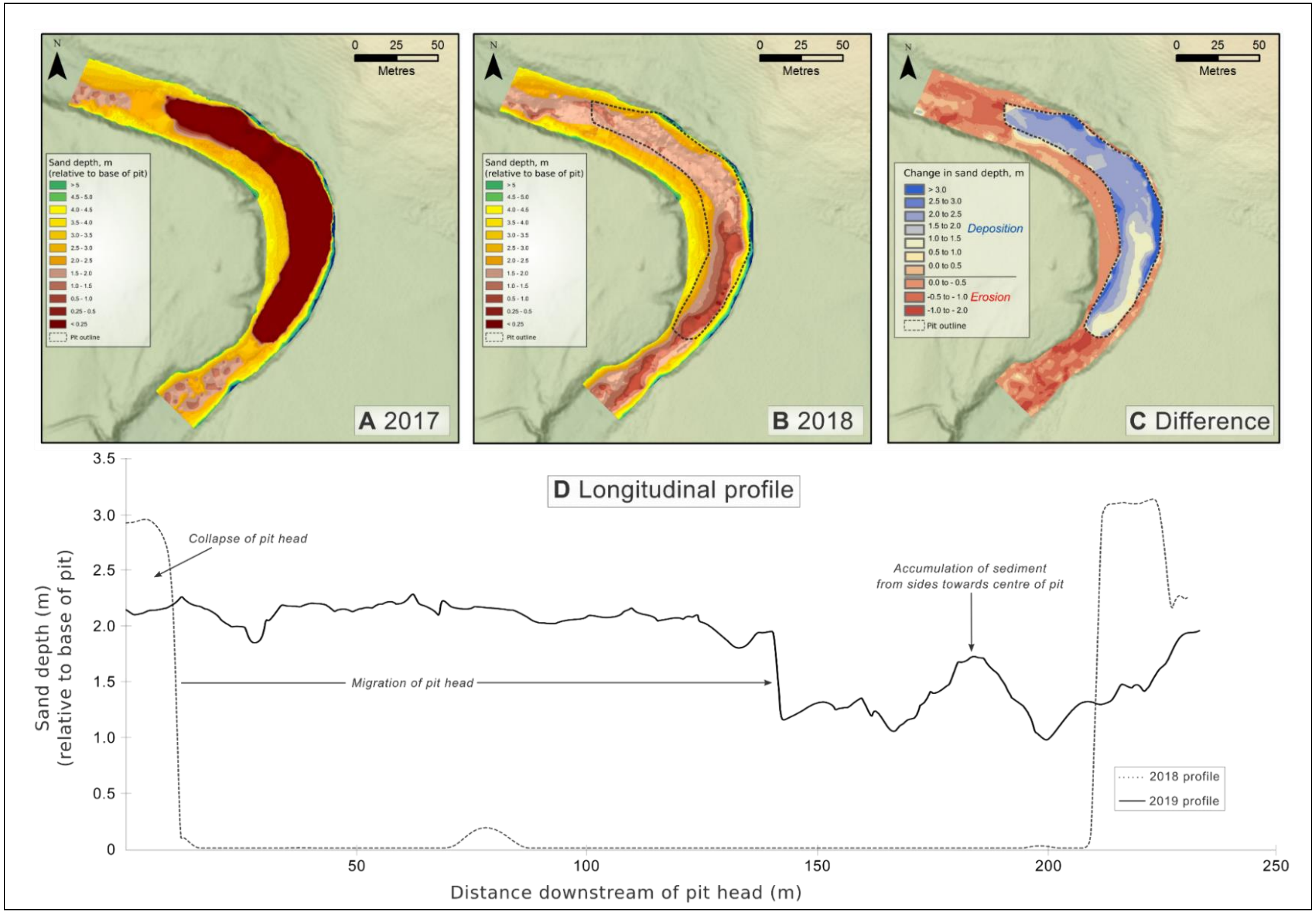


Figure 6.4: Channel surveys documenting the infill of pit 2 at the Corndale extraction site in (A) 2018 straight after extraction, (B) 2019 and (C) DEM of difference showing the pattern overall pattern of infill, (D) an annotated longitudinal profile of the pit illustrating migration of the pit head and tail, and accumulation of sediment sourced from the margins of the pit. Flow in A-C is from top to bottom, flow in D is from left to right.

The Claybanks pit partially re-filled between 2017 and 2018, but sediment was then scoured and re-distributed between 2018 and 2019 (Figure 6.5). The bulk of sediment accumulated as a point bar that has grown outwards across the pit, leaving a series of disconnected hollows on the outside of the meander bend and a gently sloping pit tail. The disconnected holes merged into a single narrow channel between 2018 and 2019 and at the same time, sand was scoured at the downstream end of the pit: causing the tail of the pit to migrate (Figure 6.5C and D, Figure 6.6B). Overall a net volume of 1,750 m^3 of sediment accumulated in the Claybanks pit (and remained there) between 2017 and 2019, 37 % of the total volume of the empty pit.

The channel bed surrounding each of the extraction pits has eroded, but scour is most intense at the tail of each pit. The pattern of downstream scour of pits 1 and 2 is irregular (Figure 6.3C and F), but at the tail of the Claybanks pit a continuous, narrowing channel has formed (Figure 6.6B and C).

As distance from the extraction pits increases, uncertainty in the magnitude of streambed erosion increases. Extraction pits had a known depth and geometry immediately before their extraction in 2018, so the pre-infill baseline is simple and well understood. The pre-infill streambed outside the extraction pits was interpolated from LiDAR surveyed in 2010. This means that the pre-infill bed profile in sections covered by LiDAR include scour that accumulated between 2010 and 2018, not just erosion that occurred between 2018 and 2019 (when the pits were filling). As a result, the total bed erosion in these sections is actually the cumulative erosion caused by repeat extraction, not the erosion that occurred between 2018 and 2019. Regardless of this uncertainty, further afield, the pattern of pit infill is remarkably clear.

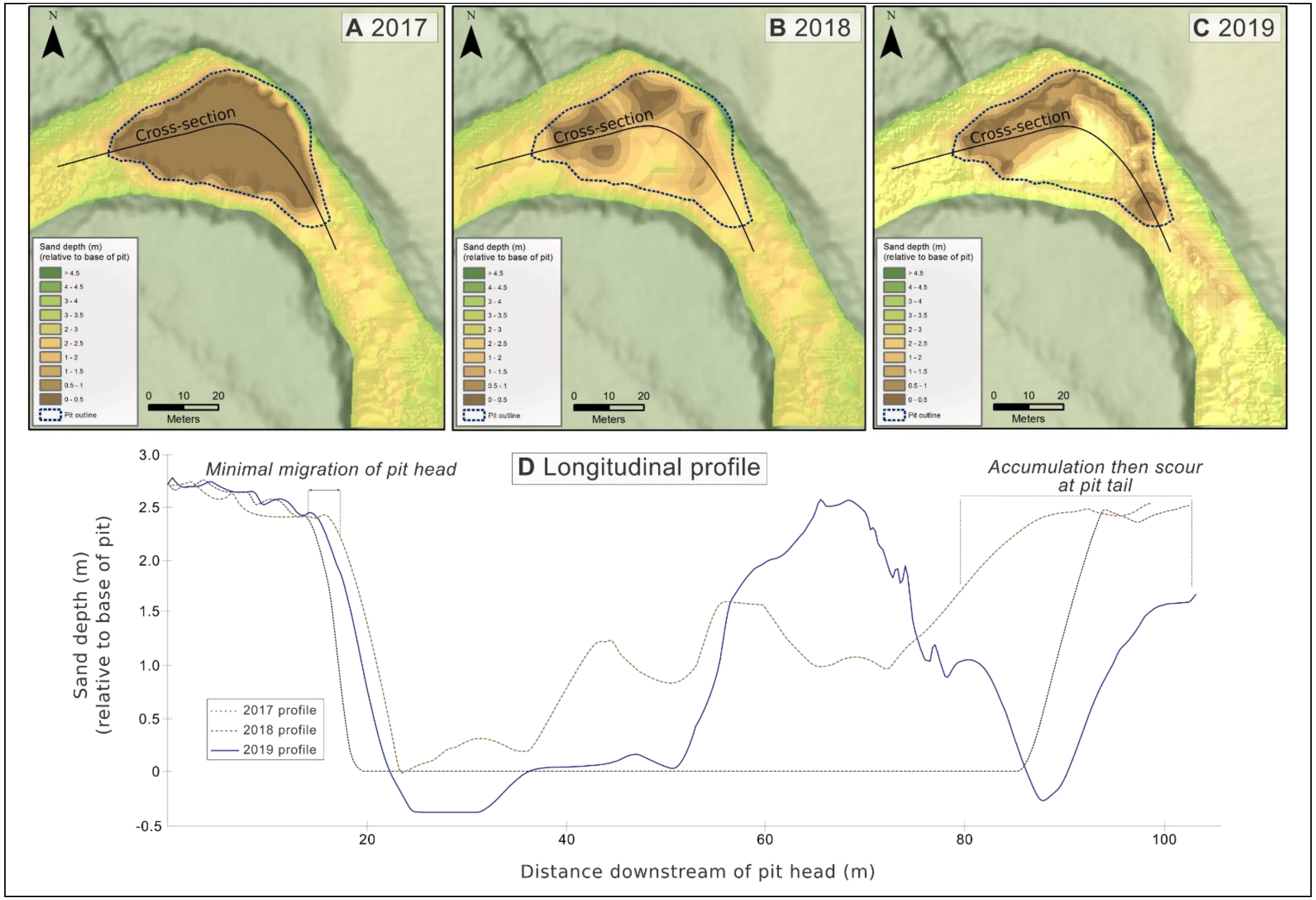


Figure 6.5: Channel surveys documenting multiple stages of infill of the Claybanks extraction pit, which was excavated on a sharp meander bend downstream of the Corndale site (A) 2017 straight after extraction, (B) 2018, (C) 2019 after sediment in the pit was re-worked and (D) an annotated longitudinal profile of the pit showing the lack of migration of the pit head and the fill and then scour of sediment at the tail of the pit. Overall sediment has accumulated in the pit as a large point bar, and a deep channel has formed on the outside of the meander bend. Flow in all boxes is from left to right.

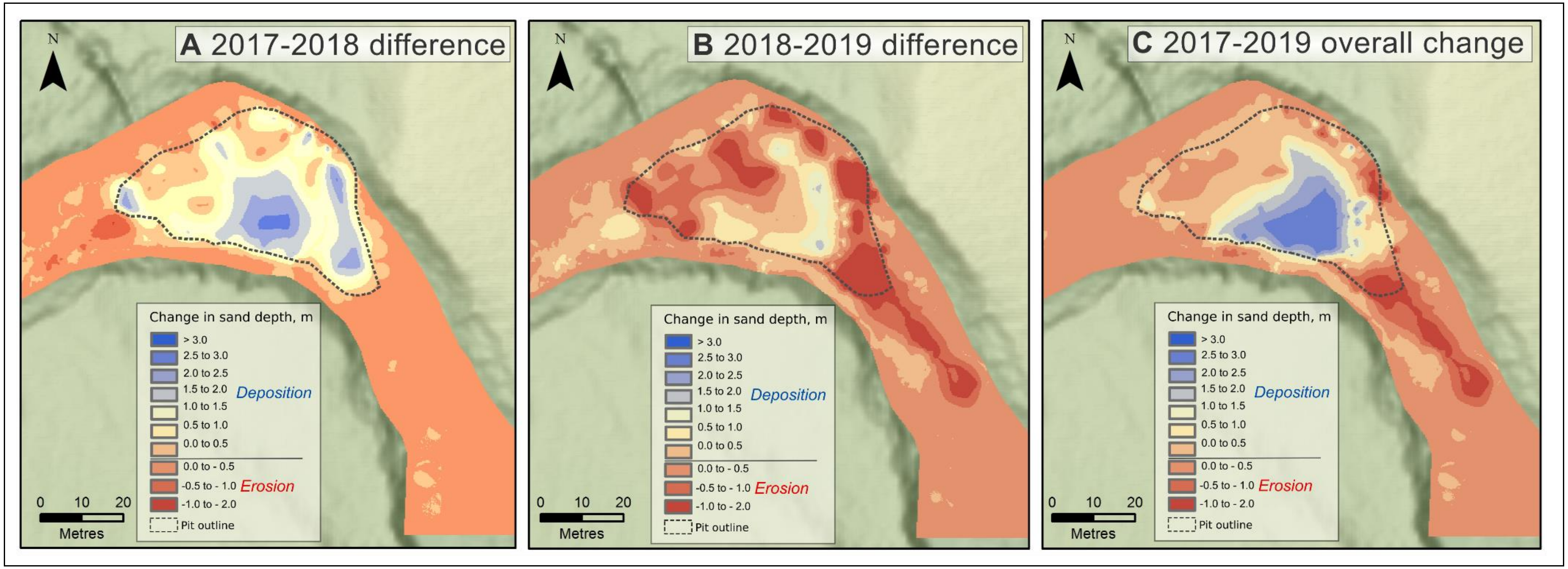


Figure 6.6: DEM of Difference for the Claybanks extraction pit, showing (A) the accumulation of sediment between 2017 and 2018, (B) the scour of sediment from the outside of the meander bend and accumulation on the downstream portion of the point bar between 2018 and 2019 and (C) the overall accumulation and erosion of sediment between 2017 and 2019. Flow in all boxes is from left to right.

6.2.3 Vegetation

The literature review presented in Chapter 2 identified a gap: how in-stream vegetation interacts with an extraction pit. Observations of in-stream vegetation, in this case beds of the emergent macrophyte *Phragmites australis*, around extraction pits are presented here.

Beds of *Phragmites* have colonised the margins of the Claybanks extraction pit and extend across the streambed upstream and downstream of the pit. The *Phragmites* form dense stands and occupy features that are regularly submerged and features that are dry most of the year.

With the exception of some local changes at the margins of the Claybanks extraction pit, *Phragmites* coverage was relatively stable over the study period. Vegetation was not present upstream or downstream of the Corndale extraction site in 2010 and no vegetation has established since. At the Claybanks extraction pit, *Phragmites* covered the streambed upstream and downstream of the pit in 2010 (Figure 6.7A). By 2014 *Phragmites* coverage around the pit had decreased, especially on the streambed immediately upstream of the pit (extractors do not remove or otherwise disturb beds of *Phragmites* present at the time of extraction). A narrow, *Phragmites*-free low-flow channel also formed upstream and downstream of the pit. The Claybanks pit was not re-excavated over this period but did re-fill with sand (Figure 6.7B). Between 2014 and 2018 *Phragmites* cover was mostly stable, with some encroachment along the true-right margin of the pit (the inside of the meander bend), at the upstream end (Figure 6.7C). The pit was excavated right after the 2014 (Figure 6.7B) photo was taken and by 2018 had partially re-filled the pit. The narrow low-flow channel remained in place.

Figure 6.7: Changes in the distribution of *Phragmites* around the Claybanks extraction pit, showing coverage in (A) February 2010 at the end of the Millennium drought, (B) In January 2014. Question marks indicate uncertainty as to extent of *Phragmites* due to shading of in the aerial image by bank vegetation and, (C) in April 2018. Photo B source is Google Earth. Flow in all boxes is from left to right.

6.2.4 Hydraulic model results

This section presents the results of the hydraulic model outlined in Chapter 5. The approach was to model two different scenarios with the same input discharge (bankfull discharge of 70 $m^3 s^{-1}$), but different model bathymetries: a bathymetry without extraction pits, and a bathymetry with the 3 m deep extraction pits 'burned' into the streambed. Depth-averaged velocity, bed shear stress, total sediment transport rate and secondary circulation values from the pit-free scenario can be compared with the corresponding values calculated. Hydraulic variables were compared across the two scenarios by generating maps of 'hydraulic difference' (similar to the way digital elevation models are compared). In addition, a third model scenario that used the 'with-pits' bathymetry but an input discharge of 35 $m^3 s^{-1}$ (0.5 x bankfull) was also run, so the influence of pits on could be compared between discharges. After the channel hydraulic results are presented, the associated morphodynamic model (the pattern of erosion and deposition predicted by the hydraulic model) will be presented.

6.2.4.1 Corndale pit 1

Relative to the pit-free channel, flow velocity decreases within extraction pit 1 by up to 0.5 m s^{-1} (Figure 6.8B). Flow velocity slightly increases upstream of the pit (by approximately 0.06 m s^{-1}) and on the true left-hand side of the bed downstream of the pit (by approximately 0.11 m s^{-1}). The pattern of velocity change is mirrored by a decrease in bed shear stress within the pit, but an increase in bed shear upstream of the pit and on the true left side bed downstream of the pit (Figure 6.8D).

In this straight section of the pit, the net secondary flow vector (recall that this is the net effect of both outwards flow across the water surface and inwards flow across the bed) reverses direction: changing from towards the true right bank to towards the true left bank. Introducing the pit has little impact on this flow cell (Figure 6.8F). As flow approaches the meander bend the secondary flow vector reverses direction again, shifting the flow momentum towards the outside of the meander bend (on the true right of the channel). Unlike the unaltered straight section, the extraction pit alters the distribution of momentum across the site of the former point bar in two ways: by increasing the outward-momentum on the *inside* of the meander bend (on the point bar), but at the same time *decreasing* the outward-momentum in a narrow region against the cut bank (the direction of this secondary flow vector is unchanged, still towards the outside of the channel, but the magnitude of secondary flow velocity decreases in this region) (Figure 6.8D). This has the net effect of leading to a tighter, faster flowing secondary flow cell that moves around the inside of the meander bend.

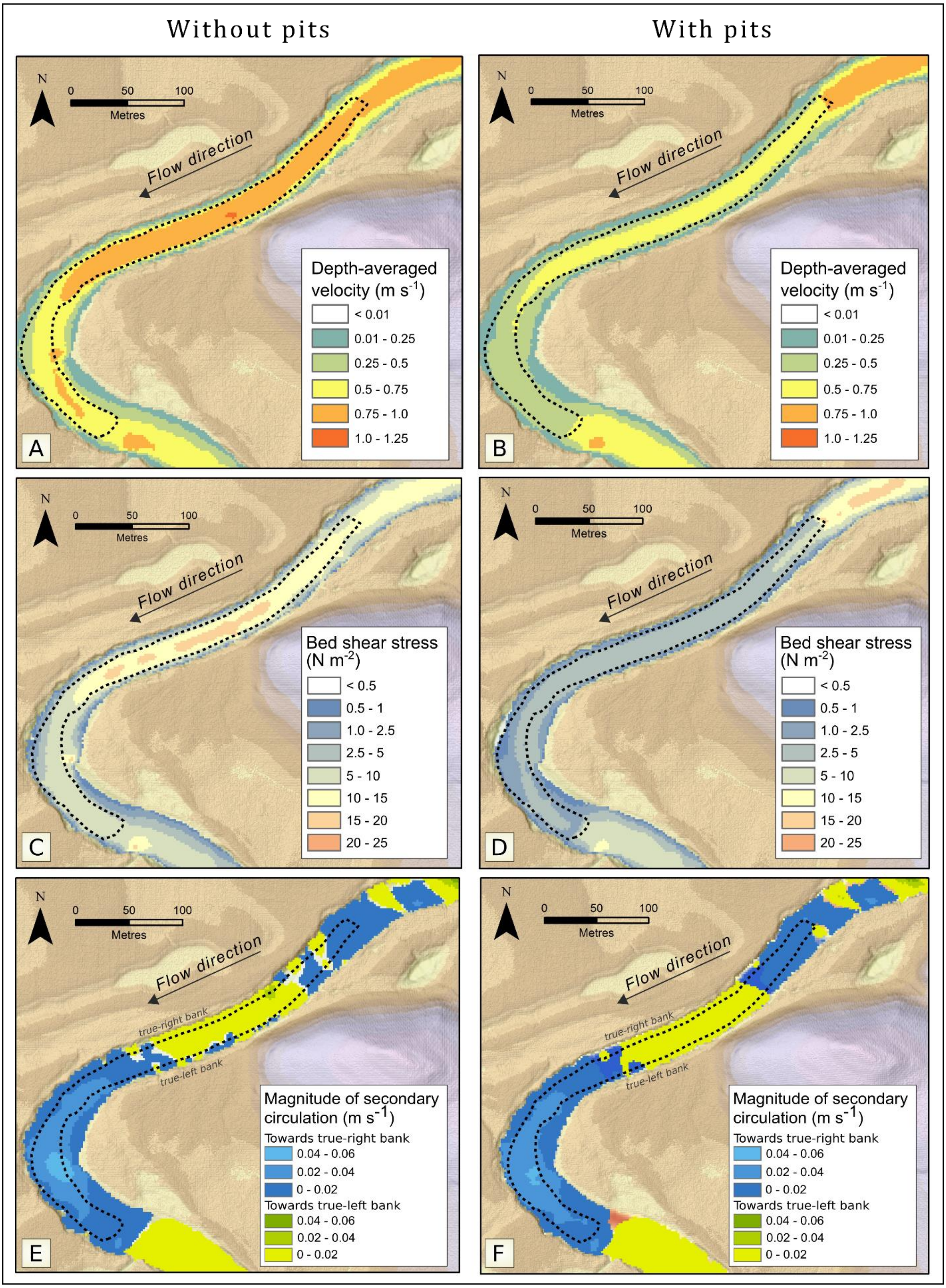


Figure 6.8: Modelled hydraulic variables at bankfull discharge (70 $m^3 s^{-1}$) at Corndale pit 1. Depth-average velocity without pits (A) and with pits (B), bed shear stress without pits (C) and with pits (D) and the magnitude and direction of secondary circulation without pits (E) and with pits (F).

As bankfull flow moves through the straight section of the pit and approaches the head of the point bar, the sediment transport rate falls to 0. This generates a long ‘finger’ of sediment being transported through the centre of the upper portion of the pit (although a very low transport rate of 0.01 kg/m/s) (Figure 6.9A and C). The sediment transport rate is negligible across the point bar, regardless of whether the pit is present. Immediately downstream of the pit, the dominant path of sediment transport switches from the true right side of the channel to the true left side of the channel, but the overall change in transport rate in this section is small (Figure 6.9A and C).

This pattern of pit infill occurs at bankfull discharge. At lower discharges (for example 35 $m^3\ s^{1}$ – half of bankfull discharge) this elongated zone of bedload transport does not develop in the pit. Bedload transport increases at the advancing head of the pit, where the avalanche face has developed, but quickly falls to zero within the pit (Figure 6.9B and C). A lobe of suspended sediment extends 30 m into the pit at this lower discharge, ~35 m less than the suspended sediment lobe that developed at bankfull discharge (which extended 75 m into the pit). The pattern of bedload transport and suspended sediment transport described above are a snapshot of sediment transport occurring at the start of the pit-infill process, before accumulating sediment modifies pit geometry.

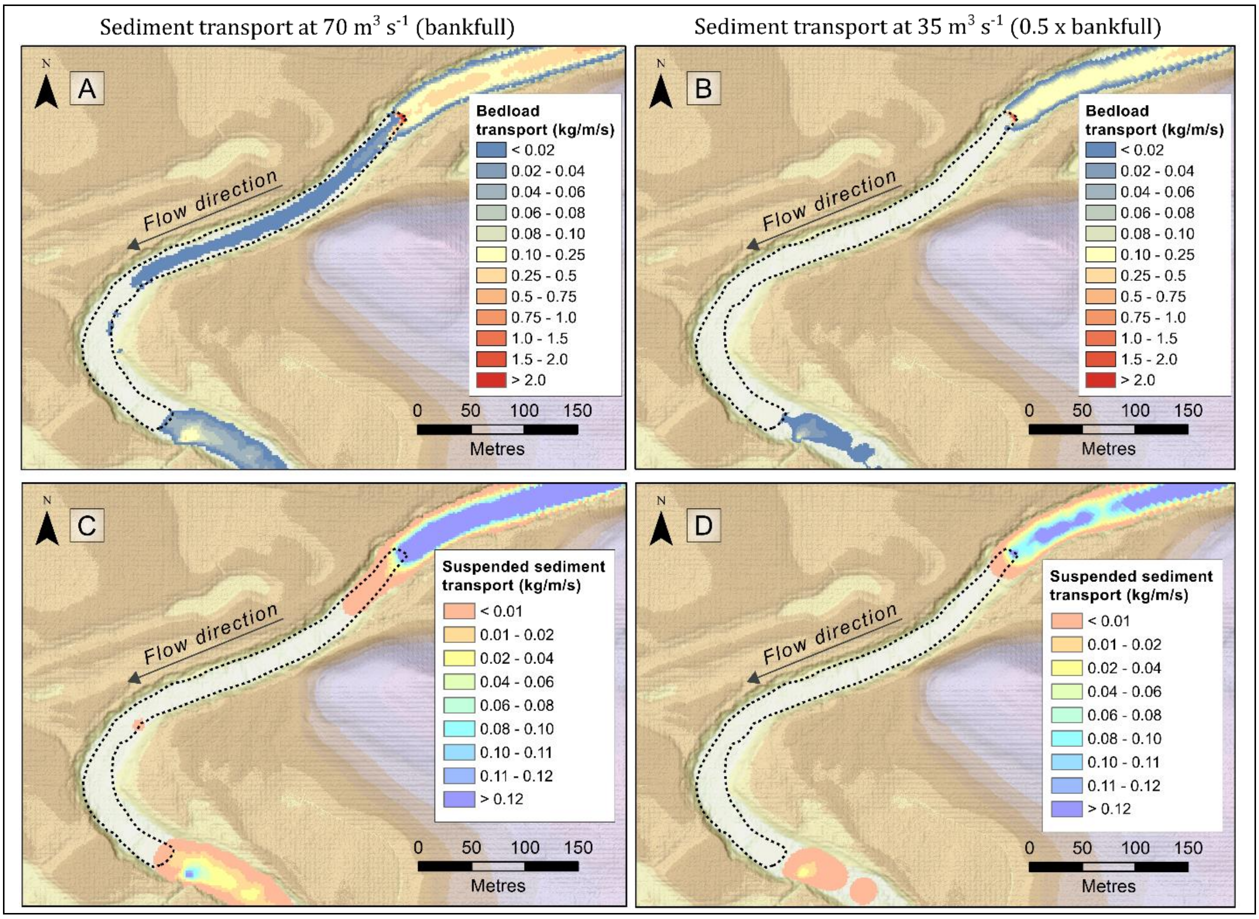


Figure 6.9: Bedload transport (kg/m/s) in Corndale pit 1 for (A) a discharge of 70 $m^3\ s^{-1}$ (bankfull) and (B) discharge of 35 $m^3\ s^{-1}$ (0.5 x bankfull). (C) is suspended sediment transport (kg/m/s) for a discharge of 70 $m^3\ s^{-1}$ and (D) suspended sediment transport for a discharge of 35 $m^3\ s^{-1}$. Note the intrusion of bedload and suspended sediment into the at bankfull discharge that is largely absent at the lower discharge.

6.2.4.2 Corndale pit 2

Depth-averaged velocity decreases within Corndale pit 2, but depth-averaged velocity increases immediately upstream (by only 0.01 m s^{-1}) and downstream of the pit (by approximately 0.07 m s^{-1}) (Figure 6.10B). The key point is that increases in depth-averaged velocity around the pit, but upstream of the pit in particular, less than 10 % of the typical velocities modelled for the pit-free scenario (which ranged from 0.7 – 1.5 m s^{-1}).

Bed shear stress is also much lower within pit 2 (dropping from 8.9 N m^{-2} without pits, to 1.9 N m^{-2} with the pit), and like pit 1, peak bed shear stress immediately downstream of the pit shifts from one side of the channel to the other (for pit 2, from the true left to the true right) (Figure 6.10C and D).

The net direction of secondary circulation-driven momentum is towards the outside of the meander bend with and without an extraction pit. However, extraction pit 2 influences the magnitude of secondary circulation driven momentum in the opposite manner to pit 1: outward momentum *decreases* on the inside of the bend (where the original point bar was) and *increases* on the outside of the bend (Figure 6.10E and F).

Like pit 1 the sediment transport rate (bedload and suspended load) falls to zero across most of pit 2, regardless of discharge (Figure 6.11). The exception is a relatively short finger of bedload transport that extends extending into the pit from the upstream end at bankfull discharge (Figure 6.11). Like pit 1, a wider zone of suspended sediment transport also extends into the pit, but not as far as the zone of bedload transport. Both the zone of bedload transport and suspended sediment transport within the pit disappear at a discharge of 35 m^3 s^{-1}. The pit also slightly increases the sediment transport rate upstream of the pit (by only 0.02 kg m^{-1} s^{-1} a 10 % increase relative to no pits), at the downstream lip of the pit, and downstream of the pit (by up to 0.6 kg m^{-1} s^{-1} a 12 % increase relative to no pits). The change in sediment transport pattern downstream of the pit mirrors the switch in bed shear stress: the sediment transport rate increases on the true right but decreases on the true left of the channel.

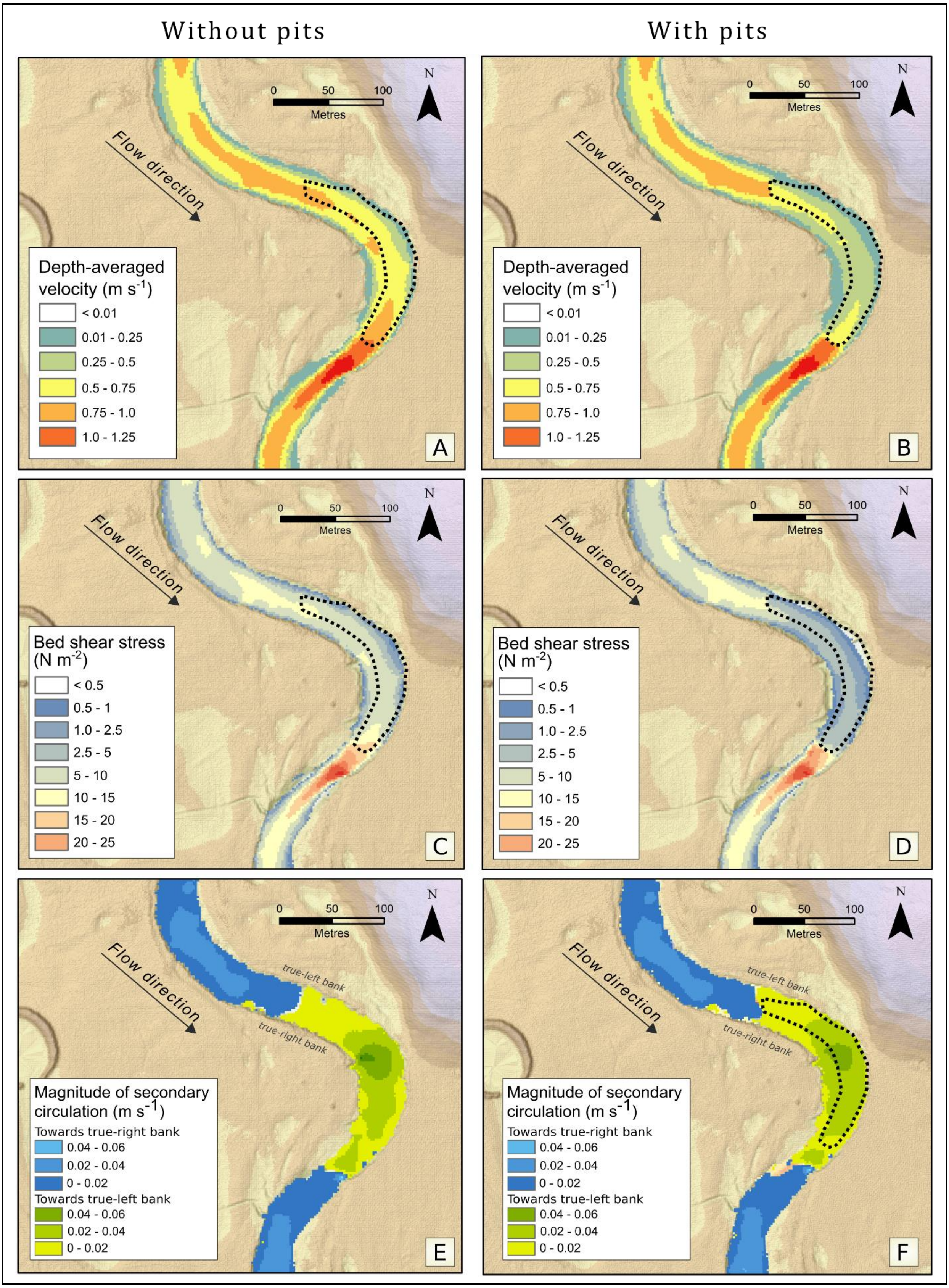


Figure 6.10: Modelled hydraulic variables at bankfull discharge (70 m3 s-1) at Corndale pit 2. Depth-average velocity without pits (A) and with pits (B), bed shear stress without pits (C) and with pits (D) and the magnitude and direction of secondary circulation without pits (E) and with pits (F).

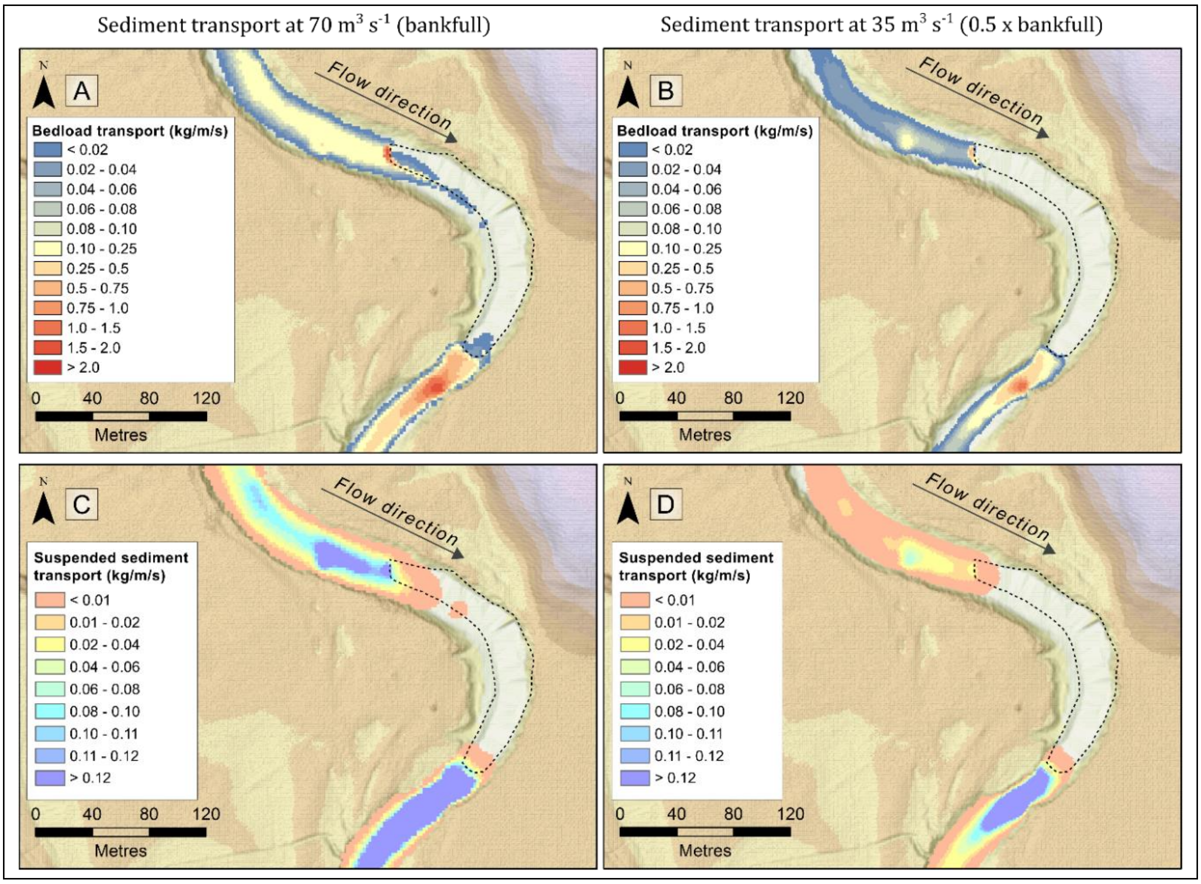


Figure 6.11: Bedload transport (kg/m/s) in Corndale pit 2 for (A) a discharge of 70 $m^3 s^{-1}$ (bankfull) and (B) discharge of 35 $m^3 s^{-1}$ (0.5 x bankfull). (C) suspended sediment transport (kg/m/s) for a discharge of 70 $m^3 s^{-1}$ and (D) suspended sediment transport for a discharge of 35 $m^3 s^{-1}$. Note the pattern of bedload transport at the upstream end of the pit at bankfull discharge, where sediment hugs the inside of the meander bend.

6.2.4.3 Claybanks pit

The Claybanks pit, excavated on a sharp meander bend, decreases flow velocity on the inside of the meander bend by 0.45 m s^{-1} (which covers most of the pit) and increases flow velocity on the outside of the meander bend, along the cut bank, by up to 0.5 m s^{-1} (Figure 6.12A and B). Upstream of the pit, on the true left side of the channel, velocity increases, as does a narrow zone immediately downstream of the pit, on the true right of the channel (Figure 6.12A and B).

The change in bed shear stress caused by the Claybanks pit follows a similar pattern to change in depth-averaged velocity: decreasing from 2.4 N m^{-2} to as low as 0.04 N m^{-2} over the former point bar and increasing on the outside of the meander bend (with the average increase in bed shear stress of ~ 2 N m^{-2}) (Figure 6.12C and D). Overall, the increase in bed shear stress upstream and downstream of the pits is small (~ 9 %) relative to the bed shear stress without pits.

The Claybanks pit changes the magnitude (but not the direction) of the secondary circulation driven momentum in a similar manner to Corndale pit 2. Outward momentum decreases at the upstream and downstream margins and along the inside of the meander bend, but outward momentum increases on the outside of the bend, along the cut bank.

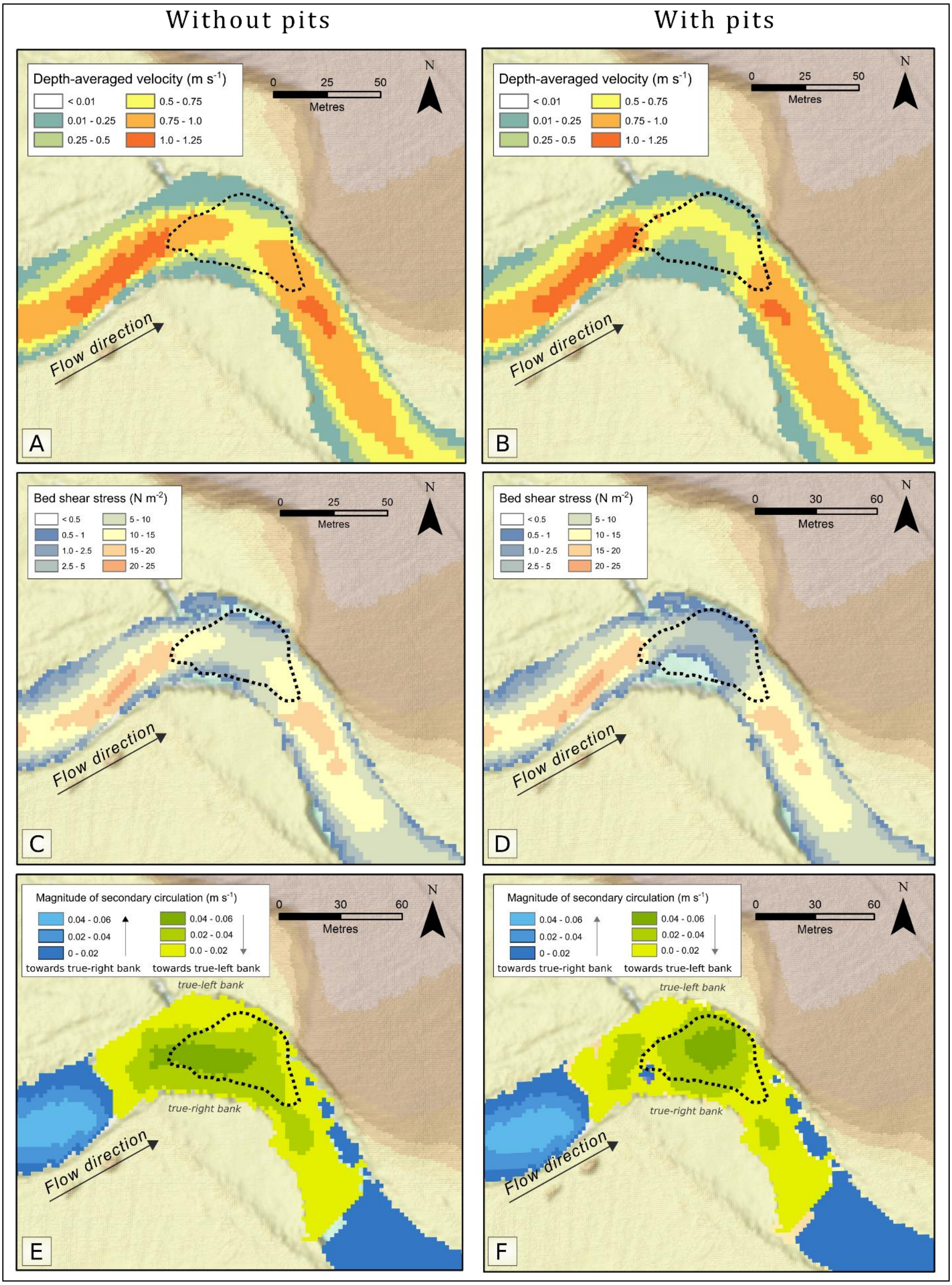


Figure 6.12: Modelled hydraulic variables at bankfull discharge (70 m3 s-1) at the Claybanks pit. Depth-average velocity without pits (A) and with pits (B), bed shear stress without pits (C) and with pits (D) and the magnitude and direction of secondary circulation without pits (E) and with pits (F).

At bankfull discharge a zone of bedload transport extends into the pit (Figure 6.13A) but unlike pit 2 (which is also on a meander bend) this zone of bedload transport hugs the outside of the meander bend, not the inside of the meander bend like in Corndale pit 2. At bankfull discharge a lobe of suspended sediment transport also enters, but this area of suspended sediment transport extends across the width of the pit (Figure 6.13C), including the inside of the meander bend, over the original point bar. Both bedload transport and suspended sediment transport then begin again within the pit, at the tail of the pit (but still within the pit itself). At half of bankfull discharge (35 m^3 s^{-2}) bedload transport quickly falls to zero in the pit (Figure 6.13B), and the lobe of suspended sediment transport does not extend as far into the pit (Figure 6.13D). Similarly, bedload and suspended sediment transport then begin again within the pit, but very close to the tail of the pit, so less of the pit bed is experiencing either mode of sediment transport than at bankfull discharge.

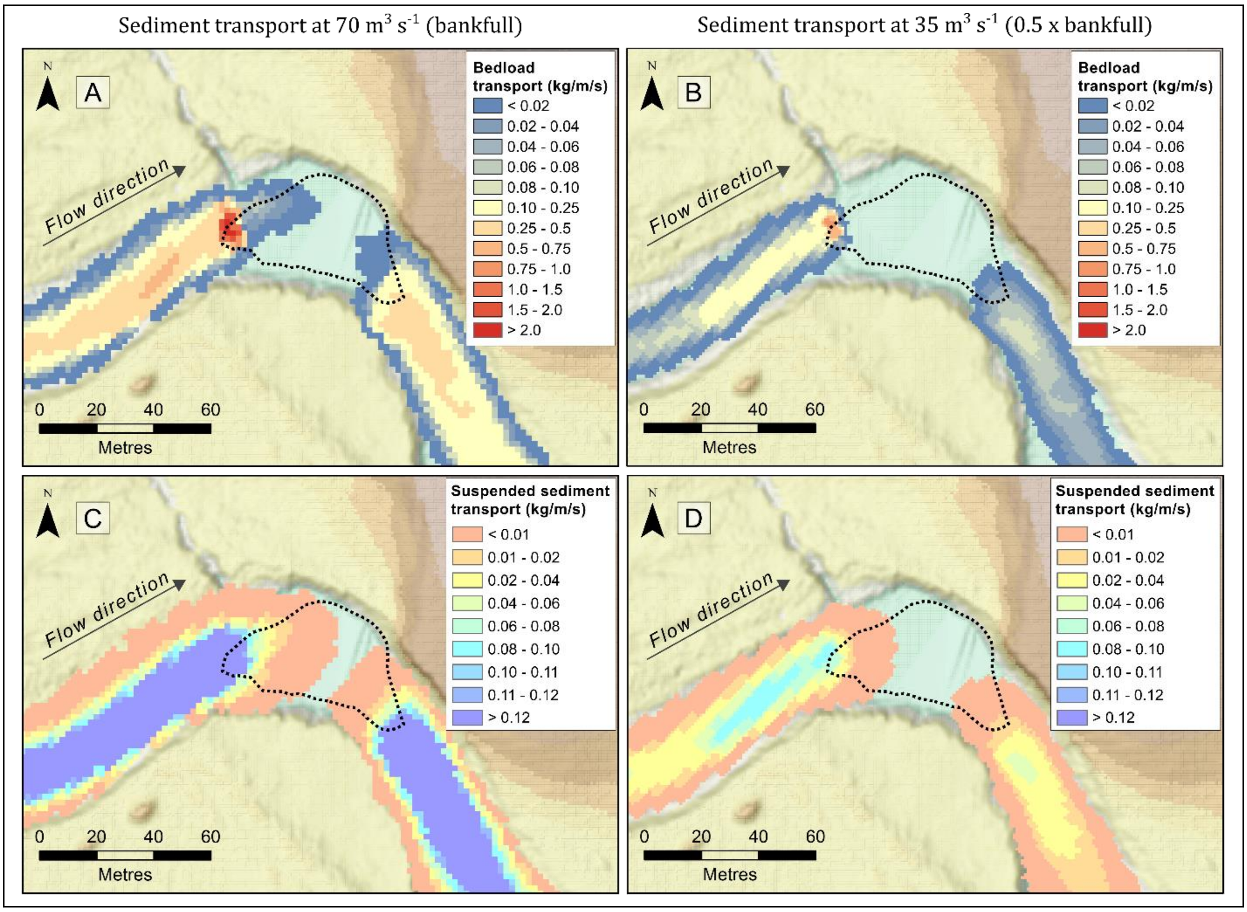


Figure 6.13: Bedload transport (kg/m/s) in the Claybanks extraction pit (A) a discharge of 70 m^3 s^{-1} (bankfull) and (B) discharge of 35 m^3 s^{-1} (0.5 x bankfull), (C) suspended sediment transport (kg/m/s) for a discharge of 70 m^3 s^{-1} and (D) suspended sediment transport for a discharge of 35 m^3 s^{-1}. Note that at bankfull discharge bedload transport hugs the outside of the meander bend while suspended sediment evenly covers the pit.

6.2.4.4 Pit interaction

All three extraction pits begin to fill at the same time. None of the pits merge together as they fill and migrate.

Pits 1 and 2 are close enough together (the downstream end of pit 1 is 530 m from the upstream end of pit 2) for changes in hydraulic conditions caused by pit 1 to slightly increase the bed shear stress in the bed immediately upstream of pit 2 (Figure 6.14). Bed shear stress, depth averaged velocity and the total sediment transport rate all increase in the streambed between the two pits (relative to the no-pit scenario), but by less than 10 %. The small increase in depth-averaged velocity, bed shear stress and total sediment transport rate are a combination of the downstream impact of pit 1 and the upstream impact of pit 2, although the relative impact of each pit on this small total change is difficult to discern. Hydraulic changes caused by pit 2 only extend 150 m downstream of the pit exit and therefore do not impact the flow field over any downstream pits (Figure 6.14).

The streambed between Corndale extraction pit 2 and the Claybanks extraction pit (3.25 km of river length) is largely unchanged compared to the pit-free scenario, apart from some changes confined to two meander bends (Figure 6.14). Changes at each of the meander bends extends over a stream length of ~150 m. The changes are disconnected from each other and from the upstream and downstream extraction pits. Changes in the channel form and the total sediment storage in this part of the study reach are presented in the reach scale results chapter (Chapter 7).

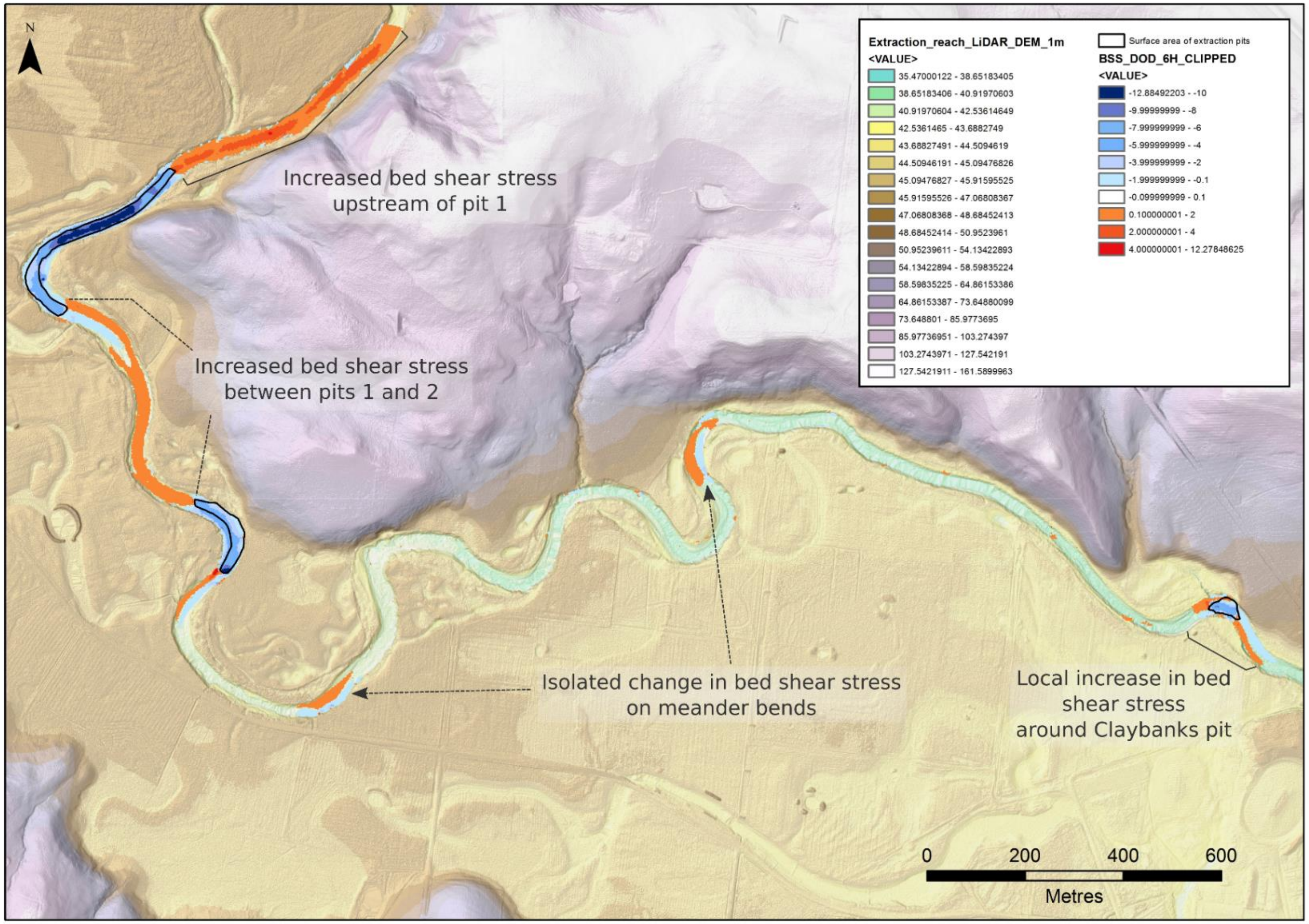


Figure 6.14:The changes in bed shear stress for the upper part of the study reach, where bed shear stress has increased upstream of pit 1, and between pits 1 and 2, and in the area immediately surrounding the Claybanks pit. Apart from some isolated changes in bed shear stress on meander bends, the Corndale pits (pits 1 and 2) has little influence on the hydraulics of the Claybanks pit, which is 3.25 km downstream.

6.2.5 Morphodynamic modelling results

This section presents the results of the morphodynamic modelling. The morphodynamic modelling predicts how channel hydraulics, which have been altered by the presence of extraction pits, will translate into the erosion and deposition within and around the pits. I remind the reader that the morphodynamic modelling was run for two discharge scenarios: bankfull discharge (70 $m^3 s^{-1}$) and 0.5 x bankfull discharge (35 $m^3 s^{-1}$).

All scenarios were run with a continuous, at-capacity sediment supply. In reality, pits are subject to a stochastic flow pattern, and the particular sequencing of flow events will determine how the channel evolves. Thus, the relatively long-duration of flows (10 days) simulated in the Delft3D model is used to assess the overall pattern of sediment erosion and deposition, *not* the absolute magnitude of erosion and deposition or rate of pit infill (which will vary year to year). Therefore, the effect of the pits on the pattern of deposition are amplified and should be considered a maximum for the channel.

Overall the morphodynamic model predicts a pattern of in-fill for Corndale pit 1 and 2 that reflects the pattern of sediment transport described in the previous section. The two discharge scenarios have similar pattern of infills, but the bankfull scenario delivers more sediment to the pits. The predicted pattern of in-fill for pit 1 and 2 closely matches the pattern of infill captured by the channel surveys (Figure 6.3 and Figure 6.4). The predicted pattern of in-fill in the Claybanks pit does not resemble the in-fill pattern surveyed in either 2018 or 2019 (Figure 6.5). The two extraction pits excavated on meander bends do not behave in the same manner. I now consider the pattern of in-fill predicted for each of the three extraction pits in more detail.

6.2.5.1 Corndale pit 1 infill pattern predicted by the morphodynamic model

The pit head advances in the same pattern as the bankfull scenario, but after 10 days at half bankfull discharge only migrates 20 metres (compared to 46 metres at bankfull) and the smaller lobe of deposition that leads the avalanche face only extends a further 20 metres into the pit. There has been some erosion across the upper, untouched portion of the point bar (outside the pit). Unlike the bankfull scenario, there has been some deposition on the inside of the meander bend (within the pit) (Figure 6.15A).

After 10 days of continuous bankfull flow, sediment has deposited in the upper 100 m of the pit (Figure 6.15B). At the same time, the bed of the pit has scoured (in the same area as the zone of elevated bedload transport in Figure 6.9A), and sediment has been deposited along the pit margins (Figure 6.15B). The head of the pit migrates downstream by 46 m, and a second lobe of deposition then extends a further 30 m into the pit. Sediment is deposited against the downstream end of the pit. The model predicted scour up to one metre deep downstream of the pit in both scenarios, but the length of that scour channel decreases from ~100 metres at bankfull discharge to ~60 metres at half-bankfull discharge.

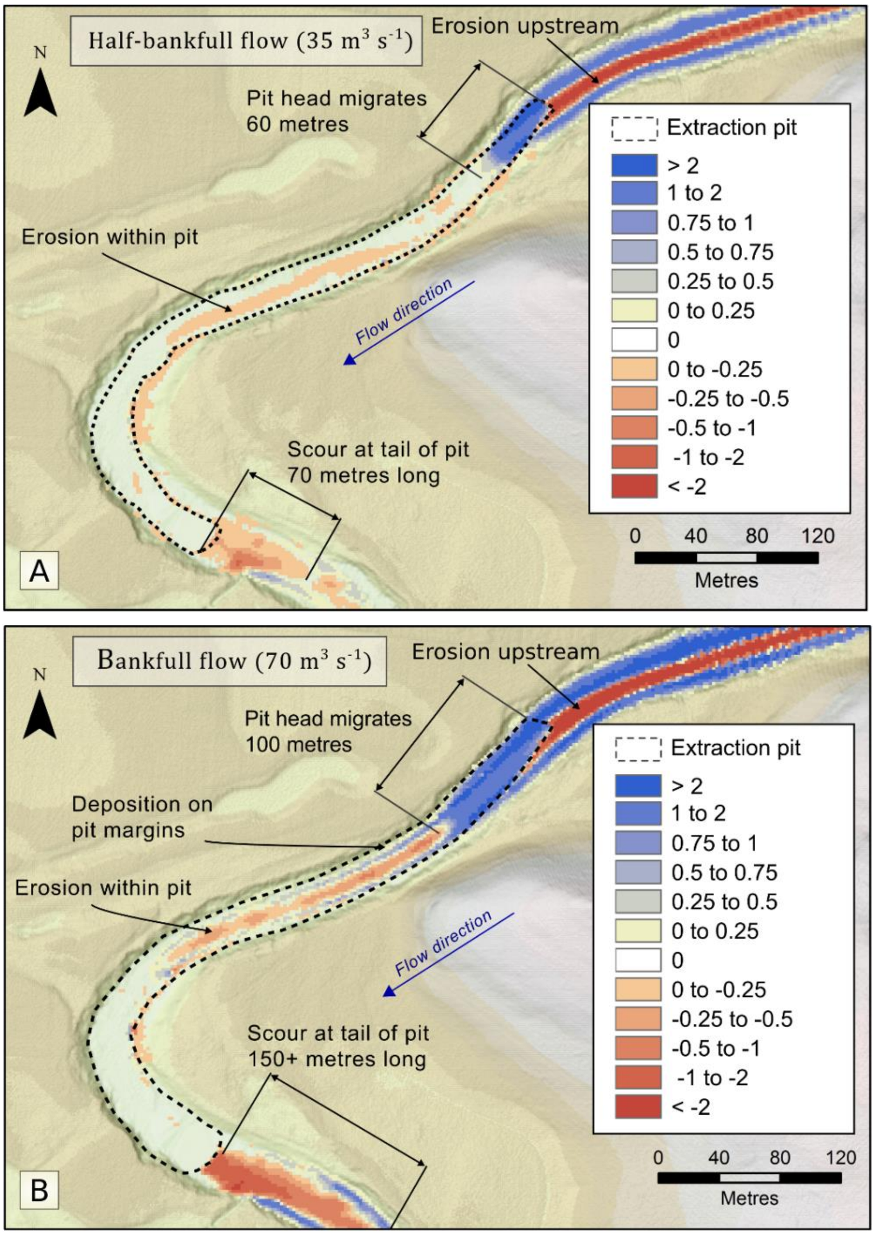


Figure 6.15: Erosion and deposition predicted for Corndale pit 1 by the morphodynamic model after 10 days of continuous flow at (A) half-bankfull scenario, showing the advancing pit head, scour on the bed of the pit and migration of the downstream end of the pit, (B) bankfull scenario, showing migration of the pit head, deposition along the pit margins, increased scour along the centre of the pit and a much larger scour zone downstream of the pit.

6.2.5.2 Corndale pit 2 infill pattern predicted by the morphodynamic model

The pattern of infill predicted for Corndale pit 2 matches the pattern of bedload transport predicted by the hydraulic model (Figure 6.11A). The head of the pit is predicted to migrate along the inside of the meander bend, so that the pit face is not uniform (Figure 6.16B). This pattern of pit-head migration emerges in both discharge scenarios but is more pronounced at bankfull than at half-bankfull (Figure 6.16A). At bankfull discharge a scour zone forms within the pit, at the downstream end (predicted depth < 1 m), but this scour disappears when discharge falls to half-bankfull. In both scenarios a long, deep scour zone forms immediately downstream of the pit.

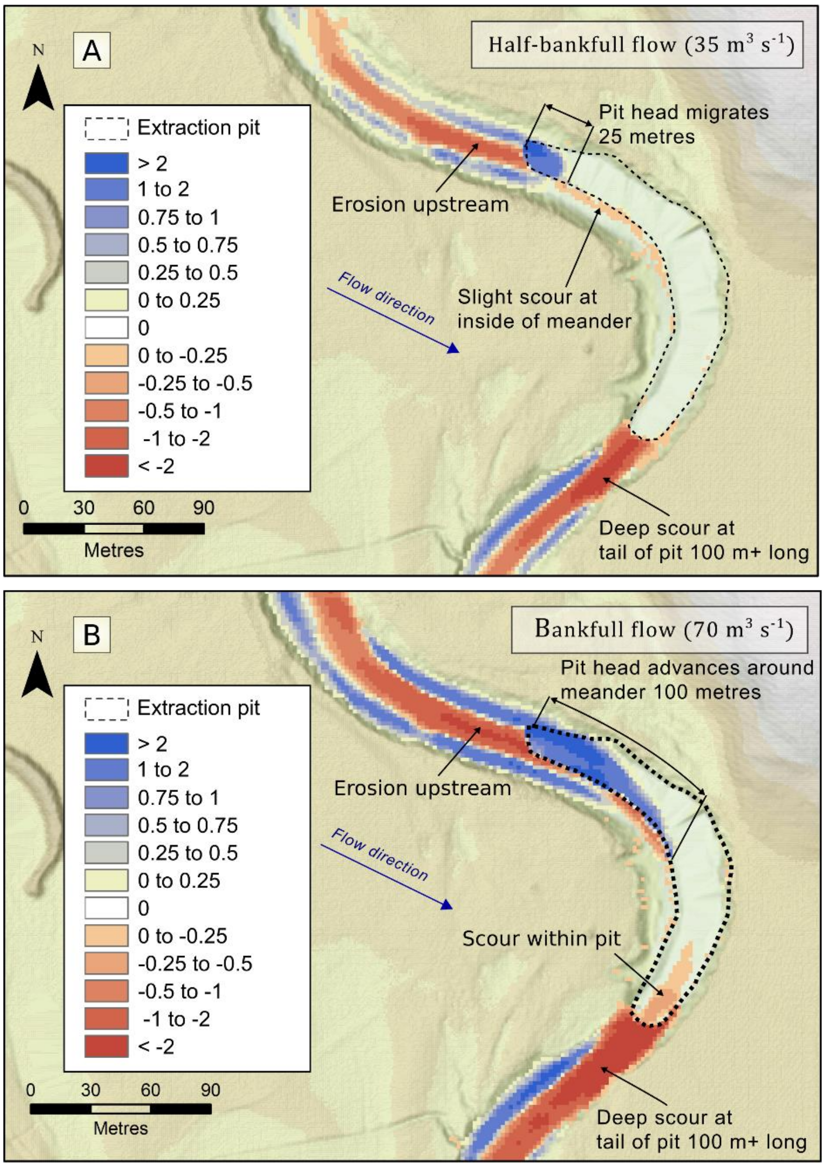


Figure 6.16: Erosion and deposition predicted for Corndale pit 2 by the morphodynamic model after 10 days of continuous flow at (A) half-bankfull scenario with a pit head that has only just advanced into the pit, scour along the margin of the pit, on the inside of the meander, and deep scour downstream of the pit, (B) bankfull scenario showing the advancing pit hugging the inside of the meander bend and scour both within the pit and downstream of the pit.

6.2.5.3 Claybanks pit infill pattern predicted by the morphodynamic model

The bankfull discharge scenario predicts that the Claybanks pit will completely re-fill in ten days, and that deposition will be greatest on the inside of the meander bend and on the outside of the meander bend, with a channel cutting between the two areas (Figure 6.17B). A narrow scour zone formed upstream and downstream of the pit. After ten days of half-bankfull flow the Claybanks pit has not filled (Figure 6.17A). A lobe of deposition, which spans the width of the channel, extends into the pit from the upstream end. At the same time, sediment is eroded at the tail of the pit, against the inside of the meander (Figure 6.17A). The apex of the outside of the meander, at the bend apex, remains sediment-free. Scour zones form upstream and downstream in the both scenarios, but are deeper under bankfull flow.

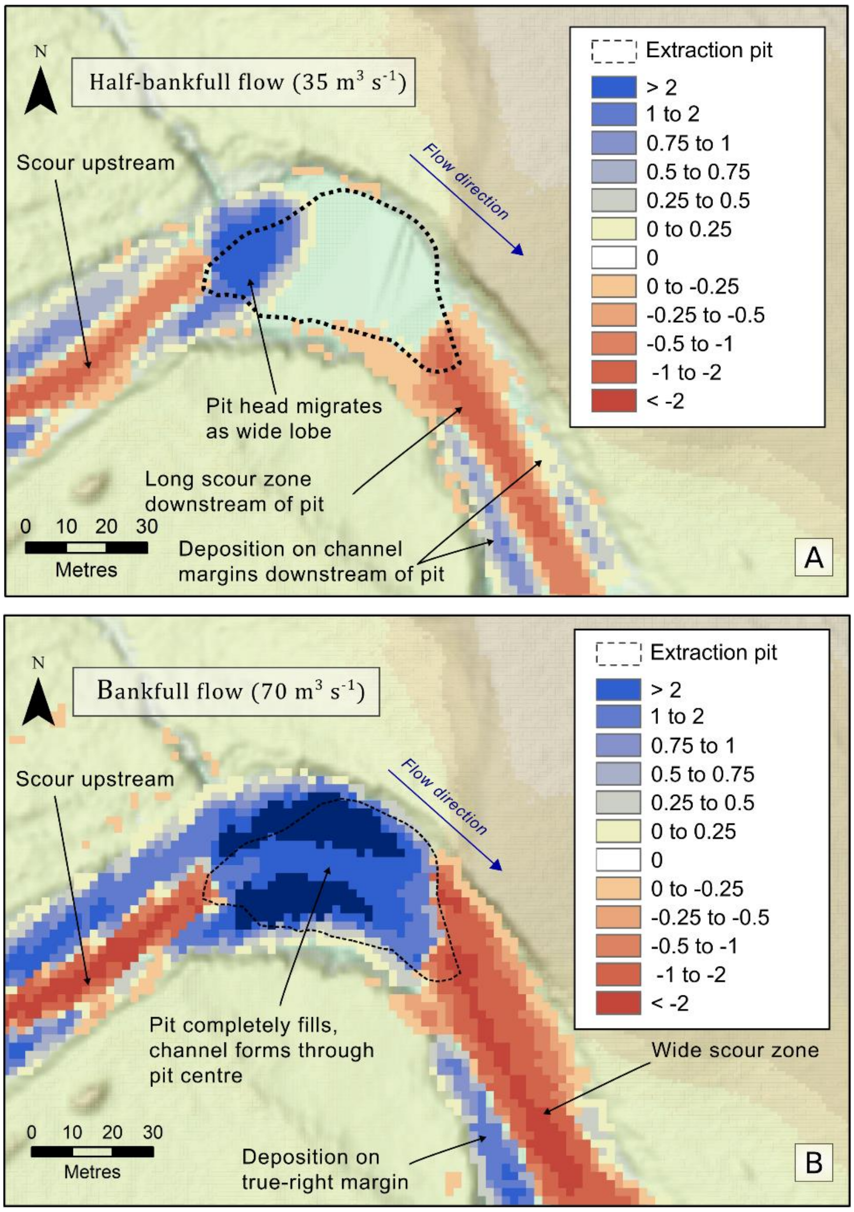


Figure 6.17: Erosion and deposition predicted for the Claybanks pit by the morphodynamic model after 10 days of continuous flow at (A) half-bankfull scenario showing the lobe of sediment extending into the pit, and at the same time, erosion at the downstream end of the pit, on the inside of the meander. Downstream of the pit a scour channel has formed, but sediment is also deposited along the channel margin, (B) bankfull scenario with the pit completely filled and pronounced deposition on the inside and outside of the meander bend, with a channel through the centre of the pit. Note that this deposition pattern in (B) is nothing like the pattern surveyed in the field.

6.2.6 Summary of pit surveys and hydraulic and sediment transport modelling

Pits fill from their upstream end, but they also fill from their lateral margin inwards at the same time. In pit 2, excavated on a meander bend, sediment accumulates on the point bar first and then migrates towards the outside of the channel. This process means that on meander bends the migrating head of the extraction pit does not advance uniformly.

The downstream end of extraction pits does not migrate in a uniform fashion and in the case of pit 1, does not migrate downstream at all. Instead, sediment has accumulated against the downstream wall of pit 1. The intense scour downstream of the pits is not spread across the entire width of the streambed but is concentrated into a narrow zone on the true left (pit 1 and 2) or the centre of the channel (Claybanks pit).

In-stream vegetation (*Phragmites australis*) established around the Claybanks extraction pit, but none of the Corndale pits. Between 2010 and 2018 *Phragmites* surrounding the Claybanks pit changed their pattern of coverage, expanding along the margin of the pit but receding in the channel centre, where a narrow low-flow channel has formed.

Extraction pits alter the flow field compared to the pit-free channel. As expected, flow velocity bed shear stress and total sediment transport rate all reduce as flow crosses the pit. Depth-averaged velocity, bed shear stress, bedload transport rate and suspended sediment transport rate increase immediately downstream of all three pits, but these flow properties only change upstream of pit 1; the flow field upstream of pit 2 and Claybanks is largely unaffected. Secondary circulation is also modified in all three pits. In pit 1 the outward component of secondary circulation, which dominates over the inward component with and without extraction pits, increases over the inside of the meander bend, but slightly decreases on the outside of the bend. In pit 2 and the Claybanks pit, the location of peak magnitude in secondary circulation (which is also net-outward with and without the extraction pits) is shifted towards the outside of the meander.

The morphodynamic model performs well for pit 1 and 2, closely predicting the magnitude and pattern of deposition at the head of the pit and along the margins of the pit. However, the morphodynamic model under-predicts sediment accumulation at the downstream end of pit 1. The model performs the worst in the Claybanks pit, predicting the exact opposite pattern of deposition to that observed in the channel surveys (the model predicts deposition on the outside of the meander bend, but in reality, deposition starts on the inside point bar).

6.3 Discussion

This chapter has used multiple sources of information to test the conceptual model of pit evolution outlined in Chapter 5. This conceptual model predicted how extraction pits excavated in a medium sized sand-bed river would re-fill with sediment, how the pits would migrate and how the pits would interact. The model I developed included four aspects that are missing from existing models of pit evolution:

1. the combined effect of sediment moving as bedload and in suspension
2. the two-dimensional pattern of pit-infill and changes in the flow field over the pit
3. the interaction between extraction pits and in-stream vegetation
4. the evolution of extraction pits excavated on straight channel segments and on meanders.

The conceptual model was evaluated using repeated channel surveys, a two-dimensional hydraulic and sediment transport model, and by collating observations from extractors who excavate the pits.

Pit infill did not proceed as the conceptual model outlined in Chapter 5 predicted. The conceptual model I developed predicted that the head of the extraction pit would steadily migrate downstream, and at the same time the downstream end of the pit would rotate in a downstream direction as a scour profile developed downstream of the pit. The upstream end of pit 1 did migrate downstream by 210 metres over the twelve months between surveys, but also filled from the channel margins towards the centre of the pit at the same time. Pits excavated from meander bends began to re-build point bars from the base upwards, from the inside towards the outside of the bend and from upstream to downstream at the same time. In short, the simple models of pit-infill used to build the conceptual model in Chapter 5 are based on flume studies and do not capture the inherently stochastic and two-dimensional nature of pit-infill in natural channels. In the following discussion I explore four ways the results in this chapter modify our understanding of pit evolution in natural, sand-bed channels: the pattern of infill under varying flows when sand is transported as bedload and suspended load, how excavated point bars re-build after extraction, upstream and downstream impacts of a single extraction pit that is repeatedly excavated, and how in-stream vegetation impacts pit infill. I conclude with a revised conceptual model for pit evolution in natural, sand-bed channels.

6.3.1 Pit infill in a straight channel

The key differences between the pattern of infill predicted by the conceptual model and the pattern of infill observed in this study is the degree to which sediment transport occurs within the filling pit. The sediment transport modelling shows that at both bankfull and 0.5 x bankfull discharges a zone of bedload transport and a trailing zone of suspended sediment transport both develop at the upstream end of the pit. At the same time sediment is deposited along the pit margins. The field surveys show close agreement with the model predictions, with a deep scour channel in the centre of the pit, migration of the head of the pit, and deposition on the pit margins.

In flume experiments, bedload arriving at the head of the pit fills the pit by falling down an avalanche face, causing the head of the pit to migrate downstream. At the same time the downstream end of the pit rotates in a downstream direction and a scour profile develops downstream of the pit. This conceptual model assumes no sediment transport through the pit and the intervening bed of the pit remains unchanged. The two-dimensional hydraulic and sediment transport modelling results for Corndale pit 1 show sediment is transported along the bed of the pit at bankfull discharge (but that sediment transport falls to zero within the pit at half of bankfull discharge).

Instead, at bankfull discharge bedload transport and suspended sediment transport abruptly decrease at the head of the pit (but does not fall to zero), and then gradually decreases towards zero with distance into the pit. Sediment rains out from suspension in the upper 75 m of the pit and a long, but narrow zone of bedload transport funnels material along the bed for a further 300 m into the pit (Figure 6.18). The narrow zone of bedload transport is also present in the pit-free modelling scenario and roughly coincides with the location of the narrow, deep section of the pit captured in the 2019 survey.

The fact that bedload transport is zero within the pit during the lower discharge of 35 $m^3 s^{-1}$ (half of bankfull discharge) and that the lobe of suspended sediment transport only extends 30 m into the pit (compared with 75 m for the bankfull scenario) show that changes in discharge impact both the *rate* of pit infill (by changing total sediment supply) and the *pattern* of infill (by determining whether sediment is mobilised along the bed of the pit).

The accumulation of sediment on the bed of the pit (further downstream than the advancing head of the pit) is caused by the collapse of the pit walls and presumably some deposition from newly arriving sediment along the pit margin. Pit-wall collapse, evident by the V-shape of cross-sections in Corndale pit 1 and 2, was also observed in the flume experiments of Barman *et al*. (2018). Extraction of the pit during low flows removes support for the sand along the pit margins. As the pit fills with water, pore pressure increases, grains become more buoyant, and the walls slump towards the channel centre, creating the V-shaped cross-section. In this manner pit wall collapse is a slight re-distribution of material within the pit as it relaxes following excavation, not an infill process per se. Deposition along the pit margins is also predicted by the morphodynamic model at bankfull discharge.

The close match between the location and extent of the scour channel that develops on the bed of pit 1 as it fills (where the 'channel' is a sediment-free zone also prone to scour), and the area of elevated shear stress predicted by the pit-free scenario of the hydraulic model suggests that the two-dimensional, channel-scale hydraulics operating in natural sand-bed rivers are a primary control on the pattern of pit infill. While the overall trend of an advancing pit-head was observed in the Glenelg River, the detailed pattern of deposition will vary according to the strength and direction of secondary flow cells in meander bends, flow direction as it approaches the pit and the initial shape of the pit and most importantly, fluctuating discharge. For example, site-specific patterns of flow depth and velocity drove the particular rate and pattern of deposition in the extraction pits and point bars studied by Owens *et al.* (2010) and Rempel and Church (2009).

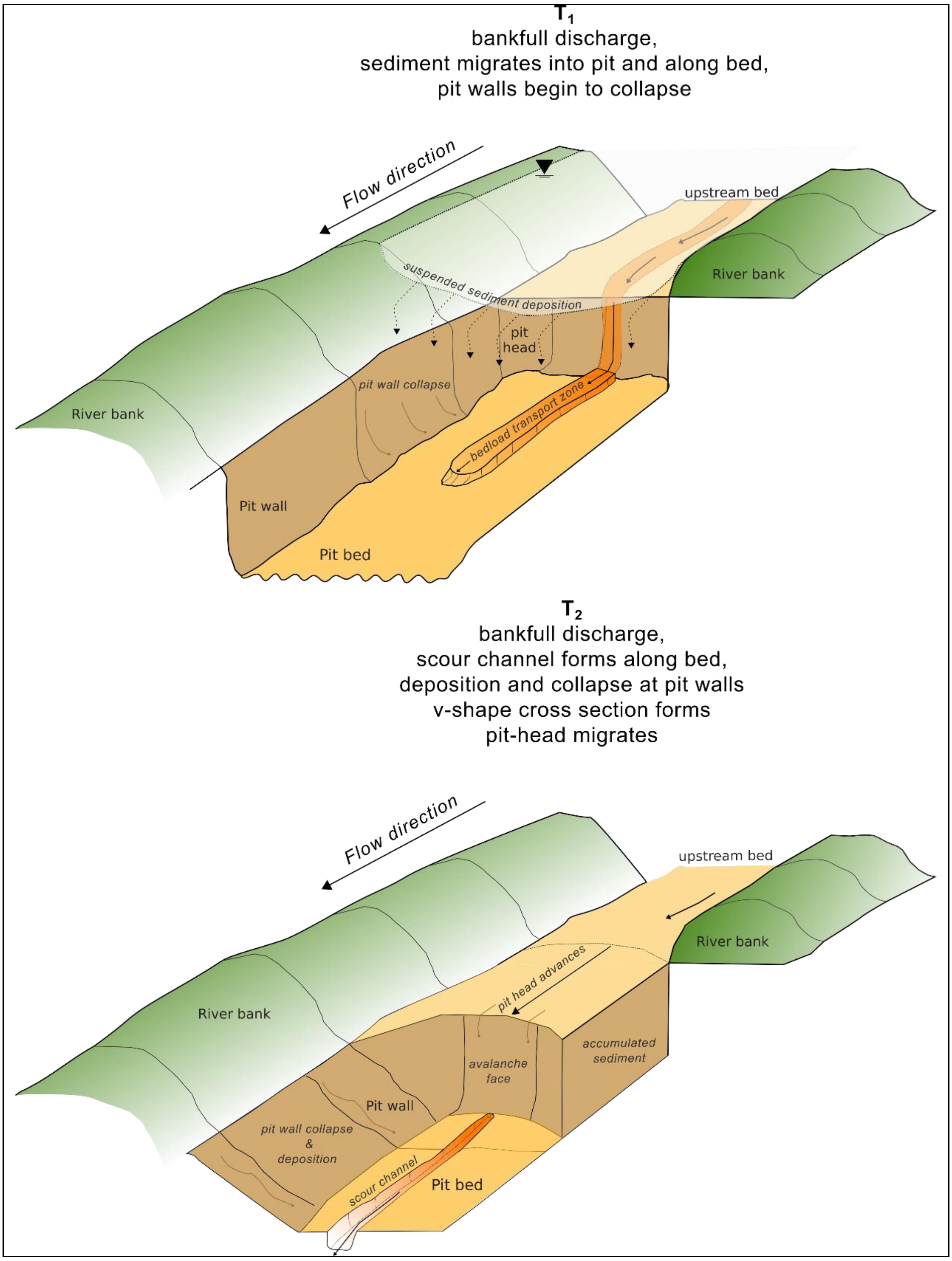


Figure 6.18: Modified conceptual model of pit infill in straight channels, showing at T_1 (beginning of pit infill) sediment settling from suspension and the transport of bedload down the avalanche face and into the pit, and collapse of the pit walls, T_2 the resulting change in pit geometry, the pit head has migrated downstream, wall collapse and deposition along the margins have generated a V-shaped cross-section and a scour channel has formed in the bed of the pit.

6.3.2 How point bars re-build following extraction

This study also examined the infill of pits excavated at the toe of point bars. In most published examples point bar extraction is by 'scraping' – where the entire surface of the exposed point bar is evenly lowered. The scraping technique is employed in wide, gravel bed rivers where the point bar surface is near is horizontal, and a clear break in slope delineates the point bar from the adjacent bank. In the Glenelg River the extractors completely remove the toe of the point bar, and the higher elevation section of the point bar that mantles the adjacent bank is left untouched.

Overall excavated point bars in the Glenelg River re-build in two ways. 1) accretion from the base upwards, from the inside outwards and form upstream to downstream – all at the same time, and 2) from the base upwards, from the inside of the meander towards the outside, and from the downstream to upstream (*not* from upstream to downstream), all at the same time. These patterns can be seen in Corndale pit 2 and the Claybanks pit, respectively. The different fill pattern of the Claybanks was surprising. Closer inspection of flow pattern in the channel revealed a recirculating eddy on the inside of the meander of the Claybanks pit which induced weak upstream flow (Figure 6.19). Recirculating eddies did not form in either of the other pits.

The two re-build patterns are driven by deposition form two different flow cells: point bars that are fed sediment by the inwards component of a secondary flow cell sweeping along the channel bed (pit 1 and 2), and point bar formation within recirculating flow cells that form when sediment enters the low-velocity eddies (the Claybanks pit). I consider each type of re-building in more detail below.

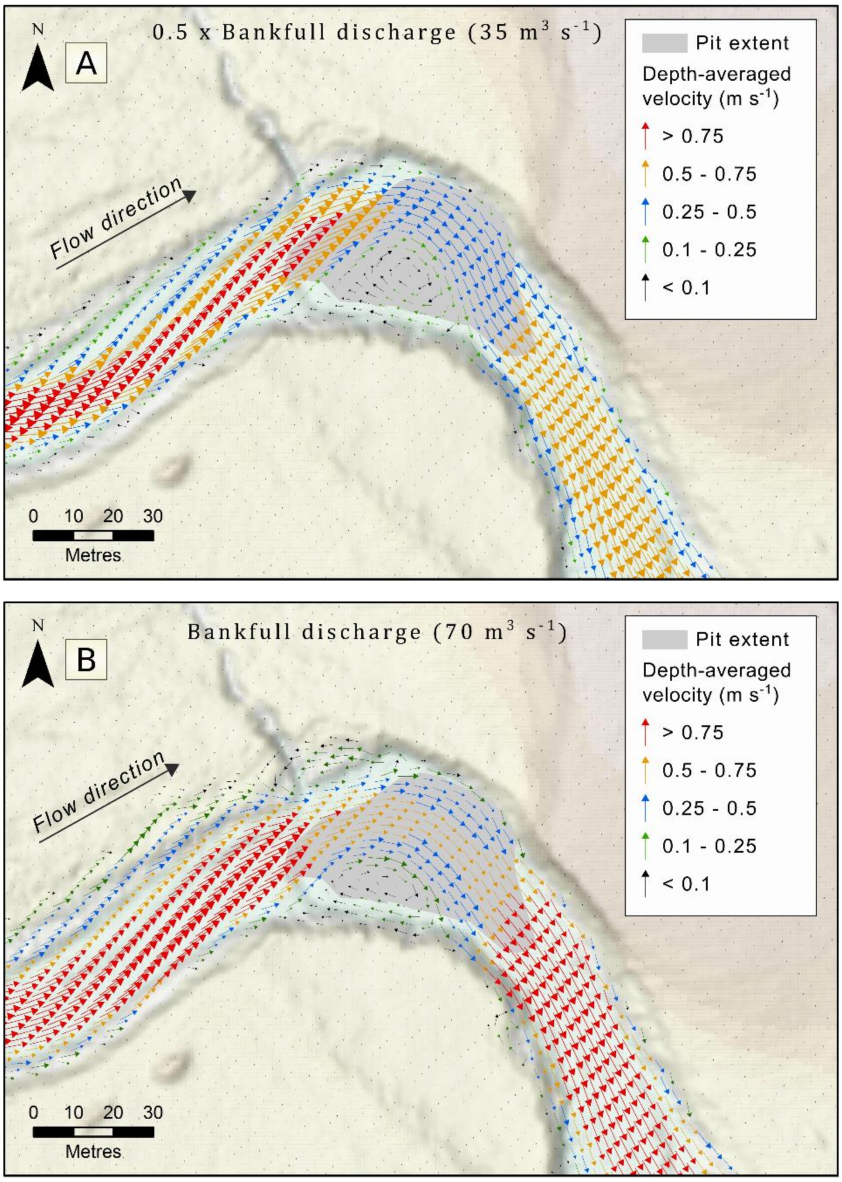


Figure 6.19: Depth-averaged velocity vectors at the Claybanks extraction pit for (A) half-bankfull discharge and, (B) bankfull discharge, showing the development of a recirculating eddy and weak upstream flow on the inside of the point bar. Note that the location of the flow cell shifts towards the inside of the meander and slightly upstream as discharge increases.

6.3.2.1 Horizontally accreting point bars

The upwards and outwards growth of point bars is driven by the channel-scale flow pattern that originally built and maintained the point bar. Pit excavation does not change the direction of secondary circulation and or the pattern of velocity within the channel, only the magnitude of these variable is altered. Sediment that falls to the bed near the outside of the meander bend is swept inwards by the secondary flow cell, feeding the vertical and horizontal growth of the point bar (Dietrich *et al.*, 1979; Dietrich and Smith, 1983; Bridge, 1993). Point bar growth initiates when sediment supply to the head of the meander is restored (Figure 6.20). This means that when extraction pits extend upstream of the point bar, such as in Corndale pit 1, and to a lesser extent, Corndale pit 2, the pit head must migrate downstream to the head of the original point before point bar rebuilding can begin.

Pit 1 and pit 2 are each at a different point of the re-building process. Corndale pit 1 has not yet started to re-build as the migrating pit head has not reached the head of the original point bar. Corndale pit 2 is part way through the rebuilding process but has not yet reached its pre-extraction elevation or extent. Once the point bars have re-built, further sediment inputs will either exchange across the bar surface and move downstream, or will settle adjacent to the bar, fill the channel and 'extinguish' the point bar by burying it.

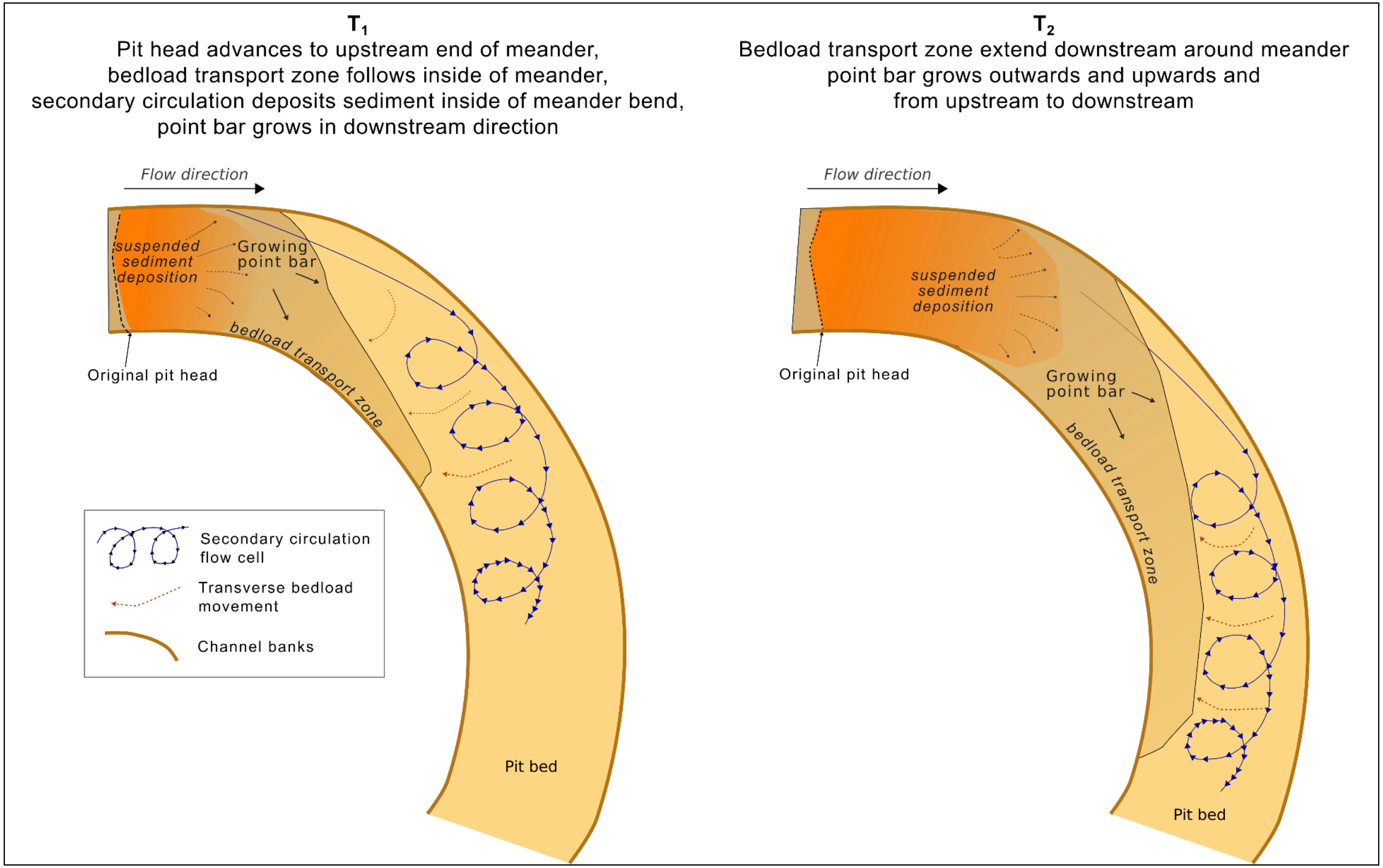


Figure 6.20: Point bar re-building following extraction. The point bar grows when secondary circulation cells are fed sediment by the migrating pit head, bottom currents sweep this sediment towards the inside of the meander, causing the point bar to grow from the inside towards the outside and from upstream to downstream at the same time.

6.3.2.2 Recirculating eddy point bars

Recirculating eddies form at sudden channel expansions (Rubin *et al*., 1990; Schmidt, 1990), in the lee of obstructions (Schmidt *et al.*, 1993) and on the inside of sharp meander bends (Leopold *et al.*, 1960; Leeder and Bridges, 1975; Ferguson *et al.*, 2003). The low velocities and weak upstream flow within the recirculating flow cell drive deposition. Deposition can be concentrated at the upstream point of flow separation, at the downstream margin where flow reattaches, the centre of the eddy (where velocity is at a minimum), or as a elongated deposit along the shear surface between the rotating eddy and the downstream flow (Rubin *et al.*, 1990). At the Claybanks site the shape of the point bar (Figure 6.5) suggests that deposition has occurred via a combination of these mechanism. At the same time sand is deposited within the eddy (which spins clockwise) a wide, deep channel has formed at the pit entry (Figure 6.21). The channel narrows as it extends around the outside of the meander bend, against the cut bank. Ferguson *et al*. (2003) attributed this narrow channel, which is part of most models of meander hydraulics, to the compression of a secondary flow cell that is forced outwards by the 'dead zone' at the inner bank (and later by the topography of the point bar that develops).

The inability of the morphodynamic model to reproduce the pattern of deposition surveyed at the Claybanks pit suggest that the depth-averaged hydraulic and sediment transport model employed here does reproduce the flow patterns controlling deposition and sediment re-working in the pit.

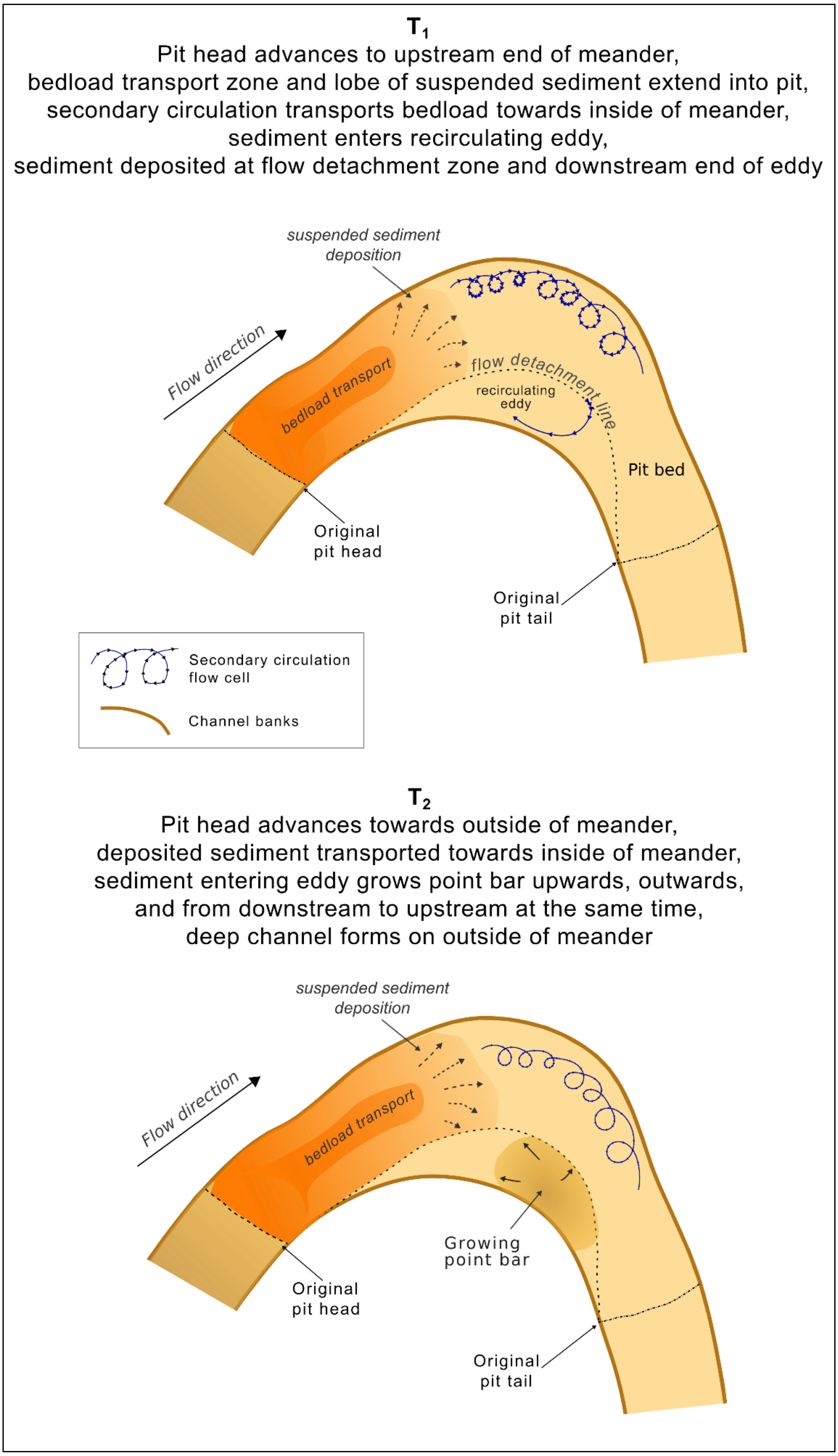


Figure 6.21: Point bar re-building within a recirculating eddy that forms on the inside of a sharp meander, with deposition proceeding from the base upwards, and from downstream to upstream on the inside of the sharp meander.

6.3.3 Bed change upstream and downstream of extraction pits

A key focus of stream managers is how extraction impacts the streambed upstream and downstream of the pits. Existing models predict that a scour profile will develop downstream of an extraction pit. Repeated extraction of the pit should cause scour to be deeper near the pit and for the profile to extend further downstream (Lee *et al*., 1993; Li and Qi, 2015). Barman *et al*. (2018) predicted that the scour profile would begin as a narrow channel at the centre of the downstream end of the pit, and that this narrow scour channel would expand to the full width of the channel over time. This pattern is not supported by this study. Narrow scour zones developed downstream of several of the pits studied here, but these have not expanded to the full width of the channel, despite the pits being repeatedly extracted over the past eight years.

Instead the scour pattern is steered by the pre-existing bed topography. For example, the scour zone downstream of pit 1 has been steered to the true left of the channel by a large, pre-existing bench (although scour channels have developed on the surface of the bench, suggesting that pit-induced scour may gradually lower these features, not undermine them from the side as the scour channel expands). Scour downstream of pit 2 is confined to a narrow channel and the scour downstream of the Claybanks pit meanders through vegetated benches that line the channel. The uniform lowering of the streambed observed in flumes is not observed in the Glenelg River. Scour zones expand to the occupy the width of the flume channel because the flume bed presents uniform resistance, a pattern rarely found in medium sized sand-bed rivers that include in-stream vegetation, accumulations of cohesive sediment, and exposed tree stumps. Repeated phases of extraction from the same pit promote this uneven distribution of scour.

Several studies have documented migrating nickpoint upstream of extraction sites (Kondolf, 1994; Rinaldi *et al*., 2005; Wishart *et al*., 2008). The modelling results indicate that flow velocity and bed shear stress is slightly elevated upstream of Corndale pit 1, but only by 0.05 m s^{-1} and 3 N m^{-2}, respectively. The change in depth-averaged velocity and bed shear stress induced by extraction pit 1 is less than 5 % (depth-averaged velocity) and 18 % (bed shear stress) of typical values modelled in the pit-free scenario. I found no evidence of nickpoints upstream of any of the pits in this study. The lack of nickpoints in the Glenelg River lends support to the contention of Wishart *et al.* (2008) that extraction technique (deep, discrete pits in the case of the Glenelg River) determines whether an extraction pit generates a migrating nickpoint in medium-sized rivers.

6.3.4 Vegetation and pit infill

Vegetation has established on the margins of the Claybanks extraction pit. Bankfull flow velocities and bed shear stress upstream and downstream of the Claybanks pit are similar to those at the Corndale pits 3.5 km upstream, but stock exclusion has removed grazing pressure from the Claybanks site. Since 2010 *Phragmites* have retreated from what is now the low-flow channel upstream of the Claybanks pit. This makes sense as *Phragmites* are highly sensitive to prolonged submergence and the return of more frequent flows post-drought would make the thalweg inhospitable. Changes in *Phragmites* coverage on the margins of the extraction pit itself are small. The slight decrease at the downstream end of the pit is likely a combination of uncertainty in mapping (where bank vegetation obscures *Phragmites* in aerial imagery) and a slight recession as water pools in the extraction pit. Either way, extraction seems to have little influence on *Phragmites* coverage around the pit itself.

Anecdotal evidence from extractors suggests that the Claybanks pit only re-fills during floods, and the beds of *Phragmites* upstream prevent significant sand ingress during 'typical' winter flows (the same 'typical' winter flows steadily re-fill the two Corndale pits upstream). Aerial imagery captured in 2015, twelve months after the pit was excavated, six months after the winter flow season but six months *before* the September 2016 flood event, show a pit that is largely sand-free. In this manner, beds of vegetation upstream of extraction pits decrease the local sediment supply, which preserves pits in the streambed for longer than in vegetation-free reaches. The sensitivity of pit infill to local sediment supply was also found for borrow pits in the Mississippi River by Yuill *et al.* (2016), except in the case of the Mississippi River the control on local sediment supply was the passage of large dunes, not the presence of vegetation. Vegetation does not inhibit pit re-fill during floods, when the flexible stems of *Phragmites* are flattened by the flow and sand enters the pit by travelling over the vegetation beds in suspension. During very low flows sand is funnelled along the low-flow channel and does not interact with vegetated bars. This suggests that the larger the upstream area covered in vegetation, the longer an extraction pit will take to re-fill.

6.3.5 Implications for conceptual models of pit evolution in natural channels

The conceptual model outlined in Chapter 5 should be modified to include two processes: a zone of diminishing bedload transport protruding into the pit, and a lobe of suspended sediment, from which sand rains from suspension to settle on the bed, trailing behind the bedload zone. This bedload transport zone is generated at bankfull discharges but not at lower discharges (e.g. 0.5 x bankfull). The advancing pit head is fed by bedload collapsing down the avalanche face and sediment settling from suspension. Because pits fill stochastically, bedload transport and suspended sediment transport at the pit face and within the pit contribute to infill.

The conceptual model in Chapter 5 should be transformed to a two-dimensional view of pit infill and include accumulation of sediment along the walls of the pit (from either deposition or the collapse of pit walls). The model should also be extended to include the two-point bar re-building processes: simultaneous upwards, outwards and upstream-to-downstream rebuilding, and upwards and upstream growth of point bars in recirculating eddies on sharp meanders.

The results also confirm that several predictions made by flume experiments are borne out in natural channels: extraction pits that span the channel width trap 100 % of incoming sediment, pit head migrates downstream as a fairly uniform front in straight channel segments, and a scour channel develops downstream of extraction pits.

6.3.6 Implications for extraction in the Glenelg River

The findings of this study have several implications for the extraction in the Glenelg River. The lack of bank erosion adjacent the extraction pits, the lack of unambiguous nickpoints migrating upstream of the pits, and the tendency for point bars to steadily rebuild suggest that the extraction technique used in the Glenelg River, where sand is carefully removed from long, deep, discrete pits, minimises the length of streambed disturbed by extraction. Similarly, erosion downstream of extraction pits was confined to a deepening thalweg and limited scour of bench surfaces, while the adjacent streambanks remained intact.

The findings of this research also suggest that extraction pits excavated from reaches where vegetation has established on the surrounding streambed (reaches where stock have been excluded) take longer to fill, under normal flood-free flow conditions than pits excavated in vegetation free reaches. Therefore, pits excavated in vegetated reaches will need to be re-excavated less frequently and can provide habitat services for a longer period at a lower cost (compared to un-vegetated reaches).

Pit 1 was excavated in February 2018, fourteen months before the survey (pit 2 was also excavated in February 2018 but it's infill may be impacted by pit 1, which lies upstream). The re-fill volume surveyed in 2019 provide a single measurement of annual sediment supply to the reach (16,450 m^3 yr^{-1}). This number is lower than the sediment supply of 20,000 m^3 yr^{-1} estimated by Rutherfurd and Budahazy (1996), but higher than the sediment supply predicted by the calibrated Delft3D sediment transport model developed for this study (12,800 m^3 yr^{-1}). Mean daily flow in the 2018-2019 flow year (3 m^3 s^{-1}) was similar to mean daily flow for the entire study period (2005-2019, 3.5 m^3 s^{-1}), but the spread of discharge values was lower (σ = 6.5 m^3 s^{-1}) in the 2018-2019 season than the spread for the entire study period (σ = 11.6 m^3 s^{-1}), because the 2018-2019 flow year did not include any flood events.

6.3.7 Limitations of the study and future research

The modelling over-predicts the depth and extent of scour downstream of the pits *following a single phase of extraction* (the observed bed scour from the surveys accumulated over 10 years at least), there are several reasons for this:

- The pits in the model were run at two discharges: a constant bankfull discharge (70 m^3s^{-1}), and half-bankfull discharge (35 m^3 s^{-1}). Both discharges generated high bead shear stress and high sediment transport rates. While the values of bed shear stress sediment transport rate are realistic, the mean daily flow rate of the Glenelg River between April and October (the winter flow season) is only 3.5 m^3 s^{-1} (i.e. bankfull flows are rare). This means that a lot of pit infill occurs during floods when large volumes of sand are delivered to the extraction reach, or very gradually, during low-flows that do not generate bed shear stress or sediment transport rates high enough to cause deep scour downstream of the extraction pits.

- Areas of the streambed that were starved of sediment and scoured when the pits were re-filling will be re-supplied with sediment during the time period between successive phases of extraction (when there is no extraction pit interrupting sediment supply).
- The sediment transport model used in this study (van Rijn, 1987) does not include an adaption/adjustment length parameter for non-equilibrium flow, which may mean that the magnitude of scour (and deposition) is over-estimated in cells starved of (or overloaded with) sediment. For example, at the upstream and downstream end of extraction pits, or on the benches along the channel margins.
- The model assumes the channel bed consists of uniform non-cohesive sand and doesn't account for the reduced scour caused by roughness elements like in-stream wood and vegetation, or the resistance offered by cohesive sediment within the bed or on benches.

6.4 Conclusion

This chapter evaluated the conceptual model developed in chapter five by examining how a sequence of extraction pits excavated in the Glenelg River evolved. The pit evolution model was evaluated using repeat channel surveys, hydraulic and sediment transport modelling, and by interviews with the extractors who remove the sediment. In combination these methods of investigation found that extraction pits did not behave solely as the conceptual model predicted.

The pattern of pit infill was discharge dependant: at bankfull discharge a zone of bedload transport developed on the bed of the pit, intruding form the upstream end. A lobe of suspended sediment also enters the pit but terminates further upstream than the bedload transport zone. At lower discharges, a bedload transport zone does not develop on the bed of the pit, and the lobe of suspended sediment entering the pit is restricted to the upstream end of the pit. A narrow scour zone forms on the bed of the pit, aligned with the bedload transport zone. Sediment also accumulated along the margins of the pit by deposition of sediment supplied to the pit and collapse of the pit walls. The downstream end of the pit does rotate to form a narrow scour zone, but this zone does not expand across the width of the streambed: the scour pattern downstream of the pit is controlled by the pre-existing bed topography.

The impact of in-stream vegetation is superimposed on these processes of pit infill. Vegetation upstream of extraction pits has the effect of slowing infill during lower discharges, but this restriction on infill disappears at higher discharges, when sediment travels over vegetation and lands in the pit. The net effect of vegetation is to preserve extraction pits in in the streambed for longer than they would persist in a vegetation-free channel.

Chapter 7: Reach-scale impacts of in-stream extraction

7.1 Introduction

This chapter builds on the pit-scale (10–100's m) results presented in the previous chapter by considering the impact of a sequence of extraction pits at the reach scale (1–10 km). The pit-scale chapter tested conceptual models of how extraction pits re-fill with sediment, how the pits change shape as they fill, and the relationship between the pattern of infill and the overlying flow field. These are practical issues managers face when deciding where in a river to extract from, appropriate dimensions of extraction pits, and the rate at which pits will be replenished (if the extraction has a commercial imperative).

At the reach scale, stream managers seek to minimise detrimental impacts of extraction (excessive bed degradation and bank erosion), but they are also interested in using extraction to accelerate recovery. In particular, managers seek to understand the depth and pattern of scour downstream of extraction sites, the impact additional extraction pits have on downstream scour, how cross-section shape changes in response to extraction, and finally, how these channel adjustments impact on, and are impacted by, in-stream vegetation.

Recall that the conceptual model described in Chapter 5 predicted that in-stream extraction would generate scour downstream, and that the depth of this scour would increase in a downstream direction, as more pits are added to the sequence (Figure 7.1). That conceptual model also predicted that, when viewed in cross-section in-stream extraction should increase bed relief, cause channel contraction and bench development and be more likely to generate scour holes in the lee of large wood on the channel bed.

The results of the reach-scale analysis are presented here in order of increasing complexity. Where appropriate, channel surveys are related to the hydraulic modelling undertaken for the reach. I begin by describing the morphology of the study reach, which I have classified into two types: an *upstream* morphology and a *downstream* morphology. I then present longitudinal profile change, which is the most common way reach-scale response to extraction is conceptualised in other studies. I then add complexity by considering the pattern of changes at cross-sections, before quantifying the variability of each cross-section and how this variability changed between 2005 and 2018. I then present the overall sediment budget for the reach. While changes in longitudinal profile and cross-section shape are measures of potential recovery within the treated reach, the sediment budget is a means of relating changes at the reach-scale to the overall passage of the larger bedload pulse. I then use the hydraulic modelling results to identify the variables that best explain the pattern of change observed in the channel. Finally, the discussion considers the implications that these findings have for models of channel response to in-stream extraction, and how these results inform interventions in the Glenelg River. I remind the reader that the methods I used to undertake the hydraulic and sediment transport modelling, the cross-section surveys, and the sediment budget calculations were presented in section 5.5.5 of Chapter 5.

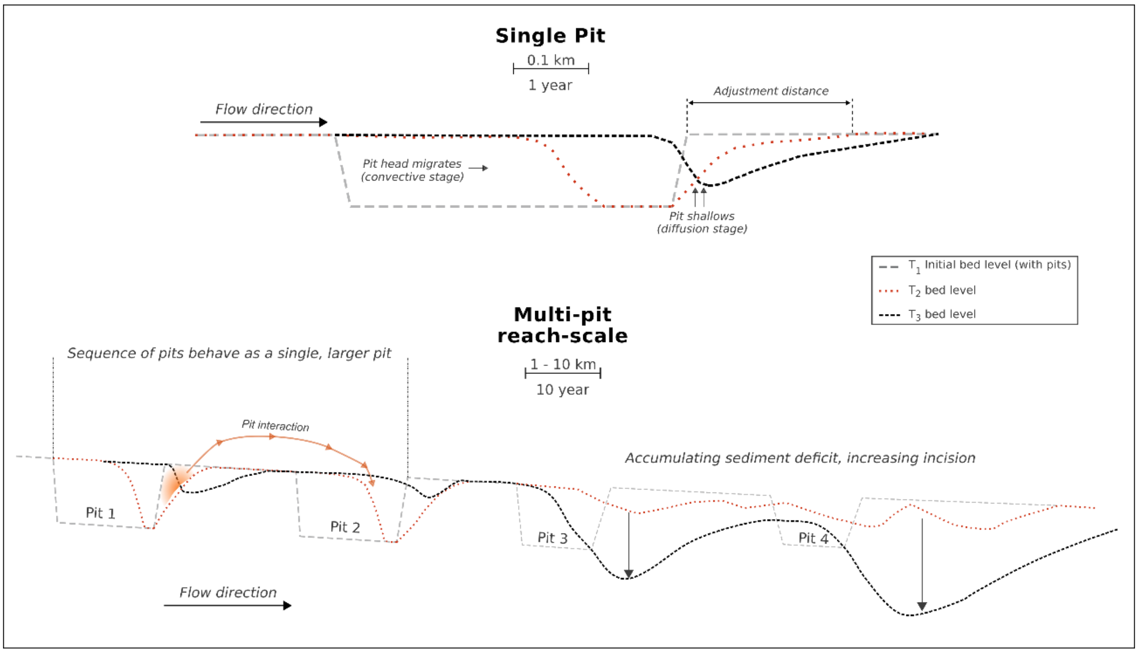


Figure 7.1: The conceptual model developed in Chapter 5, showing the predicted impact that a sequence of extraction pits would have on the thalweg profile in downstream reaches.

7.2 Results

The study reach is not characterised by a smooth transition in shape and overall morphology from upstream to downstream. Instead, channel shape, cross-section variability, vegetation abundance all changed abruptly approximately 3.7 km downstream from pit 1. Much of the upstream part of the study reach had a simple trapezoid-like shape, with sand deposits accumulated against one side of the channel (for example Figure 7.7E and H). The downstream part of the study reach had more pronounced benches with a deeper low-flow channel set between them.

The two different morphologies that have developed have also responded differently to in-stream extraction, with downstream reaches being characterised by greater thalweg erosion but a smaller increase in cross-section variability, compared to the upstream section. I now describe the morphology of the study reach in more detail, before considering channel changes between 2005 and 2018.

7.2.1 Morphology along the study reach

Overall, the study reach is comprised of two different morphologies which I term *upstream* morphology and *downstream* morphology. The *upstream* morphology is confined to the section of the reach upstream of the Claybanks extraction site. Stock can freely access the riverbed in this section (although this is somewhat restricted on meander bends with very steep banks). The Corndale extraction pits, which were repeatedly excavated over the study period, and the Rifle Range extraction pit, which was only extracted once in 2006, are within this upstream section. The *downstream* morphology is the remaining, downstream portion of the study reach and includes the Claybanks extraction pit (extracted twice over the study period) and the Island Park extraction pit (extracted once, in 2014). Stock cannot access the streambed in this reach, due to a combination of stock-exclusion fencing and residential land use adjacent to the river (Figure 7.2).

The *upstream* morphology is generally a flat, featureless sheet of sand that meanders through irregular, low-elevation benches on the channel margins (although at some cross-sections these benches are absent entirely). The channel banks support sparse, discontinuous stands of mature vegetation (mainly *Eucalyptus camaldulensis* and *Eucalyptus globulus*), but few trees shade the low-flow channel (Figure 7.3A). Steep, eroding banks are common in straight sections and on the outside of meander bends. Bank erosion is most pronounced in a highly sinuous sub-reach that includes bank protection structures, some of which have collapsed (Figure 7.3C) and exposed clay on the channel bed. Abundant in-situ tree stumps are exposed in the bed (having been previously buried by sand, or sawn off in-situ during 'de-snagging' in the 1960s) (Figure 7.3A and B). The inner margins of some of the benches have been colonised by red gum seedlings (*Eucalyptus camaldulensis*) and small patches of spiny rush (*Juncus acutus*) have established on the benches. Some isolated stands of *Phragmites australis* have established in meander bends with high banks and limited stock access.

The *downstream* morphology is very different from the *upstream* morphology. A deep low flow channel cuts through benches and bars, most of which have been colonised with dense stands of *Phragmites australis*. The banks support mature vegetation (also a mixture of *Eucalyptus camaldulensis* and *Eucalyptus globulus*) that shade the low-flow channel (Figure 7.4). Several portions of the banks exhibit signs of erosion, especially on the outside of meander bends. Several small, *Phragmites*-covered islands occur within the active portion of the channel, and sand is accumulating at their downstream margin (Figure 7.5). There are deep pools on the outside of several meander bends (Figure 7.4). Aerial imagery shows these pools were in place by 2010 and have not changed in size.

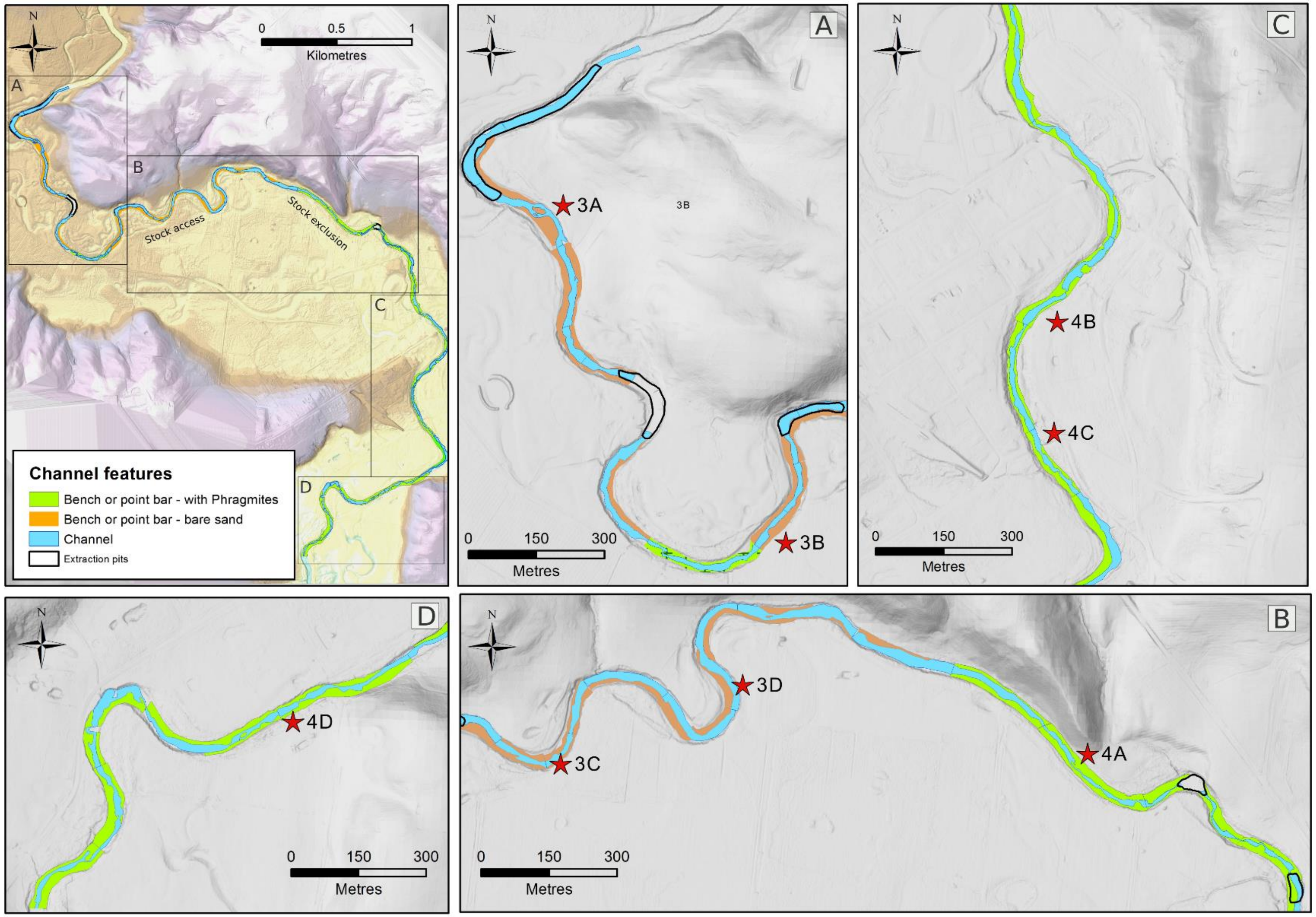


Figure 7.2: The distribution of channel features along the study reach which were mapped using the UAV imagery. Channel features were categorised as channel (standing water), bare sand point bar, bare sand bench, vegetated point bar or vegetated bench. Red stars with labels correspond to the labelled photos in Figure 7.3 and Figure 7.4.

Figure 7.3: The morphology of the upstream part of the study reach showing (A) the low-flow channel immediately downstream of Corndale pit 2, looking upstream, erosion has exhumed abundant in-stream wood that was previously buried with, (B) the low-flow channel with remnant island in the channel, and an un-vegetated point bar in the background, (C) bank protection structures on the outside of a meander bend (flow is from right to left) sand has accumulated between the structures (in the lee of the upstream groyne) but has scoured in the lee of the downstream groyne, (D) the low-flow channel inset within benches, showing exposed tree stumps on the channel bed. The location of each photo is shown on Figure 7.2.

Figure 7.4: The morphology of the lower section of the study reach, where stock have been excluded from the riverbed and *Phragmites* have colonised many surfaces, showing (A) *Phragmites*-lined benches on the channel margins, which support some mature vegetation near the base of the adjoining bank, and a deep low-flow channel, (B) bank erosion and collapse of vegetation (flow is from away from viewer), (C) a deep low-flow channel cutting through *Phragmites*-covered benches that have been partially eroded and, (D) The uneven colonisation of the channel margins by *Phragmites* which have established on the true left (left of the image) but not on the true right in this part of the channel. Here the low-flow channel is relatively shallow. The location of each photo is shown on Figure 7.2.

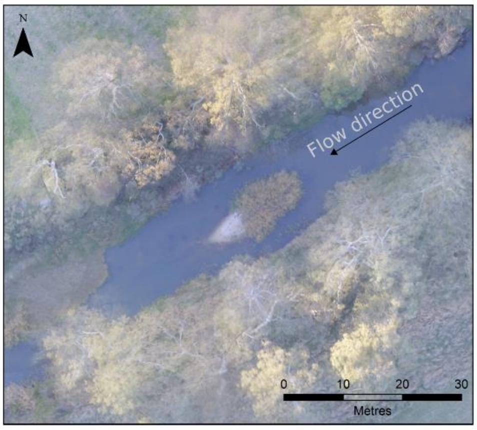


Figure 7.5: The downstream section of the study reach showing a mid-channel bar that has been colonised by *Phragmites*, with sand depositing in the lee of the bar. Flow is from right to left.

7.2.2 Change in thalweg elevations

Between 2005 and 2018 thalweg elevation decreased (the bed eroded) at most cross-sections (Figure 7.6). Thalweg elevation increased (the bed aggraded) at a small number (n= 5) of cross-sections, but these cross-sections were an exception to the overall trend: increasing bed erosion with distance downstream (Figure 7.6).

The decrease in thalweg elevation was most pronounced in the *downstream* morphology (3.7-7.5 km downstream from Corndale pit 1). Interestingly, thalweg elevation changed very little in the un-vegetated stretch of river between the Corndale extraction pits and the Claybanks extraction pit (2.5-4 km downstream of Corndale pit 1).

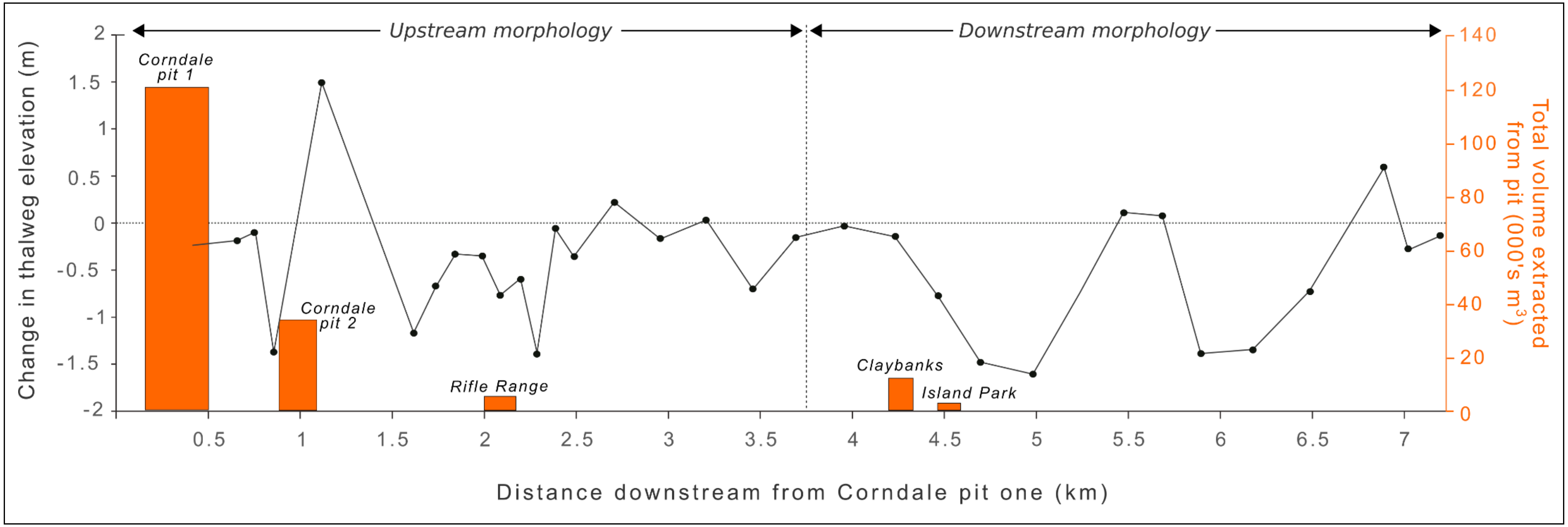


Figure 7.6: Longitudinal profile of change in thalweg elevation between 2005 and 2018. The height of orange bars denotes the total volume of sand extracted from each pit between 2005 and 2018 and the width of each bar denotes the length of streambed occupied by the pit, pits are labelled.

7.2.3 Cross-section change

7.2.3.1 Pattern of erosion and deposition at cross-sections

Overall, cross-section changes were highly variable along the river. Many of the cross-sections exhibited a pattern of point bar migration (lateral and vertical accretion of sediment on the point bar) at the same time the adjacent low-flow channel deepened. In several cases the expansion of the low-flow channel was accompanied by bank erosion, causing the entire channel to migrate. Point bar migration and deepening of the low-flow channel were most pronounced in the *upstream* morphology. While in the *downstream* morphology several stretches of channel have become deeper (low-flow channel erosion) and narrower (aggradation at higher elevations, along the channel banks) (Figure 7.7G and H).

The overall pattern of point-bar migration upstream, and a combination of point-bar migration and channel narrowing downstream, emerges from the significant variability between individual cross-sections. In some sections benches and points bars have remained stable or aggraded while the adjacent low-flow channel eroded (Figure 7.7C and F), and in other sections point bars have developed cut-off channels (Figure 7.7B) or benches have been removed entirely by erosion *and* the low-flow channel has degraded (Figure 7.7A). At the same time point bars have migrated and benches have been altered, benches have started to form in reaches that were bench-free in 2005 (Figure 7.7F and H). While bank slope and position has remained stable at most cross-section sites, several channel segments widened by up to 4 metres (Figure 7.7A and E).

In segments where bars and benches are subtle and have low relief (relative to the thalweg) *Phragmites* have spread across the entire feature. In sections where features have much greater relief, such as steep point bars or 'benches' that slope upwards towards the channel banks, *Phragmites* tend to be confined to the lower sections, where they line the margins of the low-flow channel. Higher-elevation sections of bars and benches are usually bare sand or are covered by short grasses (Figure 7.8A).

High-resolution aerial mapping using a UAV revealed that even when cross-section surveys documented bench aggradation, this pattern is longitudinally discontinuous. Several of the 'aggrading' benches also exhibit scour zones on their surface, whether or not they have been colonised by *Phragmites*. Bench scour occurs at the head and tail of bars, as elongated patches on the bench/bar surface (Figure 7.8B) and as cut-off channels against the toe of adjoining banks (Figure 7.8C).

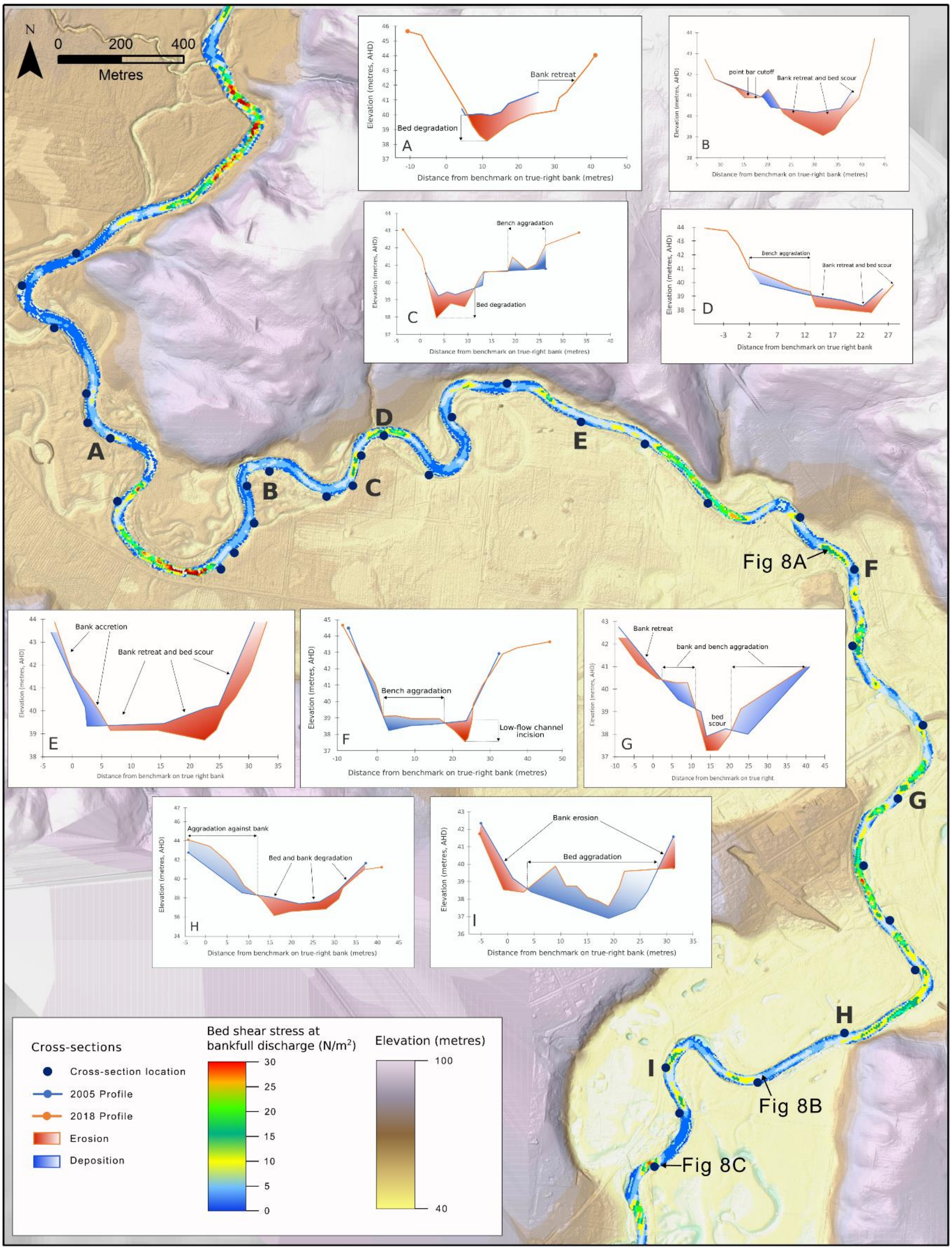


Figure 7.7: The distribution of depth-averaged bed shear stress along the study reach at bankfull discharge (70 $m^3 s^{-1}$). Cross-sections, and their location within the study reach illustrate the different ways the channel shape has responded to extraction. The location of the aerial photos shown in Figure 7.8 are identified.

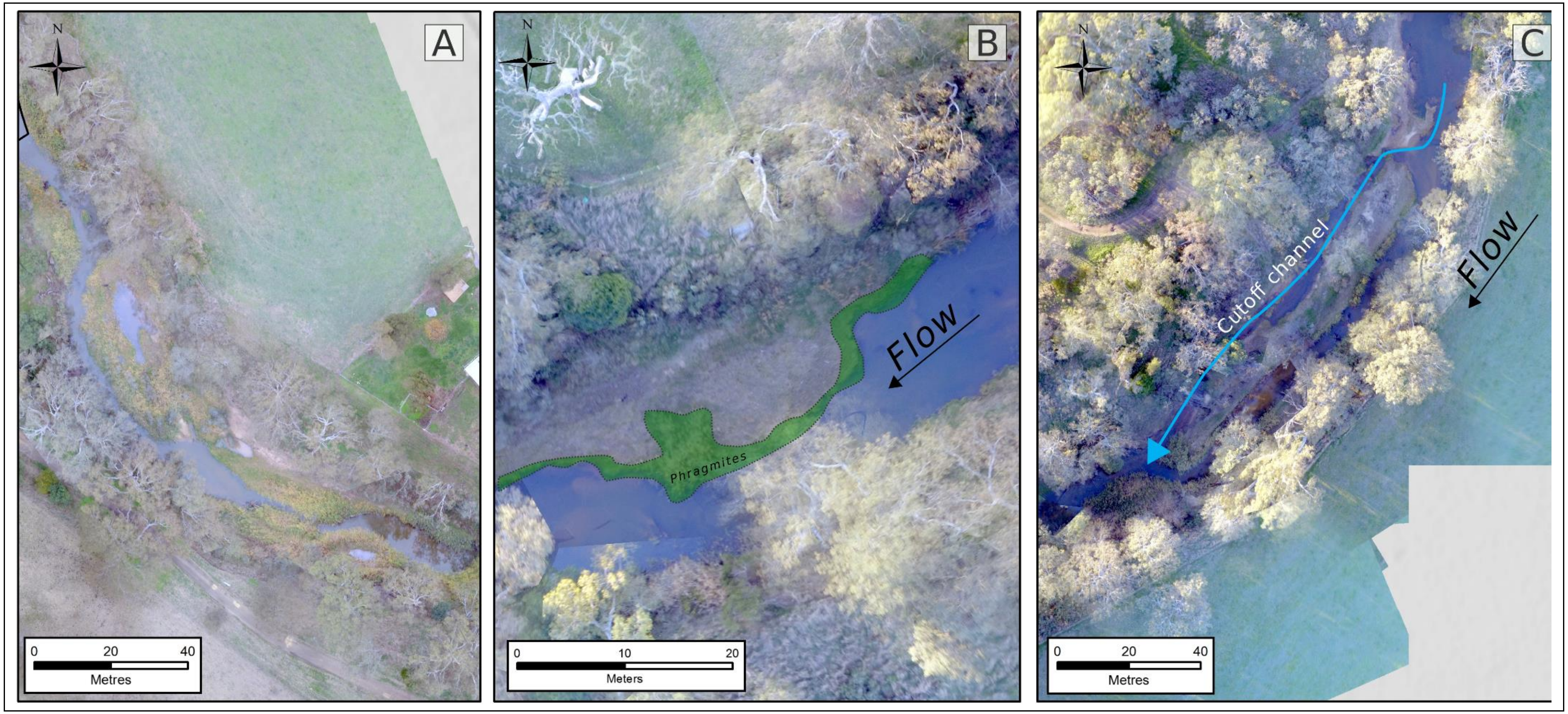


Figure 7.8: The distribution of *Phragmites* on benches and point bars in the downstream section of the study reach showing (A) benches and point bars covered in *Phragmites* with elongated scour holes forming and the erosion of the downstream end of features, (B) how *Phragmites* line the low-elevation margin of a feature but do not grow across the high elevation parts, (C) a cut off channel dissecting a *Phragmites* covered bench in the downstream section of the study reach.

7.2.3.2 Cross-section variability

The two distinct channel morphologies described in section 7.2.1 gave rise to two different levels of channel complexity, which was quantified using the standard deviation of cross-section elevations. In 2005 the *upstream* morphology was less complex than the *downstream* morphology (Figure 7.9). Channel complexity increased for almost every cross-section between 2005 and 2018. As a result, the 2018 pattern of cross-section variability follows the same trend as it did in 2005, but overall complexity was higher in both parts of the study reach (Figure 7.9). The average increase in the standard deviation of cross-section elevations was 0.38 standard deviations in the *upstream* morphology but only 0.19 standard deviations in the *downstream* morphology. The exception to this pattern was a segment downstream from Corndale pit 2 (between 1 and 1.8 km downstream of pit 1), where complexity slightly decreased between 2005 and 2018 (Figure 7.9).

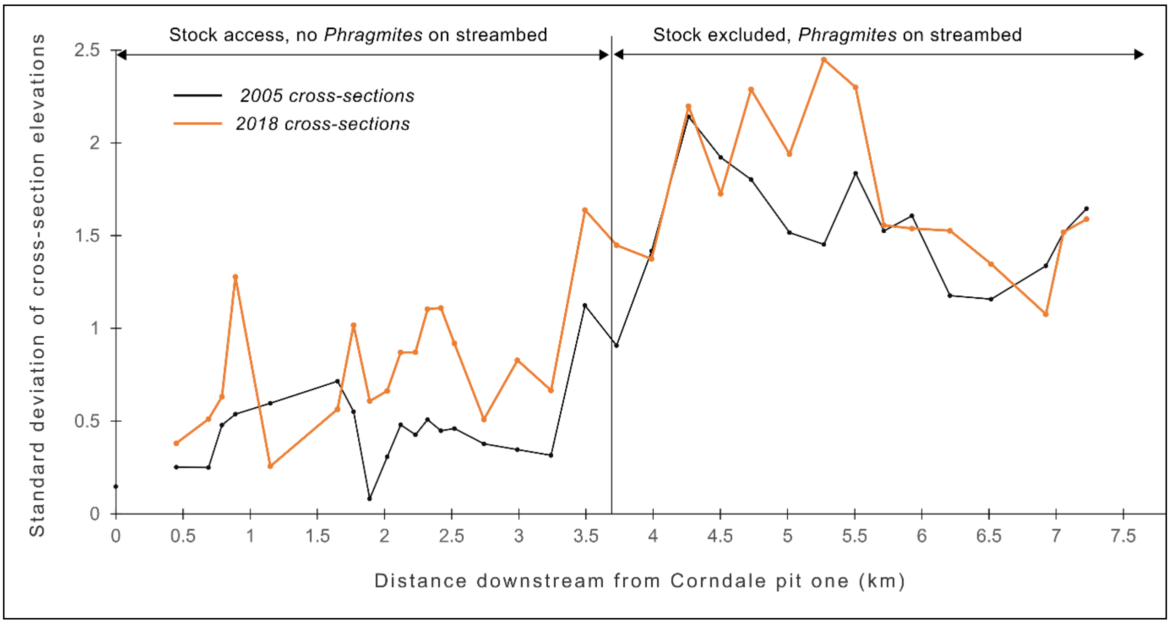


Figure 7.9: Standard deviation of cross-section elevations in 2005 (black) and in 2018 (orange) for the study reach. Stock have been excluded downstream of 3.7 km mark since at least 2000

7.2.4 Sediment budget results

The calibrated sediment transport model predicted that 180,620 m^3 of sand was supplied to the study reach between 2005 and 2018. Extractors removed a total of 177,240 m^3 of sand from four different extraction pits over the same period. The total volume of sand scoured from the reach by the Glenelg River, calculated using the DEMs of difference for cross-sections combined with the feature mapping, was 27, 800 m^3. The total volume of sand exiting the downstream end of the study reach was calculated as 31,170 m^3 (Table 7.1). Interestingly, the volume of sediment eroded over the ~ 8 km long study reach was significantly less than the total volume of sediment removed by extraction (27,800 m^3 cf. 177,000 m^3) (Table 7.1).

The change in sediment storage per river metre (change in storage at cross-section divided by the length of river represented by that cross-section) also varies along the river. Upstream, vegetation-free reaches exhibit an average decrease in sediment storage of -0.38 $m^3\ m^{-1}$ (σ = 10 $m^3\ m^{-1}$, *n* =19). Downstream, vegetated reaches exhibit an average decrease in storage of -1.23 $m^3\ m^{-1}$ (σ= 16 $m^3\ m^{-1}$, *n*=15). While sediment storage decreases more on a per river-metre basis in downstream reaches, a small number of highly erosive cross-sections skew the average value. Changes in sediment storage are much larger between individual reaches than the difference between the upstream and downstream sections: the standard deviation of the per-metre volume change for all reaches was 17 $m^3\ m^{-1}$. Although the *change* in storage (between 2005 and 2018) was greater in the *downstream* morphology, many of the cross-sections in this section has with a greater initial volume of storage in 2005 than *upstream* cross-section.

Table 7.1: Sediment budget for the study reach between 2005 and 2018. The output is much smaller than the input because bed erosion did not compensate for the volume of sediment removed by extraction. Negative values are erosion or extraction (sediment removed from reach), positive values are sediment supplied to reach or volume exiting the reach at the downstream end.

Sediment budget component	Value (m^3)	Details
Sediment input (I)	180,620	Derived from the calibrated sediment transport model and the Casterton flow series, 2005 - 2018
Volume extracted	-177,240	Measured from extraction records
Change in sediment stored within reach (ΔS)	-27,800	$\sum$ (each cross-section DEMoD x length of sub-reach)
Net sediment sinks (extraction + ΔS)	(-177,240 + -27,790) = -149,450	
Sediment output (O)	O = I -ΔS 180,620 – 149,450 = 31,170	The volume of sediment passed downstream between 2005 and 2018

7.2.5 Explanatory variables

The pattern of cross-section averaged bed shear stress, from upstream to downstream, tracks changes in thalweg elevation: increases in bed shear stress correspond with a decrease in thalweg elevation, and a decrease in bed shear stress corresponds with either much less thalweg erosion, or slight thalweg deposition (Figure 7.10). Although the longitudinal *pattern* of bed shear stress matches the longitudinal pattern of thalweg change, the *absolute* magnitude of bed shear stress is a poor predictor of the total vertical change in thalweg elevation (Figure 7.11A). Similarly, the average bed shear stress at each cross-section shows no relationship with the change in the volume of sediment stored at each cross-section, regardless of whether vegetation is present in the channel bed (Figure 7.11B).

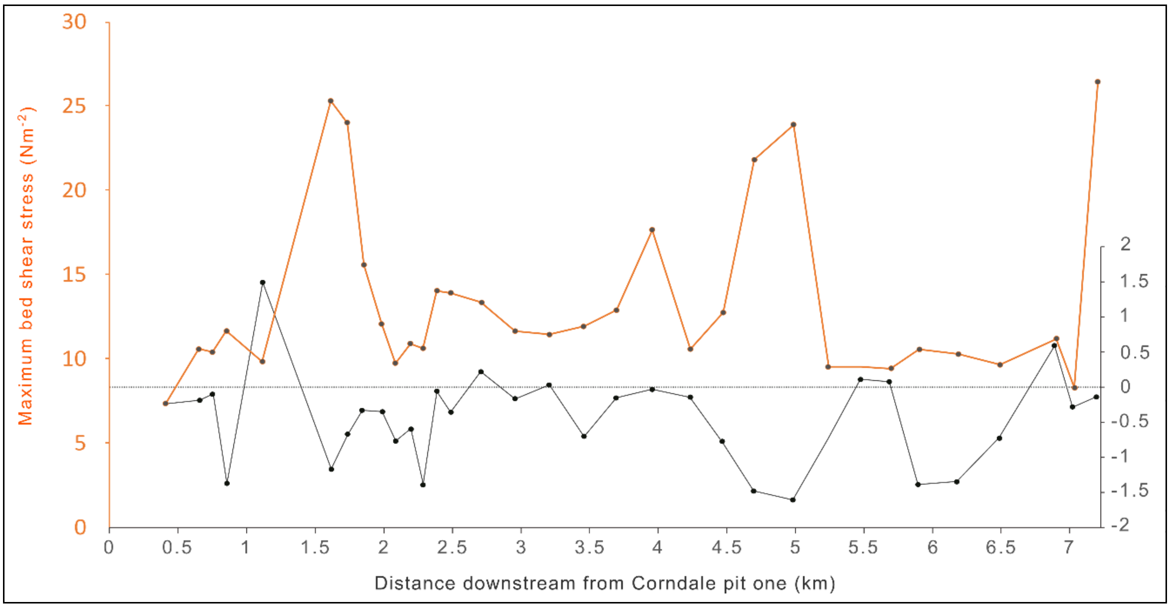


Figure 7.10: Longitudinal profile of change in thalweg elevation (identical to the profile in Figure 7.6) with the corresponding maximum bed shear stress at each cross-section at bankfull discharge
(70 m^3 s^{-1}).

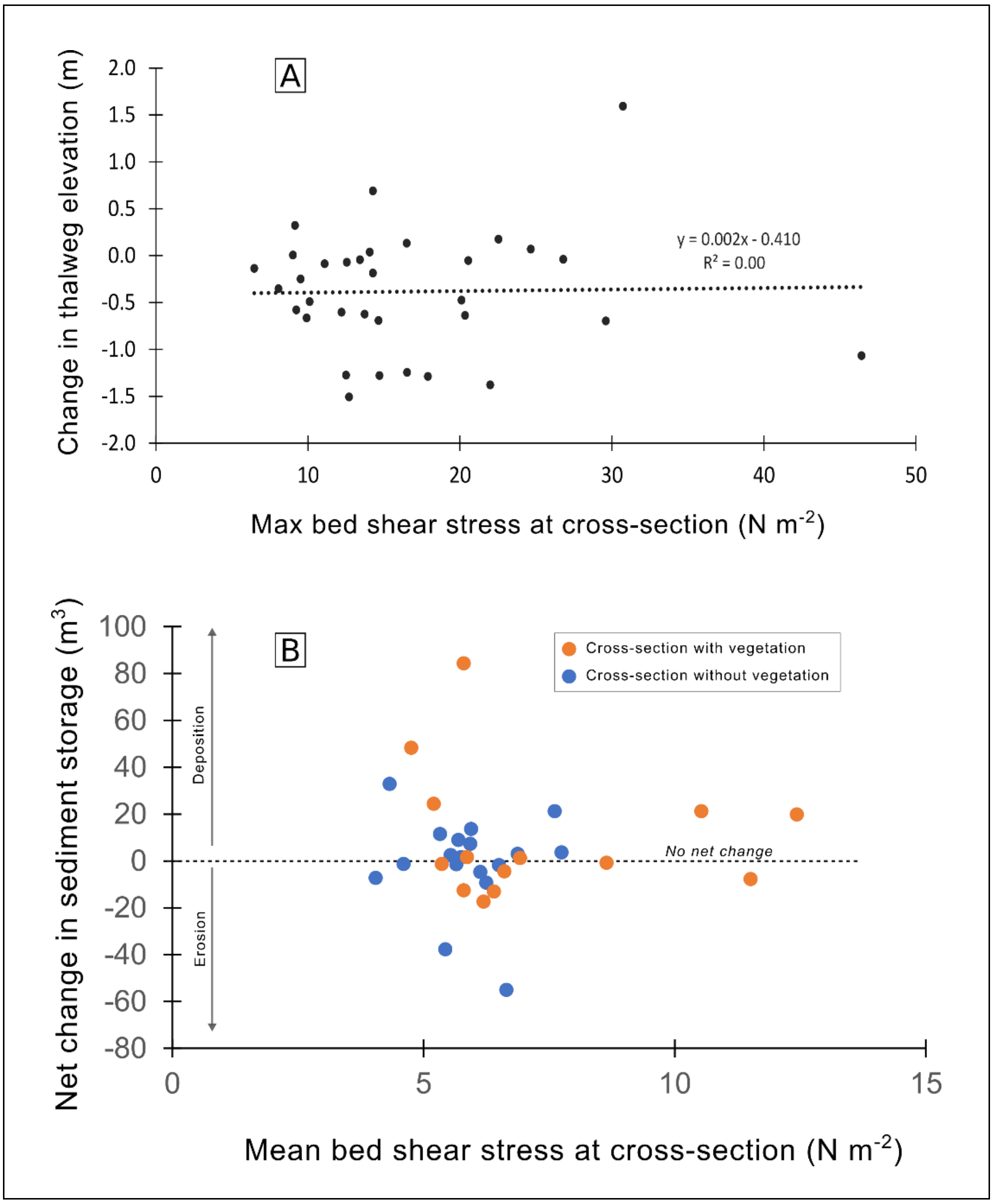


Figure 7.11: Scatterplot of (A) maximum bed shear stress at each cross-section vs. change in thalweg elevation at each cross-section and, (B) average bed shear stress at each cross-section vs. the change in the volume of sediment stored at each cross-section, where the coloured dots indicate whether *Phragmites* were present on bars and benches at each cross-section.

7.2.6 Results summary

Extraction removed most (98 %) of all sediment supplied to the study reach between 2005 and 2018. At the same time, the river eroded 27,800 m^3 of sediment from storage within the reach and passed this material downstream. At the downstream end of the study reach, the Glenelg River is still in a strong sediment deficit.

The upstream un-vegetated part of the study reach, and the downstream vegetated part of the study reach, were classified as distinct morphologies: the *upstream* morphology and the *downstream* morphology. The *upstream* morphology, which includes the extraction pits, is heavily dissected by scour channels near the pits, but these scour channels give way to a relatively flat, featureless morphology for the remainder of the *upstream* morphology. The *downstream* morphology has extensive in-stream vegetation (mostly beds of *Phragmites australis*) which have colonised point bars and the benches lining the channel margins. A deep low-flow channel meanders along the middle of the channel bed. Cross-section variability is lower in the *upstream* morphology but abruptly increases at the transition to the *downstream* morphology.

Between 2005 and 2018 changes in the shape of many cross-sections appears to be the result of point bar migration combined with deepening and slight widening of the low-flow channel. However, this overall pattern of change is not evident for all cross-sections. Bench aggradation, bench erosion, bank retreat, thalweg scour and thalweg aggradation all occur in different combinations at the cross-sections. Changes in sediment storage at cross-sections was also highly variable: deposition increased sediment storage at some cross-sections and erosion decreased storage at other cross-sections. The overall trend in the change in thalweg elevation change was clear: thalweg erosion increased from upstream to downstream.

Bank erosion is visible but not widespread in both morphologies. Aerial imagery comparisons did not identify any new pools, other than the re-filling extraction pits, between 2010 and 2018, and the pools present in 2010 did not change overall shape or size.

Between 2005 and 2018, the *increase* in cross-section variability was greater in the *upstream* morphology compared to the *downstream* morphology. However, the increase in variability that occurred at most cross-sections did not change the overall pattern in variability present in 2005: the *downstream* morphology remained much more variable than the *upstream* morphology in 2018.

The pattern of thalweg change, from upstream to downstream, tracks the pattern of maximum bed shear stress predicted by the hydraulic model: cross-sections with higher bed shear stress are (usually) associated with a decrease in thalweg elevation and cross-sections with lower peak bed shear stress are (usually) associated with either a smaller decrease in thalweg elevation, or an increase in thalweg elevation. Although change in thalweg elevation tracked peak bed shear stress from upstream to downstream, the absolute magnitude of peak bed shear stress is a poor predictor of the absolute change in thalweg elevation. Similarly, the average bed shear stress at a cross-section is a poor predictor of the total change in sediment storage at that cross-section, whether or not vegetation was present on the streambed.

7.3 Discussion

This chapter has examined the reach-scale (1-10 km) impact of a sequence of five extraction pits, three of which were repeatedly excavated over an eight-year period, in a sand-bed river. I examined change in an eight-kilometre reach using repeat cross-section surveys, a detailed sediment budget, hydraulic and sediment transport modelling and by classifying morphology. I used the changes in the cross-section shape and elevation to quantify the change in sediment storage within the reach, while the sediment transport model was used to calculate the annual volume of sediment supplied to the study reach.

The key motivation for this study was to assess whether in-stream extraction accelerates recovery of a sand-bed river impacted by a bedload pulse. The definition of recovery adopted in this thesis was geomorphic, not ecological (*cf.* Sedell *et al.,* 1990; Palmer *et al*., 2010), in nature. The premise of using in-stream extraction to accelerate recovery is that by decreasing sediment supply, extraction pits would cause downstream reaches to adjust. Downstream adjustment will be erosional and should include: an increase in the number and size of pools, increased bed relief, more landforms supporting vegetation and an overall increase in channel complexity. Compared to other studies that have examined the channel adjustments generated by in-stream extraction (Kondolf, 1997; Rinaldi *et al*., 2005; Rovira *et al*., 2005; Padmalal *et al*., 2008a; Martin-Vide *et al*., 2010; Calle *et al*., 2017), the Glenelg River is unusual because sediment extraction rate was equal to sediment supply.

The conceptual model developed in Chapter 5 predicted that channel scour would accumulate in a downstream direction, as successive extraction pits are added to the sequence, and that the length of river impacted by scour would extend well beyond the area of streambed directly disturbed by extraction. It also assumed that changes in cross-section shape would track this scour pattern. The magnitude of thalweg scour did accumulate in a downstream direction, but this occurred in a sporadic manner. Cross-section variability, a surrogate for channel complexity, also increased in a downstream direction, but not in a consistent manner. Instead, cross-section variability abruptly increased at approximately the same point in the river that vegetation colonised the streambed. Changes in cross-section shape were highly variable, inconsistent and showed no clear pattern from upstream to downstream.

7.3.1 Change in thalweg elevation and sediment storage along the reach

The complicated series of changes in thalweg elevation and sediment storage are best explained by the distribution of bed shear stress in the channel. Channel sections with higher bed shear stress are prone to higher sediment transport rates, which cause erosion. When sediment eroded from high transport zones passes through areas with lower relative bed shear stress, transport rates fall, and sediment is deposited. The pre-existing shape of the channel (width, depth and slope), which determine the magnitude and distribution of bed shear stress, is the dominant control on the pattern of adjustment downstream of extraction pits. This pattern was also observed by Martin-Vide *et al*. (2010) , who found that the presence of a pronounced low-flow channel in a gravel bed river subject to extraction set a feedback process in motion: extraction caused channel incision, the incised channel contained greater flows, bed shear stress increased in the low-flow channel, transport capacity increased, and incision was enhanced.

The absolute changes in sediment storage (m^3) and thalweg elevation (m) are the outcome of stochastic flows and a similarly variable local sediment supply. It is therefore unsurprising that the bed shear stress calculated from a single flow (bankfull), under the assumption of unlimited sediment supply, is a poor predictor of the magnitude (rather than the spatial distribution described above) of storage change or thalweg erosion. However, the point of the hydraulic modelling was to explore which control (hydraulic variables, vegetation cover, distance from extraction pit) explained the observed pattern of channel change, not to construct detailed relations that predict the magnitude of erosion and deposition with high precision.

Clearly the pre-existing morphology of the channel, upon which the sediment deficit is imposed, is a major control on how reaches respond to extraction. In the Glenelg River there were two kinds of morphology present when the most recent phase of extraction began: the *upstream* morphology which was free of vegetation, and the *downstream* morphology, which had dense stands of *Phragmites australis*. The difference in morphology was mirrored in the 2005 cross-section complexity values: the *downstream* morphology was much more complex than the *upstream* morphology.

I now consider how the difference in vegetation cover between the two segments of the study reach has shaped the channel's response to extraction.

7.3.2 How in-stream vegetation controls a channels response to extraction

In sand-bed rivers such as the Glenelg River, in-stream vegetation plays a fundamental role in controlling how the channel responds to extraction. For example studies of the downstream impact of extraction have shown that incision of the low-flow channel can promote vegetation growth on channel benches (Calle *et al*., 2017), which promotes sediment storage, or lower water tables can inhibit vegetation growth on benches (Martin-Vide *et al*., 2010), which promotes erosion.

Many of the bars covered in *Phragmites* have been dissected by scour (i.e. *Phragmites* does not prevent all erosion), and several islands in the channel appear to have originally been connected to the adjacent benches. This scour, which occurs on the surface of bars and benches elevated several metres above the channel bed, necessarily occurred during bankfull or greater flows. At the same time, sand appears to be accumulating in the lee of small *Phragmites*-covered islands in the channel bed. Assuming the *Phragmites* encroach onto these fresh deposits and stabilise them, sand may be transferred from eroding benches to accumulating islands. The fate of these *Phragmites* is either continued aggradation to form more elevated benches that can be colonised by other species (i.e. they proceed along the biogeomorphic succession path, Corenblit *et al.* (2007)), partial degradation to become wetland features (Gurnell, 2014) or complete removal by erosion. At present, these features are moving towards the wetland phase and if extraction continues to starve sediment to the *downstream* morphology, they will be removed entirely.

The point here is that the presence of vegetation on the channel bed changes how the erosion caused by upstream extraction is expressed. When stands of *Phragmites* can colonise channel landforms and divert flow, scour becomes more concentrated, and bed relief increases. This explains why thalweg erosion was so pronounced in the *downstream* morphology, even though 87 % of the total volume extracted was from the Corndale pits, 5 km upstream. The lack of in-stream vegetation in the stretch of river between the Rifle Range pit and the start of the *downstream* morphology also explains why thalweg scour was so much less in this segment. The exposure of the more resistant clay bed may also have limited thalweg erosion in this middle segment of study reach.

Stock can access most of the *upstream* morphology, where they suppress the growth of emergent macrophytes such as *Phragmites*. The absence of these suitably adapted species means sediment is not readily trapped, pioneer landforms (*sensu* Gurnell, 2014) such as bars and benches are not built and the scour caused by extraction is more widely distributed across the channel bed. As a result, a wider low-flow channel develops and cross-section are less complex than their vegetated counterparts. At the same time, because these cross-sections start from a point of low complexity, extraction drives a larger increase in variability in vegetation-free cross-sections than in the vegetated cross-sections further downstream, which were already more complex prior to extraction.

7.3.3 Implications for conceptual models of channel response to in-stream extraction

The conceptual model (Figure 7.1) predicted that the depth of scour (the decrease in thalweg elevation) would increase in a downstream direction as successive pits are added to the sequence. Unlike many of the rivers described or modelled in the literature (for example Galay, 1983; Simon, 1989; Rinaldi *et al*., 2005; Li and Qi, 2015), channel adjustment triggered by extraction in the Glenelg has not progressed downstream as a one-dimensional wave of bed degradation. Channel adjustment varies longitudinally: the thalweg alternates between aggradation and degradation from upstream to downstream.

Given the layers of complexity added to the conceptual model (sequencing of extraction, stochastic flows, the pre-existing sediment transport pattern in the reach and the influence of in-stream vegetation) it is perhaps unsurprising that the changes documented in the Glenelg River were so complex. The detailed measurements made in this study have confirmed four predictions of the conceptual model developed in Chapter 5:

1. When a series of extraction pits are spaced close together, they behave as a single, larger extraction pit, causing erosion in downstream reaches and erosion of the streambed between the pits.

2. When additional extraction pits are added to a reach, scour depth increases in a downstream direction.
3. Extraction pits increase cross-section variability in downstream reaches. Increases in cross-section variability occur in reaches with and without in-stream vegetation.
4. In-stream vegetation is associated with greater cross-section variability (which captures bed relief) than reaches without vegetation.

At the same time, several predictions of the conceptual model were not borne out in the Glenelg River:

1. The number and size of pools in the reach did not increase relative to the pre-extraction period.
2. The component of recovery that can be attributed to extraction, as measured by the increase in cross-section variability between 2005 and 2018, did not steadily increase in a downstream direction. The *increases* in cross-section variability between 2005 and 2018 was greater in the *upstream* morphology, closer to the extraction pits, but the overall level of complexity, in both 2005 and in 2018, was much higher in the *downstream* morphology

A surprising finding of this research was that the presence of in-stream vegetation likely enhanced thalweg erosion by concentrating flow into narrow channels. This means that the location of vegetation within a reach plays an important role in determining where thalweg scour takes place.

Extraction has led to an increase in scour depth with distance downstream and an increase in cross-section variability along the entire study reach. However, no new pools have formed on the outside of meander bends, and the pools already present in 2010 have not changed size. In the upstream reaches increased cross-section variability has occurred by a deepening and slight widening of the low-flow channel, while in the downstream reaches vegetated benches have also begun to erode. The deeper low-flow channel (providing standing water during low-flows), greater bed relief and riparian shading in the downstream half of the study reach are indicative of a reach further along the recovery trajectory than the upstream half of the study reach. The pattern of recovery predicted by existing conceptual models (Rathburn and Wohl, 2001; Bartley and Rutherfurd, 2005; Fryirs and Brierley, 2016), which do not include extraction pits, has been inverted in the Glenelg River for two reasons: a sequence of extraction pits has imposed a sediment deficit that accumulates in a downstream direction, and in-stream vegetation has modified channel morphology, accelerating channel recovery. This implies that extraction has been a successful recovery strategy in the Glenelg River.

The morphology of the Glenelg River downstream of the extraction also appears to have better sediment connectivity than the ephemeral gravel bed river studied by Calle *et al.* (2017). Although the river studied by Calle *et al*. (2017) was also characterized by a variable flow regime, vegetation encroachment in the channel, and bed incision in response to extraction, the pattern of scour and deposition was much more pronounced: deep scour zones fed distinct depositional lobes on the channel bed. The segmented nature of erosion and deposition documented by Calle *et al*. (2017) is likely a result of the coarse gravels on the channel bed, with the depositional lobes forming in channel expansions during floods and the inability of lower flows to rework these deposits. The fact that sand is more easily mobilised than gravel may mean that sand-bed rivers tend to smooth out these perturbations and maintain upstream-downstream connection by a deep low-flow channel.

7.3.4 Implications for the management of bedload pulses in the Glenelg River

It is important to consider the implications the results of this study have for the management of the Glenelg River. Extraction was originally justified under the premise that the sediment supply would be reduced, channel recovery would be accelerated, and that reaches further downstream would be protected from sand ingress. This section evaluates that premise.

Like other rivers impacted by bedload pulses in SE Australia, the influx of coarse sand to the Glenelg River generated a wide, flat streambed devoid of pools and other habitat units. Approximately seventy years after transformation (assuming flat sand sheets were in place by 1946), as the river moved along its 'natural' recovery trajectory, in-stream extraction imposed a localised sediment deficit on the channel.

Prior to the most recent phase of extraction (which began in 2010) the study reach had developed benches in some sections, and vegetation had established in the lower 4 km of the reach. The establishment of vegetation in the lower end of the study reach was associated with greater cross-section complexity, even before the most recent phase of extraction. The sediment deficit introduced by the most recent phase of extraction was intended to be equal to the average annual bedload supply to the reach. Limiting extraction volumes to bedload supply should minimise the risk of rapid and damaging bed degradation in downstream reaches. Rutherfurd and Budahazy (1996) estimated an annual average bedload transport rate of 20,000 m^3 per annum at Casterton. The annual average extraction rate in the study reach between 2010 and 2018, which was based on this estimate, was 22,000 m^3 per annum. The calibrated sediment transport model used in this study found that the average annual sediment supply was approximately 22,500 m^3. The accuracy of the earlier sediment supply estimates, and the adherence to these numbers by extractors, means that the changes observed in the reach have taken place under 'ideal' management conditions: extraction matched bedload transport.

Extraction likely played some part in this improvement, but the stark difference between the *upstream* (unvegetated) and *downstream* (vegetated) sections of the study reach, and the fact that cross-section variability differs more between vegetated and unvegetated reaches than it does between successive cross-section surveys within each, suggest that in-stream vegetation is the major control on channel recovery.

Given that in-stream vegetation only established in the Glenelg River in the absence of grazing pressure, stock exclusion should be prioritised as a tool to accelerate recovery.

The erosion of bars and benches in the downstream reach also suggests that any benefits of extraction have already been realised, and that extraction-induced scour has started to undermine landform stability. Erosion of bars and benches in the downstream reach will liberate sediment which is likely to settle in small depressions and in the pools present in downstream reaches (Lisle and Hilton, 1999), counteracting the aims of extraction. Therefore, extraction in this part of the reach should cease while vegetation on the streambed can recover. Extraction may be beneficial in the future to prevent channel aggradation and pool in-fill, but the extraction rate would need to be at a much lower rate, say less than 10,000 m^3 per annum.

Extraction has not generated a nickpoint in the Glenelg River, but the lowering of the streambed downstream of the pits will increase the overall energy slopes in this part of the river. Therefore, a continued erosion of the bed downstream of the extraction pits will generate more upstream erosion with time. The pattern of upstream erosion will be controlled by the pattern of bed shear stress in the channel. Excluding stock from the reach upstream of the extraction pits would exploit this tendency for erosion by allowing vegetation to establish on the bed, increasing channel complexity.

7.3.5 Bedload pulse movement

The sediment budget developed for the study reach found that at the reach outlet, flows were under-capacity: almost all of the sediment supplied to the reach was removed by extraction and only a fraction of this deficit was closed by erosion within the reach. Assuming the per-metre rate of erosion remains unchanged, the length of river impacted by erosion can be written as a formula:

$$L_{IR} = \frac{(S_A - E_A)}{ER}$$

Where L_{IR} is the total length of river downstream of extraction sites impacted by erosion, S_A is the average annual sediment supply in $m^3\ yr^{-1}$ (22,500 m^3 in the Glenelg River at Casterton), E_A is the average annual volume of sand extracted, $m^3\ yr^{-1}$ (22,000 $m^3\ yr^{-1}$ in the study reach) and ER is the rate sand is removed from storage downstream of extraction, in $m^3\ m^{-1}$ (3 $m^3\ m^{-1}$ in the study reach). Using this formula, I have estimated the length of river subject to increased erosion under four different extraction scenarios (Table 7.2).

Table 7.2: The additional length of river downstream of extraction pits impacted by increased erosion every year under four different extraction scenarios

Percentage of annual sediment supply extracted (sediment deficit)	Additional length of river subject to increased erosion per year (km)
100	7.3
75	5.6
50	3.7
25	1.8

The length of river subject to erosion increases each year extraction is undertaken, as the adjustment zone extends downstream. Using the formula above, I predict that the adjustment zone generated by eight years of extraction from the study reach currently extends 58 km downstream of the extraction pits.

7.4 Conclusion

This chapter has analysed how an eight-kilometre long reach of a sand-bed river, which has been impacted by a bedload pulse, responded to in-stream extraction over a thirteen-year period. Channel response was examined by constructing a detailed sediment budget for the reach, using repeat cross-sections spaced along the reach, building a calibrated sediment transport and hydraulic model, and by classifying the channel morphology. The results were then compared to the reach-scale component of the conceptual model presented in Chapter 5.

The results of this chapter support several of the predictions of the conceptual model: the closely spaced extraction pits behave as a single, larger pit, which causes the bed between the pits to erode; the depth of thalweg erosion increased in a downstream direction as additional pits are added to the sequence; and overall, extraction increases channel complexity in downstream reaches. However, extraction did not drive pool scour on the outside of meander bends and existing pools did not increase in size. The most surprising result of this research was the impact of in-stream vegetation on the pattern of channel recovery.

In-stream vegetation played a more important role in channel recovery (measured as cross-section complexity and overall morphological diversity) than in-stream extraction. The presence of vegetation in the lower half of the study reach concentrated the erosion caused by extraction into a narrower channel on the bed, which enhanced thalweg erosion. The net effect of superimposing extraction and in-stream vegetation on the study reach was to invert the usual pattern of recovery observed in rivers recovering from bedload pulses. Instead of recovery progressing from upstream to downstream, the downstream segment of the reach was further along the recovery trajectory than upstream segment of the reach. This 'inverted' pattern of recovery was the initial aim of extraction. Scour induced by extraction has started to erode many of the vegetated bars and benches and now threatens their stability.

My results have implications for the use of in-stream extraction to accelerate recovery in sand-bed rivers impacted by bedload pulses, and for the management of sand extraction in the Glenelg River. Most importantly, stock exclusion, which allows vegetation to establish on the streambed, should be prioritised for two reasons: vegetated landforms lock sediment into storage and prevent it from moving downstream, and when stock exclusion is used in conjunction with in-stream extraction, channel complexity is increased more than with extraction alone. Further sand extraction from the study reach is likely to drive more erosion of channel features and should therefore be suspended until erosion ceases. Currently, I predict that the 58 km of river downstream of the extraction pits is impacted by extraction-induced erosion. If aggradation resumes in the reach, extraction could re-commence but at a rate well-below the rate of bedload transport.

Chapter 8: Interacting local scale interventions

A note to the reader: this chapter was written as a stand-alone paper that has been submitted to the journal *Applied Geography*. A complete copy of that submission is included in the Appendix B. An abridged and altered version is included here, which better integrates with the rest of the thesis.

8.1 Introduction

Chapters 6 and 7 evaluated the conceptual model for in-stream extraction presented in Chapter 5. A finding to emerge from the reach-scale part of the model was that in-stream vegetation can play an important role in shaping channel morphology downstream of extraction sites. The work in the Glenelg River evaluated changes from extraction over a thirteen-year period. I now shift the focus to Bryan Creek, a tributary of the Wannon River that is recovering from a bedload pulse. The purpose of the change of field site within the catchment is to consider additional layers of complexity: the effectiveness of several local-scale interventions ($10–10^3$ metres in river length) implemented at the tail of a bedload pulse, when catchment scale erosion control measures have already been undertaken.

Recall that the small headwater tributaries that feed Bryan Creek were treated with extensive erosion control measures in between 1960 and 1980 (Chapter 3). These actions have slowed gully erosion and limited sediment inputs to Bryan Creek. The Bryan Creek study considers the changes produced by reach scale restoration actions in the trunk stream now that the major catchment issue (sand inputs) have been addressed.

Restoration activities in degraded trunk streams tend to involve multiple, diverse and disjointed interventions perhaps over hundreds of metres or a few kilometres of the stream and its riparian zone. This is because the stream is often owned by different landholders or managed by different groups. The messy reality of this sort of program of work is not amenable to controlled trials of effectiveness, which makes project evaluation very difficult. As a result, project evaluations tend to be similarly piecemeal or absent entirely.

The effect of an intervention would ideally be determined with a BACI experimental design against reference and control reaches elsewhere (Palmer *et al*., 2005; Woolsey *et al*., 2007). There are no appropriate reference or control reaches in this region, none were set-up at the time of the interventions, and many reaches of stream have multiple interventions. This is a common problem with post-hoc studies like this one. In this situation the best that can be done is to compare the response of reaches (direction and magnitude of change) to the response predicted by conceptual (or numerical) models, taking into account the interaction between reaches. I am fully aware of the limitations of this approach (especially the complex interactions between treated reaches), however, this is exactly the approach that managers take every day when planning projects such as these. They will assess the processes in the reach, predict the trajectory of change, the interaction between reaches, and so decide on how to intervene. This is, for example, the process when making a River Styles assessment (Brierley and Fryirs, 2000; Fryirs and Brierley, 2000; Brooks and Brierley, 2004; Fryirs and Brierley, 2016). Therefore, I take the approach, in this study, of identifying a single river where local scale interventions are all subject to the same boundary conditions and environmental history. This approach is a feasible trade-off between an ideal study design with fully independent trials and controls, and the conditions likely to be present in most stream restoration projects.

I first outline the approach to evaluating interventions in Bryan Creek. I summarise the environmental history of Bryan Creek and then build a conceptual model to predict the channel adjustments generated by each of the interventions, alone and in combination.

8.1.1 Study design

For this study I exploit the serendipitous history of Bryan Creek, a valley-floor incised stream in western Victoria, Australia which is recovering from a large bedload pulse. I use the history of change to assess the consequences and interactions of three common, local-scale interventions: fencing to exclude stock from the channel bed and banks, re-vegetation of the banks, and commercial sand extraction to starve downstream reaches of sediment. Bryan Creek is an ideal case study because:

1. The supply of sediment from headwater gullies has declined, and the bedload pulse is now migrating downstream revealing a ~30 km stretch of river at the tail of the bedload pulse. Bryan Creek is a good example of the class of small, sand-bed rivers in SE Australia (Prosser *et al*., 2001a) recovering from erosion-induced bedload pulses where sediment supply from the catchment has declined.
2. It has experienced a full range of management interventions over several decades; extraction, stock exclusion and revegetation, but in different, distinct locations. This pattern of interventions allows us to compare the effectiveness of different interventions, alone and in combination. Further, the resulting pattern of change is remarkably distinct between these reaches, isolating the effect of local interventions.
3. There is a wealth of historical photography, channel surveys, and records of management actions, for the entire waterway over an unusually long period, 50 years.

Although our focus is on geomorphic rather than ecological changes, I recognise that interventions to promote the former are often part of wider strategies to improve stream health. Thus, I also evaluate whether interventions increase geomorphic complexity, a widely-employed surrogate for geomorphic condition and habitat availability (Newson and Newson, 2000; Brooks, 2003; Bartley and Rutherfurd, 2005a; Wohl, 2016).

I briefly describe the environmental history of Bryan Creek, and predict how Bryan Creek would be expected to respond to each of the interventions. The predictions, which are based on published conceptual models of recovery, serve as a template against which observed changed in Bryan Creek can be compared.

8.1.2 Environmental history of Bryan Creek

Bryan Creek is a tributary of the Wannon River in Western Victoria, Australia and has a catchment area of 560 km^2. Here I focus on the lower 30 km, between the Douglas Bridge and Wannon River junction (Figure 8.1). The township of Coleraine is on the left bank in the middle of this reach.

In common with many southeast Australian streams, at European settlement, Bryan Creek was a chain-of-ponds, which are intermittently spaced pools separated by densely vegetated channels (Eyles, 1977a; Eyles, 1977b; Rutherfurd, 2001). Clearing of catchments in the early 19th century across western Victoria (Yazdanparast, 2016) altered catchment hydrology and initiated widespread catchment erosion, gullying and stream incision (Erskine, 1994; Prosser *et al.*, 2001b). Bryan Creek first incised, and then filled with sediment (predominantly sand) as a bedload pulse formed. As the bedload pulse migrated downstream, aided by the flood of record in 1946 (Flood Victoria, 2009), the channel widened and the channel bed became a flat, featureless sheet of sand with no vegetation on the bed or banks (Figure 8.2A and B). Management interventions described in section 8.2.3 were applied to this sand-channel.

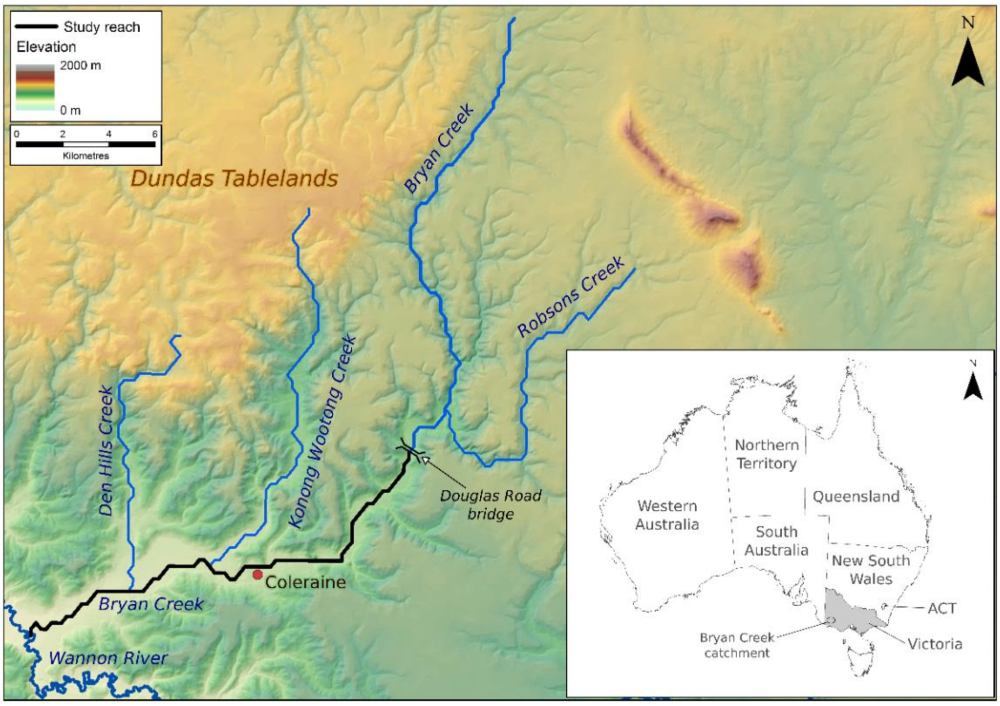


Figure 8.1: Bryan Creek catchment in western Victoria, Australia. The Wannon River junction and major tributaries are shown in blue and the study area is outlined in black.

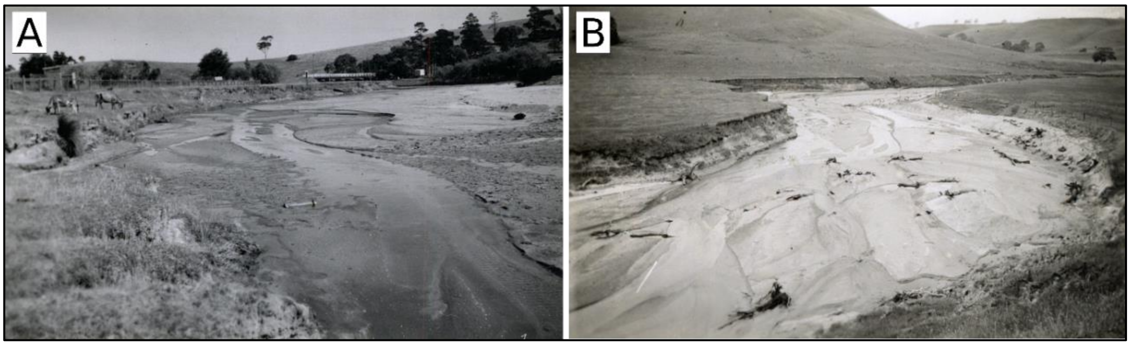


Figure 8.2: The sand pulse in Bryan Creek (A) looking downstream into the reach adjacent to the Coleraine township in 1950, (B) looking upstream toward the reach immediately above Coleraine in 1944, substantial in-stream extraction was undertaken in this reach between 1954 and 1990. Photos courtesy of Coleraine Historical Society.

8.1.2.1 Erosion control measures in the Dundas Tablelands

Erosion control works (fencing to exclude stock, wooden or concrete structures to halt gully-head migration, and grade control structures) were undertaken by the Soil Conservation Authority and Glenelg River Improvement Trust between 1950 and 1989 in the gullies that feed water and sediment to the study reach (Figure 8.3). These works have succeeded in stabilising gullies and have reduced sediment inputs to Bryan Creek (Marker, 1976; Erskine, 1994), allowing the tail of the sediment pulse to move downstream (Figure 8.4).

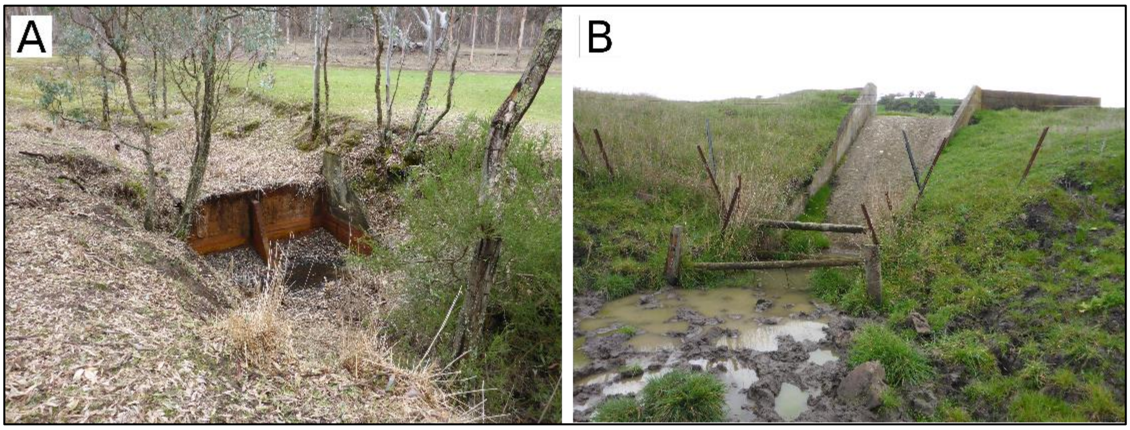


Figure 8.3: Erosion control structures, constructed in the late 1960 and early 1970s, in small headwater streams in the Bryan Creek catchment. (A) 'Drop structures' - small grade control structures which span the channel and trap sediment, (B) Concrete chutes which slow erosion by preventing nick-points from migrating upstream. Photos courtesy of Glenelg Hopkins Catchment Management Authority.

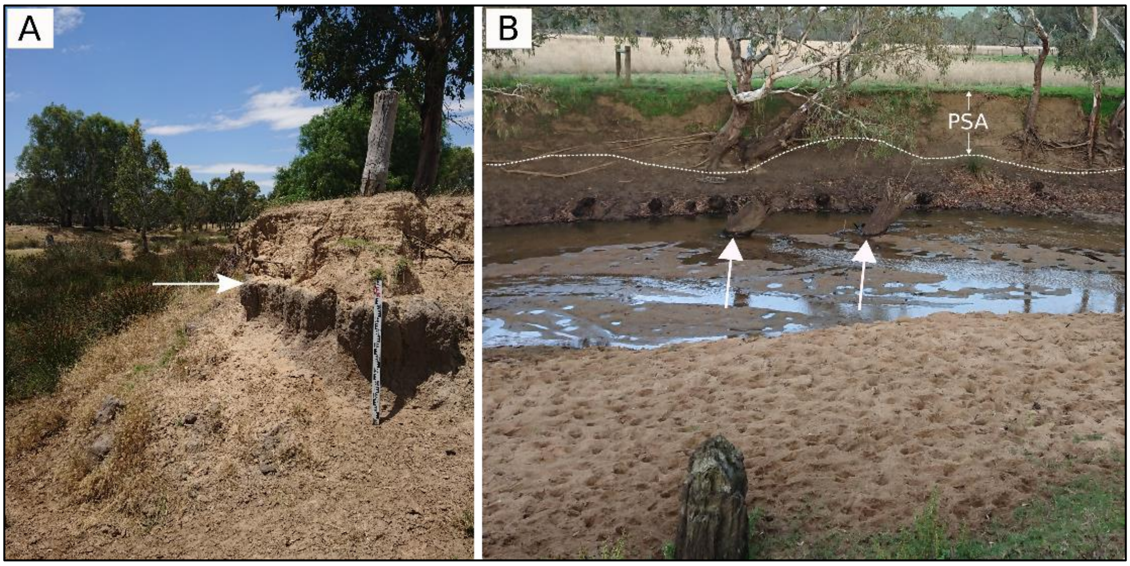


Figure 8.4: (A) looking upstream into a reach not subject to any intervention, in 2017, the white arrow points to the sharp contact between the pre-pulse riverbank comprised of dark, organic rich sediments, and the upper levee of coarse sand deposited on the floodplain when the bedload pulse formed, (B) Looking across towards the true left bank in the lower part of Bryan Creek. Dashed white line marks the contact between the former stream bank and the overlying post-European settlement alluvium (PSA), white arrows mark exhumed tree trunks in the channel bed.

8.2 Methods

The goal of this paper is to evaluate local scale interventions once the catchment scale drivers of degradation have been addressed. Observations and measurements can be used to test and refine conceptual models of river channel change associated with sediment pulses when a series of different local scale interventions have been applied to different parts of the river, at different times. I do this by separating Bryan Creek into 12 reaches, according to the extent of different local scale interventions. Here I define a *reach* as a distinct length of stream that experienced the same set of interventions. I summarise how Bryan Creek would evolve in the absence of any interventions and predict the impact of superimposing each combination of discrete, local scale intervention on the tail of a sediment pulse.

8.2.1 Predicted channel adjustment without intervention

In the absence of intervention, channel adjustments should track the downstream movement of the tail of the bedload pulse. That is, at any point in time, upstream reaches will have progressed further along their post-disturbance trajectory than those further downstream (Bartley and Rutherfurd, 2005b).

As the tail passes downstream, bed variability increases and a sequence of channel adjustments takes place (Madej, 2001) including: channel contraction, bench formation (benches are stable bank-attached bars that accrete within the over-widened channel), return of a well-defined low-flow channel (Hoyle *et al*., 2008; Fryirs and Brierley, 2016), exhumation of the pre-disturbance bed (Gilbert, 1917; Knighton, 1989; Madej and Ozaki, 1996), stable alternating bars (Erskine, 1996), establishment of in-stream vegetation (Friedman *et al*., 1996a; Erskine *et al*., 2009b), and the re-emergence of pools (Madej, 2001; Zunka *et al*., 2015). Alternatively, as the sediment supply declines, the river could also resume some other pre-pulse trajectory, such as incision (for example Bartley and Rutherfurd, 2005a; Rutherfurd, 2001).

8.2.2 Predicted channel adjustment with intervention

Local-scale interventions will accelerate this pattern of recovery by accelerating sediment removal (in-stream extraction), or by trapping and storing sediment (stock exclusion and re-vegetation). When superimposed on the tail of the bedload pulse, interventions would be expected to cause localised improvements in stream condition that slightly perturb the upstream-downstream pattern of channel adjustment i.e. the local interventions will play a secondary role to the catchment-scale processes shaping the recovery of Bryan Creek (Figure 8.7).

8.2.3 The distribution of local scale interventions in Bryan Creek

Since the 1980s stock exclusion fencing, re-vegetation and in-stream extraction have been used in five combinations, across twelve distinct reaches of Bryan Creek (Table 8.1 and Figure 8.5).

Table 8.1: The combination of intervention used, the corresponding number of reaches treated, and the cumulative length of river treated by each combination of intervention.

Combination of interventions	Number of reaches	Reach length (km)
Fence and revegetate	5	5.7
Revegetate only	1	2.8
Extraction only	2	16.2
Fence + revegetate + extraction	1	1.7
No treatments	3	3.6
Total	12	30

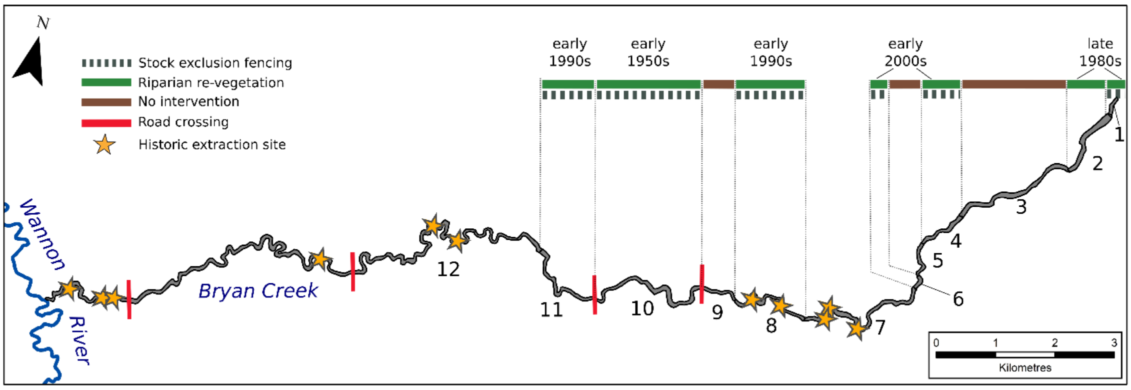


Figure 8.5: Study reach of Bryan Creek in western Victoria with treatment reaches numbered. Coloured bars indicate the type of intervention undertaken in the corresponding reach and the approximate date of intervention. The location of historical extraction sites (1954 to 1994) and road crossings are also shown. Flow is from right to left.

The following descriptions refer to the reaches shown in Figure 8.5. In-stream sand extraction was undertaken continually, but in different parts of the river, between 1954 and 1994. Stock exclusion and re-vegetation was undertaken in reach 10 first, in the 1950s. When the second phase of interventions began in the 1980s, the tail of the bedload pulse had moved further downstream and a clay bed was exposed in the upper 3 km of the river. Thus, when stock exclusion and re-vegetation treatments were undertaken in reaches 1 and 2 (Figure 8.6), the reaches already had an incising, clay-bed. Reaches 8 and 11, which are sand-bed reaches, underwent stock exclusion and re-vegetation in the early 1990s. Lastly, reaches 4 and 6 were fenced to exclude stock and had their banks re-vegetated in the early 2000s.

Figure 8.6: Looking downstream into the clay bed reach at the upstream end of the study reach (reaches 1 and 2 in Figure 8.5) immediately prior to intervention in the late 1980s. Note incision into the clay bed. Photo courtesy of the Glenelg Hopkins Catchment Management Authority.

8.2.4 Interaction of local scale interventions

Local scale interventions interrupt sediment continuity by either locking sediment into storage or removing sediment from storage. This sediment continuity causes interventions in upstream reaches to interact with interventions further downstream. Recall too, that all of these interventions are superimposed on the tail-end of a degrading sediment pulse. Further, changes are not restricted to simple erosion or deposition, but to more complicated geomorphic patterns and interactions with vegetation.

Since I have five combinations of intervention, there are 20 possible permutations of connection between them – too many to outline here. The point is that local scale interventions will interact, and these interactions will cause channel morphology to gradually change at the upstream and downstream end of intervention reaches (Figure 8.7).

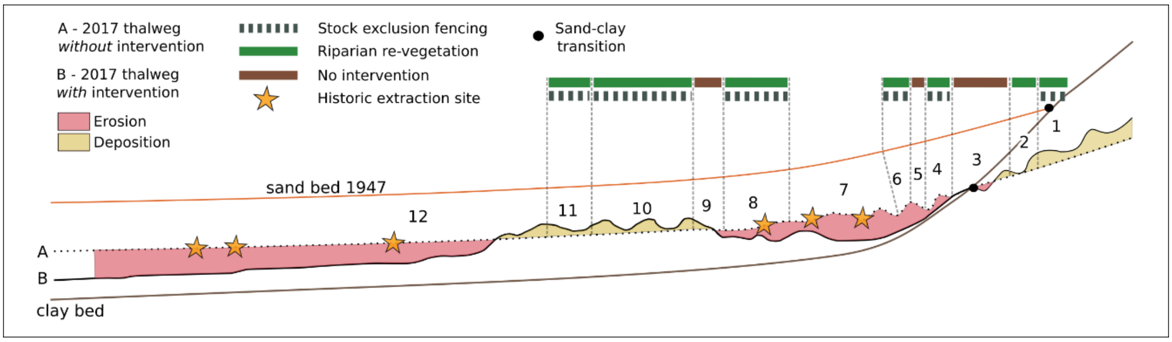


Figure 8.7: Conceptual model showing how the hypothetical thalweg profile of Bryan Creek is predicted to evolve with and without local scale interventions, numbers indicate reach number shown in Figure 8.5 and colour bands indicate the combination of interventions implemented in each reach.

I assess the impact of local scale interventions on the trunk stream in two ways: by comparing the pre-intervention longitudinal profile surveyed in 1984 with post-intervention longitudinal profiles surveyed in 2010 and 2017, and by comparing contemporary morphology of each treatment reach with the morphology predicted to emerge, for each intervention or combination of interventions.

I generated the pre-intervention longitudinal profile by compiling cross-sections surveyed in 1984 at variable spacing (50 m - 1 km) and extracting the thalweg of each cross-section. The post-intervention profile was constructed by compiling cross-sections surveyed using aerial LiDAR flown in 2010 for sections with exposed sand. A Trimble R6 differential GPS was used to survey cross-sections in 2017 in areas where standing water or vegetation had obscured the bed from LiDAR in 2010. The 2010 LiDAR cross-sections, and the 2017 GPS cross-sections, were then merged to produce a total of 553 cross-sections, spaced at 50 m intervals along the river. Thalwegs were extracted from the post-intervention cross-sections and the slope was removed from both profiles by fitting a linear trend line to each thalweg profile, and subtracting surveyed values form the 'modelled' values of the trend line. This allowed the thalweg profiles to be easily compared.

Comparison of pre and post-intervention morphology was done by surveying the river at low flow and by employing a small Unmanned Aerial Vehicle (UAV) to capture 0.05 m resolution aerial imagery. I then used field inspections and the aerial imagery to develop a simple morphological classification. The classification considers: the condition of the bed, condition of the banks, and the presence (or absence) of different types of vegetation. Reaches were classified into categories.

Comparing the mapped extent of each intervention with my morphological classification allowed me to establish the spatial and temporal association between intervention and morphology. How quickly morphology changes at the boundary between interventions can be used as an indicator of the importance of local vs. catchment scale controls. Sharp transitions provide some evidence that local scale interventions determine reach morphology. Whereas a more gradual transition is evidence for interaction between reaches, and the dominance of catchment scale controls.

8.2.5 Geomorphic complexity metrics

To supplement our subjective classification of morphology, and to objectively compare the geomorphic condition of reaches subjected to different management interventions, I employed quantitative metrics of geomorphic variability, which serve as a proxy for geomorphic complexity (Bartley and Rutherfurd, 2005a; Polvi *et al.*, 2014; Wohl, 2016). Geomorphic complexity, the diversity of stable channel features and vegetation, is widely considered to be a crucial template for habitat, improved ecological condition and biodiversity (Newson and Newson, 2000; Palmer *et al.*, 2007; Palmer *et al.*, 2010; Bernhardt and Palmer, 2011; Wohl, 2016).

Different metrics have been shown to characterise variability equally well (Polvi *et al.*, 2014; Wohl, 2016) so I use standard deviation, which is straightforward to compute and interpret, and has been successfully applied in sand-bed streams (Brooks *et al.*, 2006; Bartley & Rutherfurd 2005a). Post-intervention longitudinal complexity was calculated for each of the twelve reaches using the post-intervention 2010 and 2017 surveys. Complexity (i.e. standard deviation) was also measured across the channel using the post-intervention cross-sections surveyed in 2010 and 2017 (pre-intervention cross-sections were surveyed at too low a resolution to allow a meaningful estimate of variability).

8.3 Results

I outline changes in Bryan Creek generally, complexity metrics, the results of my morphological classification and how channel morphology relates to the different combinations of local intervention.

8.3.1 General channel changes

Between 1984 and 2017 the tail of the bedload pulse has continued to move downstream (Figure 8.8). This has caused the bed to degrade and has exposed the clay in upper reaches (Figure 8.9). Overall the flat sheet of sand present in 1947 steadily transitioned to a more complex, well-defined, meandering low-flow channel; but this change occurred at different times in different reaches. It is interesting to note that, although stock were excluded, and the banks re-vegetated from reach 10 thirty years earlier than other reaches, accelerated morphological changes began at the same time for all reaches in the early 1990s. This change coincides with the end of in-stream extraction and the expansion of emergent macrophytes into the channel.

8.3.2 Complexity metrics

8.3.2.1 Changes in the longitudinal profile of Bryan Creek

I expected that compared to the pre-intervention thalweg profile (surveyed in 1984), the post-intervention thalweg profile (surveyed in 2010 and 2017) would be more variable upstream, in the tail of the sand wave, and variability would gradually decrease in a downstream direction. This is not the pattern that has developed. There is no clear longitudinal pattern in complexity at the scale of the whole river. Instead there is remarkable variation in complexity at the scale of the reaches, and the transition in that complexity between reaches is sharp. There has been bed-degradation in the upper 5 km of the river, but also in the lower 8 km. The central portion of the river has aggraded overall.

The most dramatic change in the river is the development of deep pools in reaches 8 to 11 in the central section of the river. In these reaches, stock have been excluded by fences and the banks have been re-vegetated (Figure 8.8). In these reaches the complexity has developed by the thalweg both degrading (eroding pools) and aggrading between the pools. Reach 12 (the downstream extraction reach) exhibits both minor aggradation and degradation since 1984, with the boundaries of these aggradation-degradation zones coinciding with road crossings that fix bed elevation.

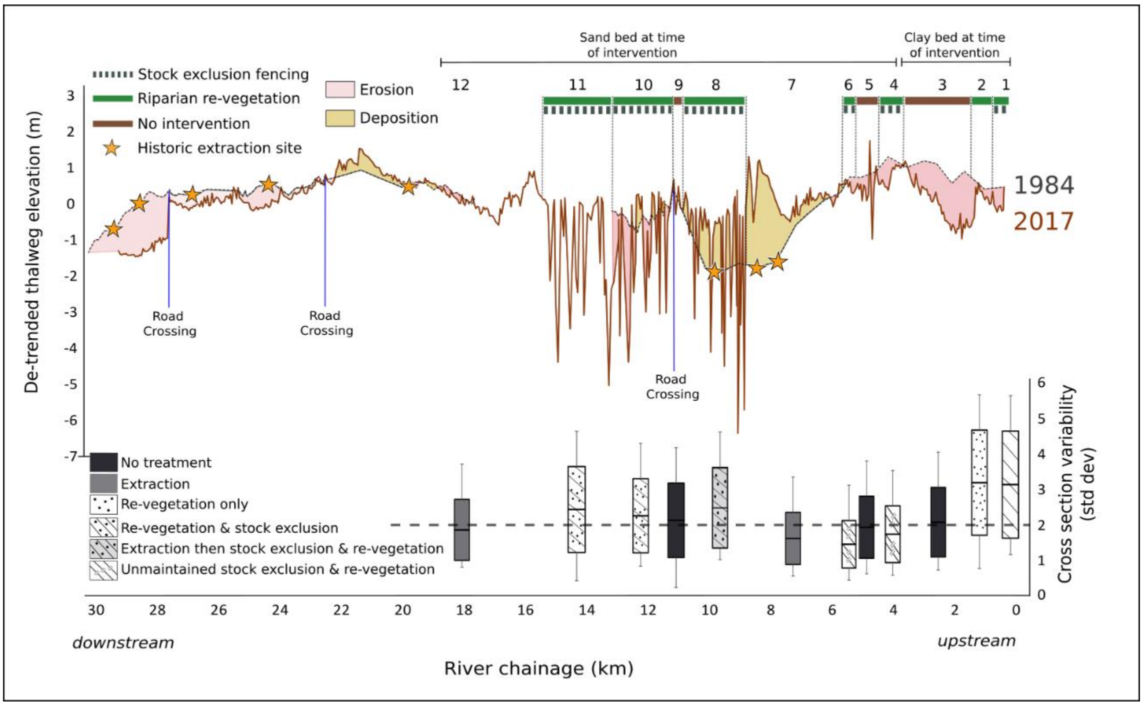


Figure 8.8: (Top) De-trended, pre and post-intervention longitudinal thalweg profiles for Bryan Creek, with the twelve intervention reaches, the combination of interventions undertaken in each reach, channel substrate at the time of intervention, and the location of historical extraction sites. Pink shading indicates erosion between 1984 and 2017, whilst yellow shading indicates deposition between 1984 and 2017. (Bottom) Box and whisker plot showing the median, lower and upper quartile values of cross-section variability for each of the 12 reaches. Symbols indicate interventions undertaken in each reach, dashed line indicates the median value of cross-section variability for reaches 3, 5 and 9, which were not subject to intervention.

8.3.2.2 Cross-section variability

I expected cross-section variability, as measured by the standard deviation of elevations, to mirror thalweg variability, being highest in upstream reaches and decreasing in a downstream direction. The expected pattern is evident in the gradual decline in median values of cross-section variability from 1.5 in reach 1 to 0.7 in reach 6. However, cross-section variability then shows a step-increase in sand-bed reaches 8, 9, 10 and 11, which have similar values of cross-section variability of 1.1, 1.1, 1.0 and 1.2, respectively (Figure 8.8, Table 8.2). Width-to-depth ratios are highest in reaches with no treatment (mean of 16.8) and unmaintained stock exclusion and re-vegetation reaches (mean of 23.7), and were lowest in reach 2, which was treated with re-vegetation alone (Table 8.2).

The graphical results are mirrored by the thalweg standard deviation for each intervention type (Table 8.2). Reaches treated with stock exclusion and re-vegetation and reaches treated with extraction *then* stock exclusion and re-vegetation (reaches 10, 11 and 8, respectively), have longitudinal thalweg variability values of 1.5 compared to only 0.6 in reaches not subject to intervention.

Table 8.2: Width-depth ratio, thalweg variability and cross-section variability grouped by intervention type, for each of the twelve reaches in Bryan Creek. The spatial extent of each intervention type is shown in Figure 8.8.

Intervention type	**Reaches**	**Median w/d ratio**	**Median value of thalweg standard deviation**	**Median value of cross-section standard deviation**	**Post-intervention channel morphology**
No treatment	3, 5, 9	16.8	0.6	1.0	Dissected
Stock exclusion & re-vegetation (clay bed)	1	15.2	0.3	1.5	Simple
Re-vegetation only (clay bed)	2	11.5	0.4	1.5	Simple
Extraction then stock exclusion and re-vegetation (sand bed)	8	14.8	1.9	1.1	Sequence-of-pools
Stock exclusion & re-vegetation – (sand-bed)	8, 10, 11	15.2	1.5	1.2	Sequence-of-pools
Unmaintained stock exclusion & re-vegetation	4, 6	23.7	0.4	0.7	Simple
Extraction only	7, 12	20.6	0.5	0.8	Dissected

8.3.3 Classification of reach scale morphology

In the last section I described the changes in cross-sectional and longitudinal changes in the 12 reaches. The abrupt changes in longitudinal thalweg variability are associated with changes in reach morphology. The characteristics of all twelve reaches can be classified into one of three distinct channel types:

- **Simple**: channels that alternate between dense stands of emergent macrophytes (*Phragmites australis*), long, shallow pools (~0.5 m deep) and wide, flat sections with exposed clay, sporadic in-channel vegetation and high, steep banks (typical examples shown in Figure 8.9C and D),
- **Dissected**: a network of narrow, low-flow channels cut through beds of spiny rush (*Juncus acutus*) and occasional clusters of emergent macrophytes (*Phragmites australis*), some bench development and pervasive erosional features such as bar cut-offs and near-vertical, exposed banks (Figure 8.11B and D),

- **Sequence-of-pool**: channels that alternate between dense stands of emergent macrophytes (*Phragmites australis*) and pools (~2-4 m deep), well-vegetated banks of mature red gums (*Eucalyptus camaldulensis*) (Figure 8.10).

I now consider the association between the combination of local scale interventions applied and the morphology that has developed.

8.3.4 Association between intervention type and morphological classification

Post-intervention channel morphology varied by the type of intervention applied and channel substrate at the time of intervention (sand vs. clay) (Table 8.2).

Reaches that have a clay bed (reaches 1-6), either pre-intervention or where the clay bed has since been exposed, have transitioned to a simple morphology, regardless of which interventions (if any), were applied to them (Figure 8.11). In reaches 1 and 2 this transition was preceded by a phase of deep incision in the early 1980s, while in downstream reaches (reaches 3-6) the depth of incision has been more limited (Figure 8.8).

Sand bed reaches (7-12) have transitioned to either a sequence-of-pools morphology (Figure 8.10) or a dissected morphology (Figure 8.11). The sequence-of-pools morphology has formed wherever stock have been excluded from a reach. All reaches treated with stock exclusion also had their banks re-vegetated, and the association between stock exclusion and sequence-of-pools morphology holds where the reach was previously subject to in-stream extraction (reach 8).

Although stock was excluded from sand-bed reaches at different times, all followed a similar pattern of change: a low-flow channel emerged, emergent macrophytes colonised the channel margins and then spread across the channel, pinching off the low-flow channel (or surrounding historic extraction pits) and deep pools formed. This process accelerated in reaches 8, 10 and 11 in the late 1980s/early 1990s, once in-stream extraction from reach 7 had ceased (Figure 8.12).

The dissected morphology has emerged in all other sand bed reaches, wherever stock can access the bed. The association between continued stock access and the dissected morphology holds where no intervention was ever applied (reach 9) and in reaches previously subject to in-stream extraction (reaches 7 and 12).

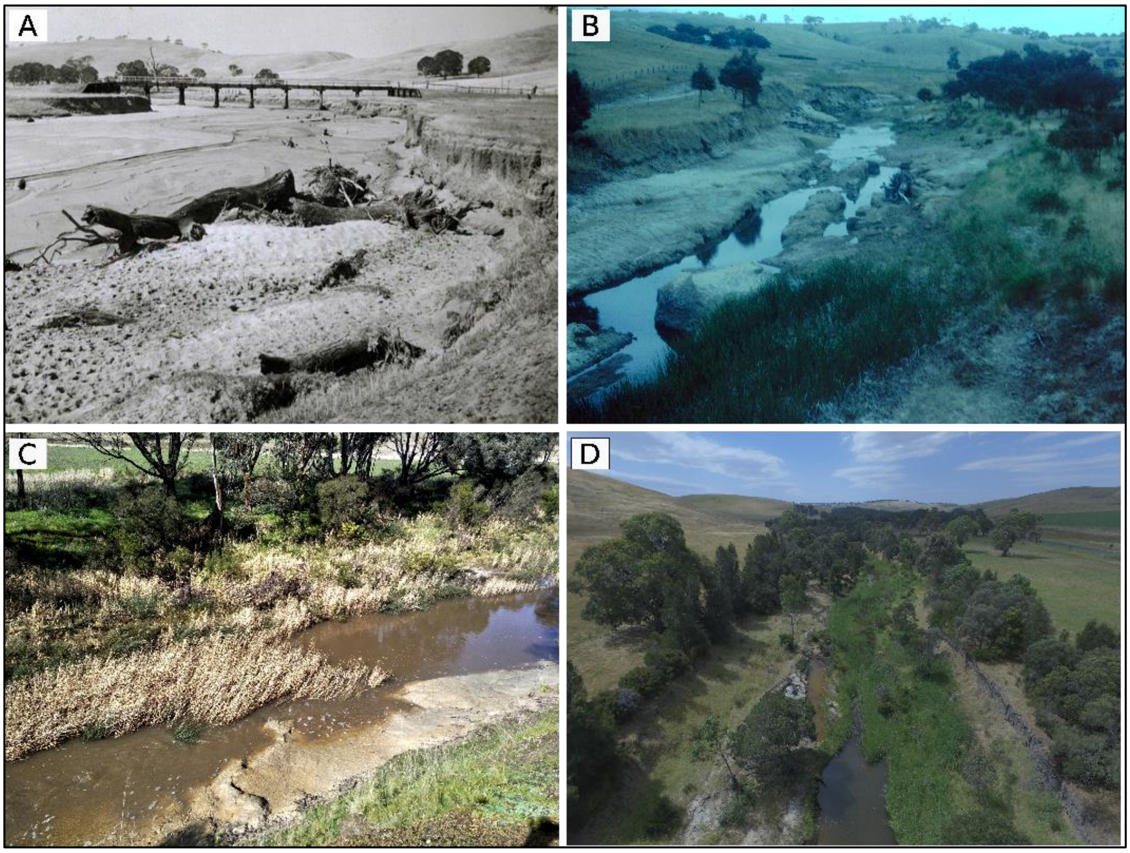


Figure 8.9: (A) Reach 1 below original Douglas-Gaze-McMahon Road bridge, looking upstream, in 1940, (B) Reach 1 looking upstream towards the current Douglas Road Bridge, which is 300 m upstream from the original bridge, in the late 1980s, incising clay bed and bank-collapse clearly visible. (C) Reach 1 in 2017, looking across from the true right bank showing re-vegetated banks, small stands of *Phragmites* and exposed clay bed. (D) Oblique aerial view of reach 2 looking upstream, showing formation of a series of shallow runs, emergent macrophytes and bank vegetation. (Photo source: (A) Coleraine Historical Society, (B) Glenelg Hopkins Catchment Management Authority).

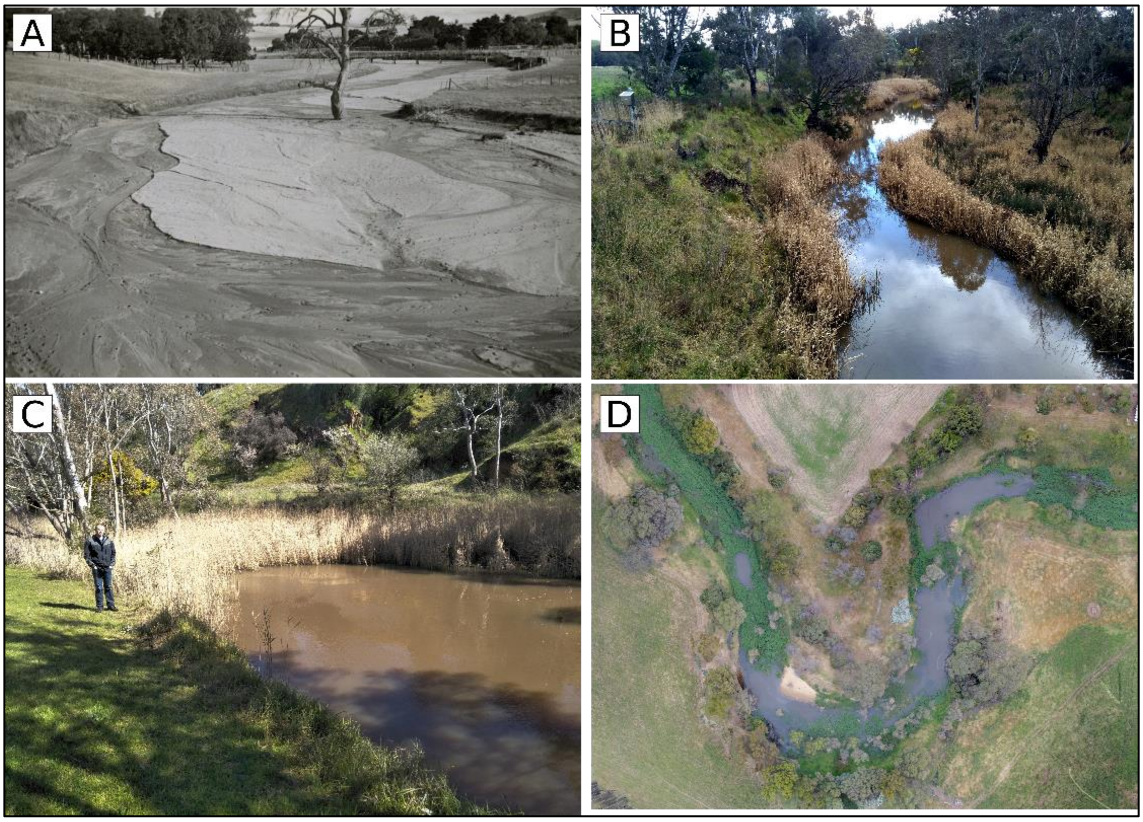


Figure 8.10: (A) view looking upstream into reach 10 beside the Coleraine township in 1940, showing wide, flat bed of sand-bed devoid of vegetation, (B) looking downstream from the upstream end of reach 8 in 2017 showing emergent macrophytes on the margin of a continuous channel, (C) pools in roughly the same location as (A) but looking downstream in reach 10 in 2017, (D) a 2017 aerial image of reach 11 showing the sequence of pools. Photo A is from the Coleraine Historical Society.

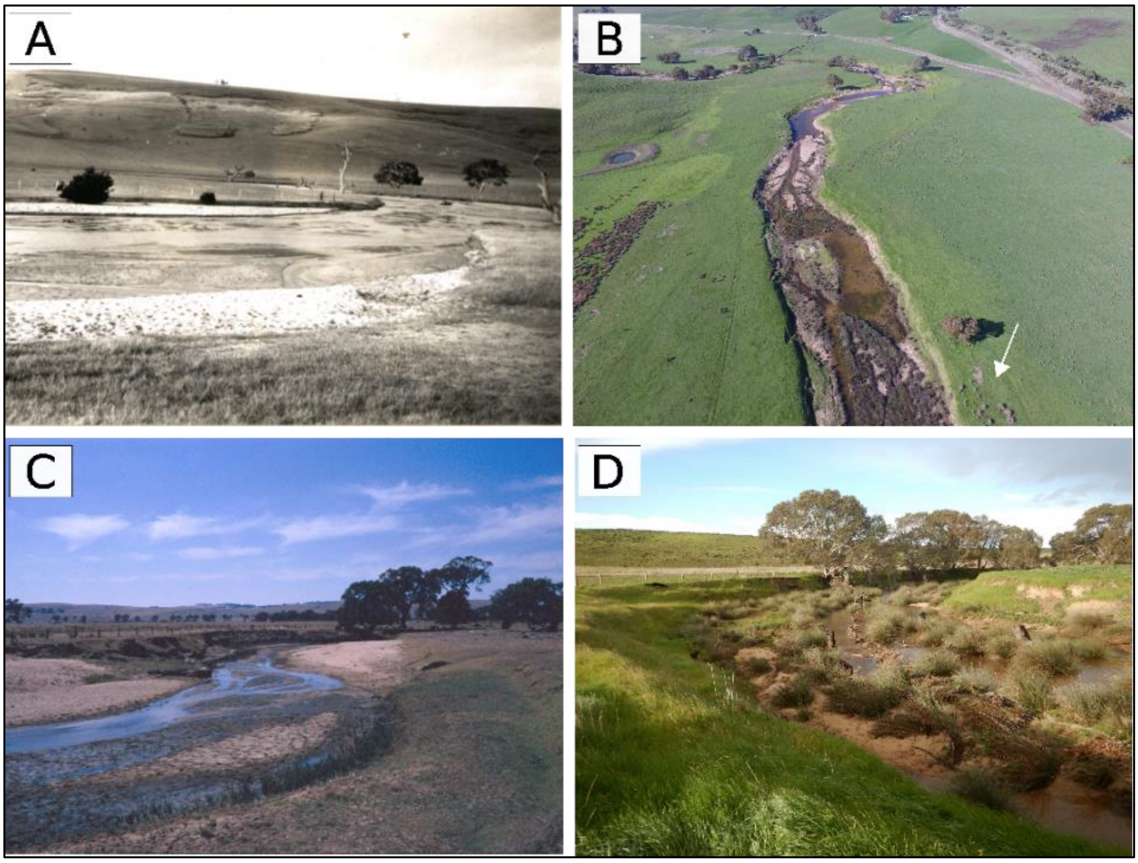


Figure 8.11: (A) Looking north across reach 7 above Coleraine in 1944, significant in-stream extraction began here in 1954, (B) aerial view of the same section in 2017 showing dissected morphology, white arrow indicates the position photo (A) was taken from, (C) representative section of reach 12 in 1994, immediately after extraction ceased, note the absence of spiny rush on the channel bed, and (D) representative section of reach 12 in 2017, showing spiny rush colonising the bed, the dissected morphology, and bar-and-bench erosion. (Photo A is from Coleraine Historical Society, and B is from Glenelg Hopkins Catchment Management Authority).

Figure 8.12. The transformation of reach 8, above Coleraine, from (A) a continuous low-flow channel in 1991 to (B) a sequence of pools by 2017. *Phragmites* spread inwards from the channel margins, pinching-off the low-flow channel.

Overall, the impact of stock exclusion and re-vegetation in sand-bed reaches has been markedly different than in clay-bed reaches. In sand-bed reaches a sequence of pools has formed, but in clay bed reaches, a simple morphology has formed. In clay bed reaches morphology was similar between reaches subject to different interventions, and stock exclusion fencing alone was not associated with clear changes in form. In sand-bed reaches the up and downstream boundaries of interventions demark sharp changes in form. Moving from upstream to downstream (reach 1 to 12), the post-intervention morphology abruptly changes from dissected (reach 7), to sequence-of-pools (reach 8), back to dissected (reach 9), back to sequence-of-pools (reach 10 and 11) and then back to dissected (reach 12).

8.3.5 Transitions in morphology

The boundary between different morphologies in sand-bed reaches is sharp and is marked by an abrupt change from a dissected to a sequence-of-pools morphology (or vice versa) (Figure 8.13). The sharp boundaries occur at the upstream and downstream ends of stock exclusion and re-vegetation reaches, where a fence spans the river. Road crossings interrupt this pattern by suppressing all vegetation where they span the river, but *Phragmites* or spiny rush (whichever is growing in the reach disturbed by the crossing) has established immediately downstream.

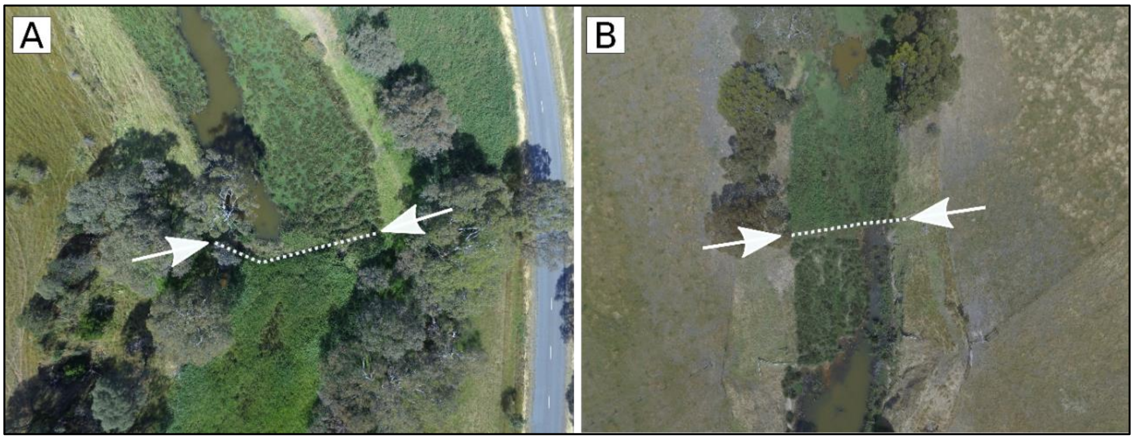


Figure 8.13: (A) The upstream boundary of reach 7 and 8 and the abrupt changes from spiny rush (upstream, top of photo) to *Phragmites* (downstream, bottom of photo), (B) the downstream boundary of reaches 8 and 9 and the abrupt change from *Phragmites* (upstream, top of photo) back to spiny rush (downstream, bottom of photo). White lines and arrows indicate the location of a stock exclusion fences.

8.3.6 Summary of results

The common feature that emerges from this complex series of changes is that sequence-of-pools morphology emerges whenever stock are excluded from a sand-bed reach by a fence, even when the reach was earlier subject to in-stream extraction. The dissected morphology dominates sand-bed reaches wherever stock access continues. The simple morphology, which includes some in-stream vegetation and shallow pools, is restricted to the clay bed sections in the most upstream reach of the Bryan Creek study. Thalweg variability is highest in sand-bed reaches where stock have been excluded, and sand has been extracted upstream. Cross-section variability is highest in clay bed reaches treated with stock exclusion and re-vegetation.

8.4 Discussion

Within the range of impacts that humans can have on stream systems, Bryan Creek is at the simple end. Like a multitude of other small streams across the world, in response to human disturbance, it has enlarged, and aggraded with sand. Once the supply of sand from the catchment has declined, I would predict a reasonably orderly sequence of channel changes as the sand pulse moves downstream, with management interventions such as sand extraction, stock-exclusion, and revegetation introducing local perturbations to that sequence. In other words, I would expect the catchment scale sediment dynamics to determine the general patterns of geomorphic change in such a simple system. That orderly sequence is not what I have found on Bryan Creek. Instead, the patterns of change have been more complex than predicted, and apparently far more sensitive to local interventions. In particular, the system is extremely sensitive to in-stream vegetation, which in turn, is driven by whether stock can access the stream. This sensitivity is demonstrated by the sharp boundaries between reaches delineated by fences.

I discuss the scale of intervention and the crucial role that in-stream vegetation plays in shaping the morphology of sand bed reaches in more detail below.

8.4.1 The impact of catchment vs. local-scale intervention on reach morphology

The overall morphology of Bryan Creek has been shaped by erosion and sediment production at the catchment scale (Erskine, 1994). However, rather than simply accelerating this pattern of morphological change (Lorenz *et al*., 2012; Molina *et al*., 2017), local-scale interventions have dramatically changed the underlying morphology of intervention reaches. In doing so, local interventions have been surprisingly effective at shaping the physical structure of the river. The next section considers possible mechanisms by which the local interventions produce these local effects.

8.4.2 Vegetation and morphology

In-stream vegetation plays a crucial role in the sand bed reaches of Bryan Creek, which alternate between dissected morphology and a sequence-of-pools morphology. The dissected morphology is associated with the invasive emergent macrophytes spiny rush (*Juncus acutus*), (Parsons and Cuthbertson, 2001), and the sequence-of-pools morphology with native *Phragmites* (*Phragmites australis*), which grows in wetlands, marshes and low-energy rivers across eastern Australia (Roberts, 2000). These macrophytes influence morphology via their differing abilities to trap and store sediment.

When stock can access the river bed they feed on stands of *Phragmites* and trample emerging shoots. This enables dense mats of spiny rush, which is otherwise out competed by the tall, fast-growing *Phragmites*, to establish on the river bed. Spiny rush reproduce by germination of flow-dispersed seeds (Greenwood and MacFarlane, 2006), which causes infestations to spread in a downstream direction. Once established, spiny rush grows into strong tussock-like domes up to 1.5 m in height. The dense, spherical root mass of spiny rush has a high tensile strength and resists uprooting during high flows, but the rooting depth is shallow (~0.1 m in depth) (De Baets *et al*., 2008). The physical characteristics of spiny rush (salt-tolerance, rapid dispersal, dense canopy, and a strong but shallow root mass) explain the dissected morphology in reaches 7, 9, and 12; spiny rush act as erosion-resistant nodules above the ground, but are undermined by deep scour, which is concentrated into a network of low-flow channels between the nodules.

Where stock have been excluded from sand bed reaches (reaches 8, 10 and 11) *Phragmites* have colonised the bed and a sequence of pools has developed. Although pool-riffle sequences have re-emerged at the tail of a bedload pulse in gravel bed rivers (Wohl and Cenderelli, 2000; Madej *et al*., 2009), or formed downstream of sediment retention structures in sediment-laden rivers (Keene *et al*., 2008), both cases require that coarse sediment is exposed to initiate riffles. This is not the case in Bryan Creek where the bed consists of well sorted sand with underlying clay. The physical properties of *Phragmites* allow the sequence-of-pools to develop. Pre and post-intervention surveys undertaken 23 years apart show that over this time pools have scoured, and the intervening bed, which is covered by *Phragmites*, has aggraded.

Phragmites can tolerate prolonged waterlogging, drought and moderate salinity levels (Greenwood and MacFarlane, 2006). *Phragmites* spread to downstream areas by dispersing seeds or rhizomes into the flow, and stands spread laterally by sending rhizomes into the surrounding sand (Engloner, 2009). These properties mean that *Phragmites* will spread through sand deposits quickly. Once established, *Phragmites* grow into tall (up to 4 m), dense stands that can impede flow and induce sediment deposition, but are flexible enough to survive higher flows (Engloner, 2009). The deep network of roots and rhizomes (up to 1 m deep) (Moore *et al*., 2012) increase cohesion and stabilise deposits, locking sediment into storage.

I propose that *Phragmites* have driven pool development by trapping mobile sand, building benches on the channel margins, then spreading towards the channel centreline, aggrading the bed at the same time. Inspection of aerial photography from 1985, 1991 and 2010 revealed that as the *Phragmites* spreads across the channel, they pinch-off the low-flow channel into a series of long, narrow pools. As they trap incoming sand *Phragmites* expand further into the now-isolated low-flow channel, but this encroachment is not uniform along the entire channel, causing the pools to shorten but also widen, whilst maintaining their position. In this manner, *Phragmites* behave as river system engineers (Gurnell, 2014), first building benches on the channel margin and then elevated 'ledges' that span the river between the pools.

The efficiency of *Phragmites* in trapping and storing sediment is supported by Zierholz *et al*., (2001) who documented aggradation of gullies colonised by *Typha* and *Phragmites* in eastern Australia. Erskine *et al*. (2012) also invoked the sand trapping and storing abilities of *Phragmites* to help explain channel contraction in Widden Brook, a sand-bed stream in eastern Australia.

8.4.3 Intervention boundaries and interaction between reaches

Overall Bryan Creek has not followed a typical recovery trajectory of a sand-bed river impacted by a bedload pulse. Given that the boundary conditions of the different treatment reaches are the same, I would expect differences between reaches to gradually disappear with time. Instead, differences in morphology between reaches have been amplified with time. A surprising finding of this research is the abrupt transitions between dissected and sequence-of-pools morphology in sand-bed reaches, and the apparent lack of interaction between reaches.

Unregulated rivers exhibit upstream-downstream continuity of sediment transport. I would expect the changes in sediment storage caused by local scale interventions, expressed as an increase or decrease in thalweg elevation, to generate changes in thalweg elevation in upstream and downstream reaches. Because the effect of a change in storage diminishes with distance from the perturbation (Simon and Rinaldi, 2006), I expected smooth transitions in morphology: the opposite of the pattern observed in Bryan Creek.

I propose that in reaches where stock have been excluded *Phragmites* has immobilised sediment, which has interrupted sediment continuity and disconnected reaches from each other (acting as barriers *sensu* Fryirs, 2013; Fryirs *et al*., 2007). By drastically reducing the movement of sediment through stock exclusion reaches *Phragmites* supresses interaction between reaches. The important point here is that interaction between reaches is regarded as the major, and historically under-appreciated, factor controlling the outcome of local-scale interventions (Wohl *et al*., 2005; Bernhardt and Palmer, 2011). Our findings in Bryan Creek show that when catchment scale drivers of degradation have been addressed, local scale interventions that promote in-stream vegetation can disconnect reaches, prevent interaction and drive localised changes in geomorphic condition.

8.4.4 Implications

The most important finding of this research is that local scale interventions can deliver substantial improvements in stream condition, at least when measured in terms of channel morphological complexity. This is especially true when sediment supply is declining at the tail of a sediment pulse. In Bryan Creek, rather than interacting to accelerate the orderly sequence of recovery from upstream to downstream, interventions interact very little, instead causing discrete changes in morphology that are separated by sharp boundaries. This suggests that once the catchment-scale issues have been addressed, individual reaches can be highly sensitive to local scale interventions that can be exploited to substantially improve stream condition.

In-stream vegetation determines the morphology of different reaches, and the sharp transitions between them. The tendency for some species of emergent macrophytes (e.g. *Phragmites*) to trap sediment and promote pool development is crucial. These findings suggest that when intervening to improve stream condition managers should focus on excluding stock so that in-stream vegetation can establish. Furthermore, these efforts should be concentrated in reaches that still have mobile sand, as once the underlying bed is exposed, interventions have little impact.

This research also implies that, although in-stream sand extraction accelerates bed degradation at the tail of a sediment pulse, this degradation does not, on its own, accelerate geomorphic recovery. Instead the trajectory of reaches subject to in-stream extraction depends on the local sediment supply, which in turn is altered by in-stream vegetation.

8.5 Conclusion

This paper has assessed the impact of local scale interventions at accelerating geomorphic recovery at the tail of a bedload pulse in a small river, once sediment supply from the catchment has declined. This was done by classifying the changes in morphology observed in 12 distinct reaches of Bryan Creek, and by comparing the level of geomorphic complexity between reaches subject to three different interventions: sand extraction, stock exclusion fencing, and revegetation. The complex restoration activities on this stream, that vary over the space of hundreds of metres, are typical of the piecemeal character of many stream restoration projects.

The pattern of geomorphic recovery observed in Bryan Creek did not conform to our predictions of gradual improvements in stream condition from upstream to downstream. Cross-section variability did decrease in a downstream direction but was similar between all sand-bed reaches. Thalweg variability did not gradually increase in a downstream direction but was spectacularly higher in reaches where stock have been excluded. Overall, local scale interventions appear to dominate over catchment scale processes in this stream.

Stock exclusion and re-vegetation had not led to a meaningful improvement in stream condition in clay bed reaches, which have continued a trajectory of slow incision. In sand-bed reaches morphology abruptly alternated between a degraded, dissected morphology and a sequence-of-pools. The boundary between the two morphologies was sharp, coinciding with stock exclusion fences that span the river, and suggesting little interaction between different interventions.

The trapping and storing of sediment by *Phragmites*, which grow in reaches where stock have been continuously excluded, and the undermining of spiny rush, which grow in reaches that stock can access, explains the two very different morphologies.

I suggest that this research has the following implications for stream managers:

1. Local scale interventions can powerfully alter catchment scale processes.
2. Once the clay bed beneath a sediment pulse is exposed interventions have much less effect on stream condition and channel complexity. Thus, interventions should occur before the underlying clay bed is exposed, while there is still mobile sand left in the channel.
3. Stock exclusion is crucial as it allows emergent macrophytes (such as *Phragmites*) to establish on the bed, and for pools to develop. In this setting, *Phragmites* can cause pools to develop in as little as 5 to 7 years.
4. Riparian re-vegetation, in this situation, had little impact on channel complexity or overall stream condition when used alone and should instead be used in conjunction with stock exclusion.

Chapter 9: Synthesis

9.1 Introduction

This thesis is concerned with the physical recovery of streams from pulses of bedload sediment. The focus has been the physical, geomorphic aspect of recovery, not the ecological or aesthetic components. Although the ecological and aesthetic aspects are important pillars of a healthy river system, the physical structure of the river provides the template for these aspects of river recovery. Improving the physical condition of a river is a critical step in moving the river towards an improved state (Dufour and Piegay, 2009).

In Chapter 2 I established the five ways of managing pulses of bedload sediment in rivers more broadly (including management of bedload pulses in large, gravel bed rivers). For this thesis I chose to focus on the recovery of the Glenelg River, in Victoria, Australia: a medium sized sand-bed river impacted by multiple pulses of coarse sand. In doing so I developed and tested three conceptual models:

1. Catchment-scale bedload pulse dynamics. This scale is the boundary condition for all interventions that seek to accelerate recovery and is the basis of the 'do nothing' option of bedload pulse management (Chapter 4).
2. Reach-scale (8 km stretch of river) response of a river to a sequence of extraction pits repeatedly excavated over a ten-year period (Chapters 6 and 7).
3. How a river (30 km stretch) responds to multiple interacting interventions, undertaken alone and in combination, over a period of 30 years (Chapter 8).

The findings of those chapters relate to the way multiple bedload pulses migrate through a catchment, and to how in-stream vegetation shapes channel morphology. This chapter synthesises the findings of the thesis and relates them back to the broader concept of river recovery. I relate the findings of this thesis to broader literature in four ways:

1. the relationship between models of bedload pulse dynamics,
2. the sequencing of interventions at the catchment scale,
3. models of extraction pit dynamics in sand-bed channels; and
4. by proposing a model that ties the use of in-stream extraction and stock exclusion to the establishment of in-stream vegetation and the subsequent increase in channel complexity.

To guide future research into the management of sand-bed rivers impacted by pulses of bedload sediment I list three future research questions, and the methods that could be used to address each question.

9.2 Catchment-scale bedload pulse dynamics and the sequencing of interventions to accelerate recovery

An important pre-condition of intervening to accelerate recovery is knowing what will happen if you do nothing. Understanding a river's 'natural' recovery trajectory allows managers to identify the recovery potential of different reaches, and to set realistic expectations about what interventions can achieve. The first step in understanding the natural recovery trajectory of a river system is to predict how sediment will be evacuated from the network. These predictions are made using models of bedload pulse dynamics.

Managers use the models of bedload pulse dynamics to estimate the recovery potential of different reaches in the catchment (Fryirs and Brierley, 2000; Brooks and Brierley, 2004; Brierley and Fryirs, 2009). Managers also use models of bedload pulse dynamics to build recovery models (or to predict recovery 'trajectories'): the sequence of changes a reach will pass through as it adjusts to a decreasing sediment supply. Recovery models are the *what* and *how* of recovery (Madej, 2001; Gran and Montgomery, 2005; Brierley and Fryirs, 2016; Mould and Fryirs, 2018).

A common conceptual model used to predict the pattern of recovery following a bedload pulse is the migrating wave model (Gilbert, 1917; Pickup *et al*., 1983; Bartley and Rutherfurd, 2005a). This study is concerned with the channel bed, not the floodplain. Models describing the passage of bed waves, not the much larger sediment waves, are most relevant to this project (James, 1999; 2006; Tayfur and Singh, 2007).

Chapter 2 of this thesis proposed that managers can concentrate their efforts to accelerate recovery at the tail of a pulse, where sediment supply is declining, assuming the leading edge, the peak and the trailing edge of a bedload pulse can be identified. Chapter 4 of this thesis found that in the Glenelg River bedload pulses did not move downstream as a series of migrating waves. Instead, a 'standing wave' model was proposed. The key implication for recovery potential is that in the standing wave model the location of peaks and troughs in sediment storage remain static, while sediment is exchanged between those storage zones. In the migrating wave model the pattern of sediment storage (and recovery potential) is determined the distance between a reach and the source of sediment. In the standing wave model, sediment stores (and recovery potential) is determined by extrinsic controls, such as valley constrictions.

The tendency for extrinsic controls—such as Holocene terraces or valley constrictions—to concentrate sediment storage at discrete reaches, and for reaches with elevated sediment flux to connect these 'sedimentation zones', has been observed in the Bella Coola River of British Columbia by Church (1983), in the South Tyne River, UK by Macklin and Lewin (1989), in the bear and Yuba Rivers by James (2006) and in several sand-bed rivers of SE Australia (Fryirs and Brierley, 2001; Hoyle *et al*., 2008). These models view bedload pulse movement as the filling of storage zones within the catchment. The standing wave model views these storage zones as 'trading zones', which fill with sediment but continue to transmit high sediment loads downstream. The filling of these sedimentation zones is in the order of decades.

The standing wave model proposed in Chapter 4 is an alternative way of conceptualising these seemingly separate sediment accumulations (described by other authors) as a single, emergent, static bed wave. In this way the standing wave model is similar to the one-dimensional model of pulse dynamics modelled by Nicholas *et al*., (1995). The Nicholas *et al*. (1995) model conceptualises a bedload pulse as a series of stationary waves along the river. Nicholas' wave peaks are located in sedimentation zones (wave forms are generated by changes in a rivers transport capacity along the river, not localised extrinsic controls such as constrictions). In Nicholas' (1995) model the amplitude of the waves oscillates over time. Nicholas *et al.* (1995) termed these catchment-scale perturbations 'superslugs'. These 'superslugs' migrate through a catchment over centuries.

Over a sufficiently long timescale (centuries) bedload pulses will evacuate a catchment. The models described above employ wave analogies or sediment compartments to conceptualise the pattern of this sediment evacuation. This pattern was described by James as an Aggradation Degradation Episode (ADE) (James, 2006b; 2018). When the ultimate source of sediment is exhausted (e.g. catchment-scale erosion or upstream inputs from mining), the 'tail' of the ADE will begin to pass downstream. When the tail of an ADE begins to migrate downstream each of the sedimentation zones filled by the bedload pulses will begin to empty, from upstream to downstream. In this manner when viewed over long timescales, bedload pulses migrate through a catchment as a single, asymmetric wave of sediment. The standing wave model is one particular way of viewing how this ADE is expressed along a river dominated by extrinsic controls.

The standing wave does not suggest that the more classical migrating waves do not occur. They do. In rivers without extrinsic controls, or long homogenous reaches of a river without extrinsic controls, pulse movement is best conceptualised as a migrating wave that disperses, and in certain cases, translates, downstream. The standing wave model is a useful alternative under two conditions: (1) when extrinsic factors locally limit sediment transport at certain points along the trunk stream, and (2) when floods are responsible for most pulse movement (due to either flow regulation or a coarse pulse that is not easily mobilised by smaller flows).

The differences between the migrating wave model and the standing wave model has implications for the sequencing of interventions in the catchment. In the standing wave model the 'peak' and 'tail' of the pulses are static at the decadal timescale and do not slowly migrate downstream. Further, the 'tail' of a migrating wave is characterised by declining sediment storage and declining sediment supply, whereas the 'tail' of a standing wave has low, but unchanging, sediment supply over several decades, before switching to a decreasing sediment supply. Each of the zones of the standing wave model may have a high sediment flux, regardless of whether sediment is stored there. This has the following implications for sequencing of interventions to accelerate recovery in a catchment:

1. Peaks of standing waves are areas with a tendency for sediment storage. These are the reaches where interventions aimed at trapping and storing sediment are most likely to be effective. Re-vegetating the streambed in these areas would exploit this storage tendency. The storage reaches would also be a good place to undertake in-stream extraction. This is because sediment would readily recharge the extraction pits and because the constriction would limit the propagation of the erosion signal into downstream reaches (assuming the sediment deficit caused by extraction does not decrease sediment supply below the volume that passes through the constriction each year).
2. Interventions that are usually undertaken to accelerate recovery at the 'tail' of a pulse should be undertaken in the low-storage zones downstream of constrictions.

9.3 Pit-scale models

This thesis has undertaken the first comprehensive test of the engineering models that describe the behaviour of an extraction pit in a sand-bed river. The pit evolution models were derived in constant-discharge flume studies and did not consider the removal of point bars from meander bends (van Rijn, 1987; Lee et al., 1993; Gill, 1994; Lee and Chen, 1996; Barman et al., 2018b; Barman et al., 2019).

Testing these models in the Glenelg River has shown that the pit infill process is discharge dependent and that pits excavated on meander ends can infill in two different ways, depending on the radius of the meander. The biggest difference between the predictions of the existing pit evolution models, and the pattern of infill observed in the Glenelg River, is that pits filled from upstream to downstream, and inwards from their margins, at the same time. Deposition along the channel margins is not included in the empirical equations describing pit infill (Lee *et al*., 1993; Lee and Chen, 1996) which suggests that these models will underestimate the time a pit will take to refill. Formation of a scour zone on the bed of pits 1 and 2 in the Glenelg River shows that if a pit is excavated in a reach regularly subject to bankfull flows (for example an irrigation channel), and with a very low sediment supply, the pit may scour its bed rather than fill. If this scour is deep and the pit remains in the bed for a long time, the geometry of the channel may be permanently altered by the pit.

On gentle meander bends the pattern of infill was shaped by secondary flow cells, while on sharp meander bends, infill was controlled by recirculating eddies at the inside of the meander and the narrow secondary flow cell on the outside of the meander. This implies that if managers target point bars for extraction in sand-bed rivers, better predictions of pit behaviour can be obtained by using depth-averaged hydraulic models, rather than the empirical models of Lee *et al.*, (1993) and Lee and Chen (1996), the analytical model of Gill (1994), or the numerical model of Barman *et al*. (2018), all of which focus on pit head migration in straight channels.

Extraction pits in the Glenelg River and in Bryan Creek were repeatedly extracted. The advantage of studying pits that were repeatedly extracted is that longer-term pit behaviour could be evaluated. This is an important extension to the pit evolution models described in the engineering literature, which only consider a single phase of pit excavation and infill. There are two major differences between the pits that were repeatedly extracted in the Glenelg River and the behaviour of single-exaction pits in the engineering models: (1) the scour channel that forms downstream of the extraction pits does not expand across the width of the channel, even after repeated extraction and (2) when extraction ceases and a reach is then quickly colonised by reedy, emergent vegetation, the pits can remain static in the streambed for decades.

Reedy, emergent vegetation preserves extraction pits in two ways (1) locking upstream sediment into storage, which reduces sediment supply to downstream pits, and prevents pit infill, and (2) by stabilising the streambed around a pit, preventing the pit from migrating or changing shape over time. Bryan Creek (Chapter 8) provides a clear example of this phenomenon. Sediment supply has been limited by the beds of *Phragmites* that colonised the stream after extraction ceased. The pits present in the bed when extraction ceased (1991) have not since filled with sand, despite large floods in 1991, 2010 and 2016 (Reynolds *et al*., 2019). I consider the controls on channel response to in-stream vegetation and extraction in section 9.5.

9.4 Possible recovery trajectories following a bedload pulse

Section 9.2 described the cases where the standing wave model of pulse dynamics was appropriate (catchment-scale, dominance of extrinsic controls) and when the migrating wave model was appropriate (reach or valley scale, no extrinsic controls). This section considers the recovery trajectories that emerged in different parts of Bryan Creek, where the migrating wave model is the most appropriate way to frame the declining sediment supply.

Bartley and Rutherfurd (2005) found that reaches at the tail of a pulse can do one of two things: increase in channel complexity (slowly at first, then suddenly once the pre-pulse bed is exposed), or, resume some pre-pulse trajectory of change, such as channel incision. These possibilities are embedded in the post-sand slug recovery pathways identified for various SE Australian rivers by Brierley and Fryirs (2000), Fryirs *et al*. (2012) Brierley and Fryirs (2016) and Fryirs and Brierley (2016). For example, a low-sinuosity section of the Wollombi Brook, NSW, initially filled with a bedload pulse, followed by incision of secondary channels into the aggraded bed and the formation of vegetated benches (Brierley and Fryirs, 2016; Fryirs and Brierley, 2016).

In Bryan Creek (Chapter 8), which lies at the degrading tail of the bedload pulse, the migrating wave model described the overall pattern of channel recovery along the river: channel complexity decreased in a downstream direction. Concurring with this model, I found evidence of the resumption of incision in upstream, clay-bed reaches of Bryan Creek. However, channel surveys also revealed that in sand-bed reaches further downstream, local-scale interventions had profoundly altered reach-scale morphology and significantly increased channel complexity in those reaches (but not in adjacent reaches). The largest improvement in condition in sand-bed reaches of Bryan Creek was associated with stock exclusion. Stock exclusion allowed vegetation to establish on the streambed. Vegetation (*Phragmites*) trapped sediment, aggraded the bed and a sequence-of-pools developed. In reaches where stock had continual access, beds of spiny rush (*Juncus acutus*) have colonised the streambed.

Spiny rush grows as short, strong, tussock-like of domes but have a shallow rooting depth (De Baets *et al.*, 2008). The beds of spiny rush trap little to no sediment but concentrate flow into a network of narrow channel between plants, causing a dissected morphology to develop. The dissected morphology emerges wherever spiny rush dominate the bed, whether the overall bed level has remained stable or degraded. The two very different responses between *Phragmites* and spiny rush reaches show that vegetation can alter recovery trajectories, but that this recovery is very sensitive to the type of vegetation that establishes.

One of the most surprising findings was that the boundary between the sequence-of-pools morphology (*Phragmites*) and the dissected morphology (spiny rush) was sharp. Reaches are disconnected and behave independently. The boundary between eroding clay-bed reaches and the dissected sand-bed reaches was more gradual. The lack of interaction between reaches runs counter to the prevailing paradigm of rivers as connected systems. Existing theories view rivers as connected systems, and disconnection usually arises due to the presence of barriers (Fryirs, 2013) such as dams, weirs or tributary junction fans (Ferguson *et al*., 2006; Rice, 2016; Thompson *et al.*, 2016). The lack of functional connectivity between reaches in Bryans Creek (Wainwright *et al.*, 2011) is likely due to the ability of *Phragmites* to trap mobile sediment and shield existing deposits from erosion, instead expending excess energy as localised scour in pools. By buffering the sequence-of-pools reach against changes in surrounding reaches, *Phragmites* disconnect Bryan Creek and cause the upstream segment to behave independently of the downstream portion.

The disconnected character of recovery in Bryan Creek demonstrates that in 'simple' cases, when sediment inputs are a long way upstream (so as to be considered a point source with respect to the downstream reaches) and the downstream segment is free of extrinsic controls, the wave recovery model can be locally altered by management interventions. The key to the highly localised recovery is a low sediment supply and the immobilisation of sediment by dense stands of vegetation. Furthermore, the highly localised recovery of reaches in Bryan Creek occurred quickly (< 10 years).

9.5 How extraction and in-stream vegetation shape reach-scale recovery from a bedload pulse

A major focus of this thesis was the use of in-stream extraction as a tool to accelerate recovery in sand-bed rivers. Chapters 7 and 8 examined the impact of in-stream extraction at the reach scale (8 km reach in the Glenelg River) and at the valley scale

(30 km of Bryan Creek, a tributary of the Wannon River), respectively. The two sites had very different volumes of sand extracted: 480,000 m^3 from Bryan Creek over thirty-five years cf. ~180,000 m^3 from the Glenelg River over thirteen years. Bryan Creek is smaller (average width of study reach was 28 m) with a catchment area of 560 km^2. The Glenelg River is much larger (average width of study reach was 38 m) and the catchment area upstream of the study reach is 5,280 km^2. The extraction in the Glenelg River is ongoing, so that changes in that stretch of river are continuing. Extraction ceased in Bryan Creek in 1991, and the current morphology of the river had developed by 2001.

The most surprising finding, consistent between the Glenelg River and Bryan Creek, was that in-stream vegetation (in this case *Phragmites australis*) increased the variability of the thalweg and of cross-sections more than in-stream extraction did. *Phragmites* transformed the channel bed under a declining sediment supply (Bryan Creek) and a more elevated sediment supply (the Glenelg River at Casterton).

I argue here that, in this class of sand-bed stream, in order for extraction to generate meaningful improvements in channel complexity, it must be combined with stock exclusion measures (using either stock proof fencing or by controlling adjacent land-use). Extraction accelerates recovery when the erosion caused by sediment removal is balanced by sediment trapping and storage by *Phragmites*. Together the two interventions rearrange the streambed into a more complex configuration. Of the two processes, vegetation trapping by *Phragmites* appears to be responsible for more channel change, with extraction playing a secondary role.

I now consider two important aspects of this model of channel recovery (1) the mechanisms by which the opposing processes of erosion and deposition interact to increase reach-scale complexity, and, (2) the relationship between river scale and the morphology that develops from this interaction.

9.5.1 How *Phragmites* changes reach morphology

The ability of vegetation to transform channel morphology is now well recognised (Bunn *et al*., 1998; Corenblit *et al*., 2007; González *et al*., 2015; Manners *et al*., 2015). Researchers initially focused on the mechanism by which trees prevented bank erosion (Abernethy and Rutherfurd, 2001; Gurnell *et al*., 2001; Gorrick and Rodriguez, 2012). More recently the focus has shifted to in-stream vegetation and how different species increase reach-scale flow resistance (Järvelä, 2002; James *et al*., 2008; Ferguson, 2013), promotes deposition (Erskine *et al*., 2012; Ortiz *et al*., 2013) or shield the toe of the bank from erosion. This research has emphasised the importance of reedy, emergent vegetation (e.g. *Phragmites australis*) in building pioneer landforms. Pioneer landforms are submerged bars and benches that induce deposition. As the landforms aggrade and expand downstream over time, they transform channel morphology (Corenblit *et al*., 2007; Follett and Nepf, 2012).

Phragmites is an especially important species for sand-bed rivers recovering from a bedload pulse because they readily establish on, and then spread across, recently disturbed surfaces of silt and sand (Hudon *et al.*, 2005). A key finding of this thesis was that *Phragmites australis*, an emergent macrophyte with a global distribution (Roberts, 2000), is associated with deposition and landform development. *Phragmites* can build benches that connect to form ledges across the channel in as little as eight years (Chapter 8). This observation mirrors findings by other researchers who have documented the association between *Phragmites* and deposition in low-energy gullies of SE Australia (Zierholz *et al.*, 2001), the rapid spread of *Phragmites japonica* across sand bars in the St. Lawrence River, Québec (Hudon *et al.*, 2005), and how *Phragmites australis* enhanced channel contraction in a sand-bed stream impacted by bedload pulses (Erskine *et al*., 2012).

While *Phragmites* is able to trap sediment and build landforms, the species is very sensitive to water depth (Armstrong *et al.*, 1999; Engloner, 2009; Horppila *et al.*, 2013) and grazing pressure (Roberts, 2000; Hayball and Pearce, 2004). This thesis found evidence that water depth limited the spread of *Phragmites* around the Claybanks extraction pit in the Glenelg River, and deep pools in Bryan Creek. In reaches where stock have not been excluded from the streambed, *Phragmites* has not established (because stock graze them).

The inability of *Phragmites* to grow in deep water means that the spread of *Phragmites* may be self-limiting: accreting bars and benches concentrate flow into deepening low-flow channel(s), then deep water in the incising channel prevents lateral expansion of *Phragmites* patches. As channels deepen, the mean water table in the channel falls and stands of *Phragmites* are progressively stranded, unable to access the water and nutrients they need to survive. If *Phragmites* patches are without access to water for long enough, they die, and the surface of the landform is exposed (see Corenblit *et al*., 2007 for a summary of 'biogeomorphic' models that describe this process in detail). Alternatively, accreting surfaces built by *Phragmites* may become suitable for other flood tolerant species. If these species sprout and then stabilise the landform then floodplain building may accelerate. This biogeomorphic succession model (Corenblit *et al.*, 2009) implies that *Phragmites* initiate a more permanent, one-way shift in channel morphology.

Some benches and bars in the Glenelg River covered in *Phragmites* have also been colonised by small tress (either river red-gum, *Eucalyptus camaldulensis*, or a species of wattle, *Acacia*). However, trees were equally common on *Phragmites*-free landforms. The extent of *Phragmites* in the Glenelg River and in Bryan Creek changed little over the last two decades. I found no clear evidence that landforms had progressed through a biogeomorphic succession in either Bryan Creek or the Glenelg River. In the Glenelg River some *Phragmites*-covered landforms have begun to erode. These observations suggest that although *Phragmites* can significantly increase channel complexity, there is an upper limit to this process. Once that limit has been reached, only a sufficiently powerful disturbance force (a sudden increase in sediment supply or erosion) will shift morphology. I now explore the reasons why Bryan Creek and the Glenelg River have responded to *Phragmites* encroachment in such a different manner.

9.5.2 How to conceptualise increased channel complexity due to stock exclusion and in-stream extraction

There is an important difference between how the Glenelg River, Bryan Creek and other reaches in the Glenelg catchment have responded to stock exclusion and extraction. In the Glenelg River *Phragmites* have aided channel contraction by accelerating bench development. Some of those benches are now starting to erode. In Bryan Creek *Phragmites* have completely transformed the morphology and a sequence-of-pools has formed. The pools and intervening bed are stable. In other parts of the Glenelg catchment (upstream of tributary junction plugs, and in the low-gradient reaches of Mather Creek, Konong Wootong Creek and Salt Creek) *Phragmites* have fully colonised the streambed and formed in-stream wetlands (Rutherfurd and Budahazy, 1996; Bartley, 1999; Lind *et al*., 2009).

The substrate in each reach is coarse sand, the climate is consistent between sites and stock have been continuously excluded from each of the reaches for over a decade. Why have *Phragmites* had such a different impact on each of these reaches? And how can managers use *Phragmites* (or any other reedy, emergent vegetation) or extraction to accelerate channel recovery?

An explanation for the different morphological responses to *Phragmites* is the inherent differences in the aggradational tendency of the reaches (Downs *et al*., 2013; Fryirs, 2017). I use the term aggradational tendency to describe the tendency for the morphology of reaches to adjust to the prevailing balance of aggradation driven by in-stream vegetation and erosion driven by excess flow energy. Aggradational tendency is inspired by, but distinct from, the concept of landscape sensitivity (Brunsden and Thornes, 1979; Brunsden, 2001). The aggradational tendency of a reach can be thought of as the ratio of driving forces (the total work done, the force that moves sediment) to resisting forces (trapping of sediment by vegetation) in a channel.

The aggradational tendency can be expressed as:

$$AT \propto \frac{TR}{\underline{\int_{i}^{i+n} \omega}}$$

Where AT is aggradational tendency (m s^{-1}) and can be thought of as the mean rate of aggradation in the channel, $\int_{i}^{i+n} \omega$ is specific stream power of the reach integrated over the period of interest (for example a summer growing season, or over several years) and has units of joules (kg m^{2} s^{-2}). The structure of the equation assures that high values of AT correspond with aggradational reaches and low values of AT correspond to erosion. TR is the sediment trapping rate of the vegetation in the channel and is calculated by the formula:

$$TR = 1 - \int_{t=0}^{t-t_i} [E_{ex}] \times L$$

Where TR is trap efficiency (kg m^3 s^{-1}), $\int E_{ex}$ is the excess total flow energy integrated over the period of interest (total work done), and L is a constant that represents the complicated set of interactions that control the trapping and storing of sediment by vegetation, e.g. whether stands are sparse or dense, flexible or rigid, and how patches change mean flow velocity and turbulence (Ghisalberti and Nepf, 2006; Nepf and Ghisalberti, 2008; Follett and Nepf, 2012; Ortiz *et al.*, 2013; Meire *et al.*, 2014; Yang *et al.*, 2016). *L* varies as vegetation grows: it increases as patches become denser, reaches a maximum value, and then starts to decrease when patches become so dense they divert flow and sediment around the patch.

Excess flow energy is the ratio of sediment transport rate (which varies according to sediment supply) to sediment transport capacity and can be estimated by the formula:

$$E_{ex} = \frac{ST_{r,i}}{ST_{cap,i}}$$

Where E_{ex} is the excess total flow (no units), $ST_{cap,i}$ is total sediment transport capacity (the maximum sediment transport rate) for the reach over the time period of interest (kg m^3 s^{-1}), and $ST_{r,i}$ is the mean rate of sediment supply to the reach over the time period of interest (kg m^3 s^{-1}).

The key assumption of this model is that reedy, emergent vegetation is able to establish on the streambed, which requires that stock are excluded. In reaches where stock can graze the streambed, *L* is zero, so *TR* falls to zero and *AT* is undefined.

The trapping rate equation shows that all other factors being equal, an increase in excess flow energy (for example in reaches downstream of extraction pits where sediment supply has decreased) will lead to a lower sediment trapping rate. Likewise, an increase in sediment supply, or an increase in the value of the constant *L,* all other things being equal, will lead to an increase in sediment trapping rate.

When aggradational tendency is low, the river removes much more sediment from a reach than vegetation can trap. When the aggradational tendency is high, vegetation traps and stores much more sediment in the reach than the river is able to erode. The morphology of rivers at the erosive end of the spectrum (low *AT* values) resemble an incising gully: deep, wide and featureless. All the sediment is removed or flushed through this type of reach. The rivers also have very low geomorphic complexity. The morphology of rivers at the trapping end of the spectrum (high *AT* values) resembles an in-stream wetland: full of sediment, flat, featureless and covered in vegetation. These rives trap almost all of the sediment supplied to the reach. These aggraded reaches also have very low levels of geomorphic complexity. The most desirable level of geomorphic complexity is somewhere between these two extremes, where erosion and sediment trapping are balanced. I therefore propose that the relationship between aggradational tendency, and reach-scale complexity is an inverse parabola.

Increasing aggradation tendency causes an increase in geomorphic complexity, up to a point. Further increases in aggradational tendency cause complexity to decline as the channel fills with sediment (Figure 9.1).

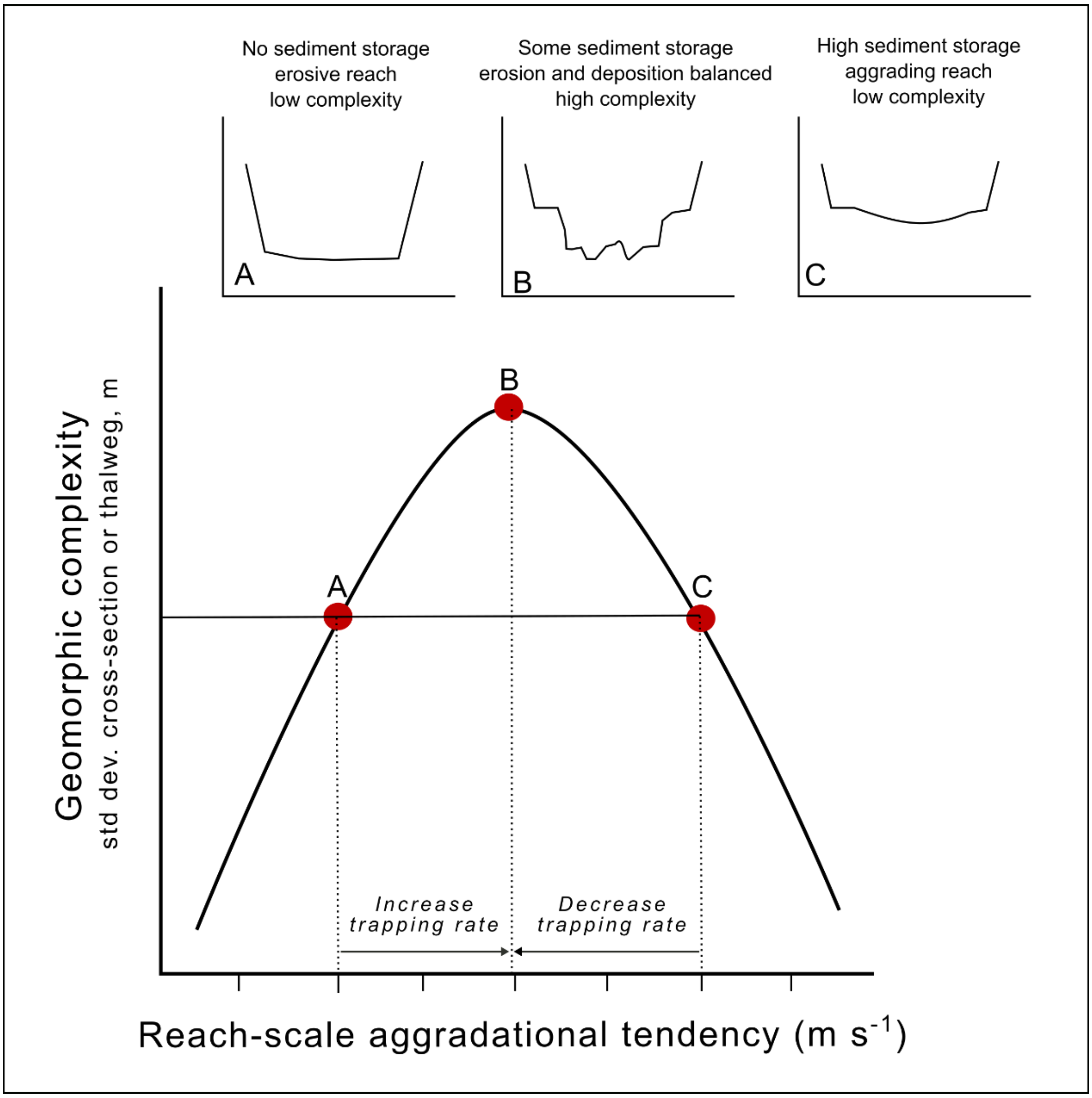


Figure 9.1: The relationship between reach-scale sensitivity to morphological change, and the level of geomorphic variability each reach generates. A, B, and C are reaches with different sensitivity values and correspond to the labelled cross-sections (top).

9.5.2.1 Application of the model

I now use this model to explore the different responses of Bryan Creek and the Glenelg River to colonisation by *Phragmites*, before relating the model to the kinds of interventions managers can use to alter the sensitivity of a reach.

The study reaches in Bryan Creek and the Glenelg River are both impacted by extraction, which has reduced sediment supply to the reaches. The decline in sediment supply decreases the sediment transport rate, which increases excess flow energy (E_{ex}). Stock have been excluded from both reaches and *Phragmites* have colonised the streambed. I assume:

- Extraction has reduced the sediment transport rate in the Glenelg River and in Bryan Creek by 80 % (the reason this is not 100 % is because erosion at the tail of the pit liberates some sediment that is supplied to the downstream reach). Therefore, the term $\frac{ST_{cap,i}}{ST_{r,i}}$ is 0.2 for both rivers.
- That patches densities of *Phragmites* grow at a similar density in both rivers, so that *L* is the same for both rivers. For simplicity, I use a value of 10 (the absolute value does not matter for this example).
- That the Glenelg River has stream power values twice that of Bryan Creek.

Using the above assumptions, the only parameter that varies between the two rives is stream power. I use the stream power values generated at bankfull discharge (165 watts in the Glenelg River and 82 watts in Bryan Creek) as a surrogate for time integrated discharge. The resulting aggradational tendency for the Glenelg River is 0.012 m s^{-1} and 0.023 m s^{-1} for Bryan Creek (Figure 9.2).

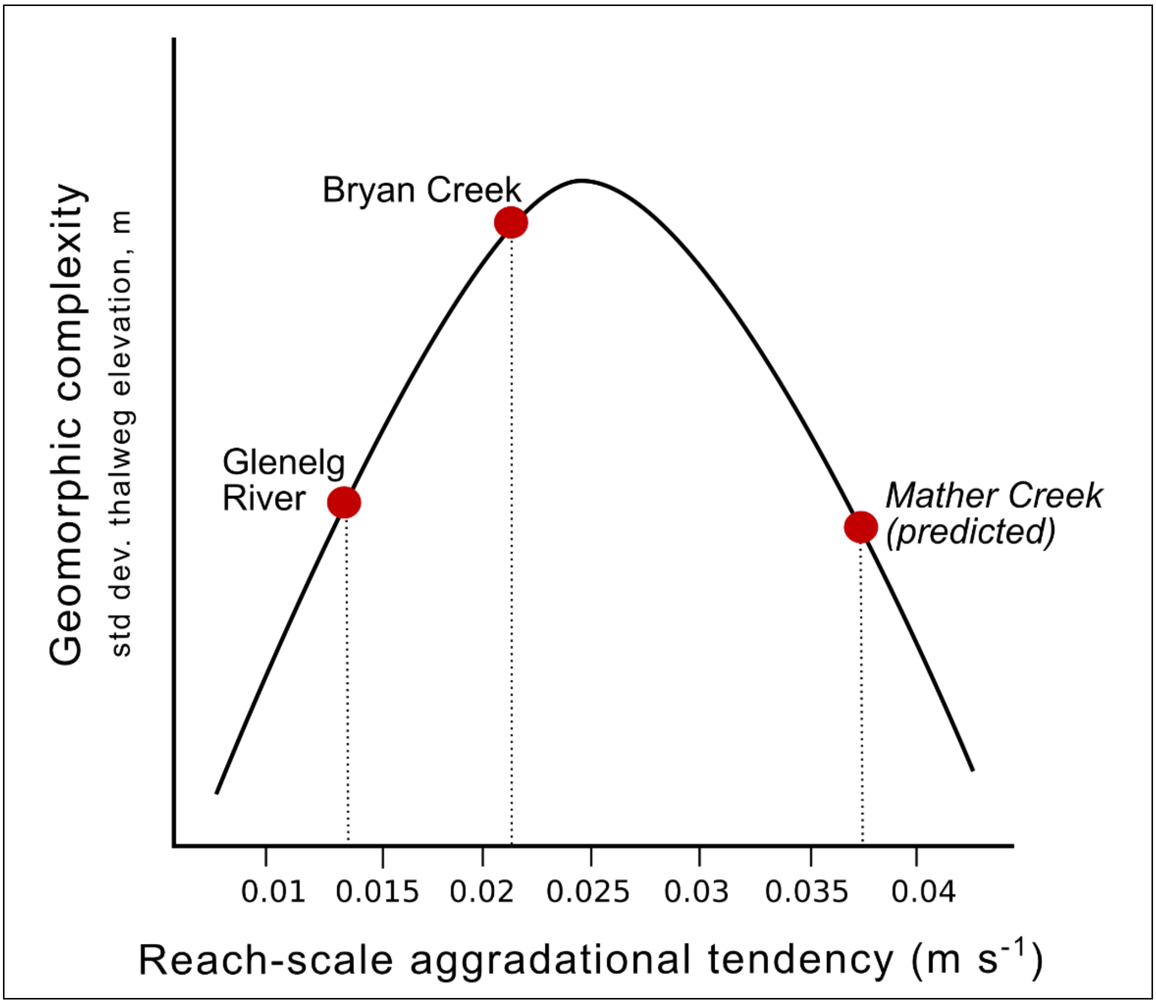


Figure 9.2: Calculated aggradation tendency value for Bryan Creek and the Glenelg River, and predicted (but not calculated) aggradation tendency value for the aggraded reach of Mather Creek, for comparison. Note that geomorphic complexity is measured in terms of thalweg elevation in this case.

The simplified example above illustrates how stream power can explain why Bryan Creek is so much more sensitive to the impact of vegetation than the Glenelg River.

The reaches treated with stock exclusion in Bryan Creek and the Glenelg River both have higher levels of geomorphic complexity than vegetation-free reaches upstream and downstream. Complexity in Bryan Creek is expressed in thalweg variation but complexity in Glenelg River is expressed in cross-section variability. Because the Glenelg River performs more work than Bryan Creek ($\int_{i}^{i+n} \omega$ is higher in the Glenelg River), the resulting values of *AT* are lower in Bryan Creek than in the Glenelg River. Bryan Creek is more sensitive to vegetation morphological change because the magnitude of flows, the frequency of flows, and the force these flows produce in the channel are so much lower than the Glenelg River.

The different sensitivities of the two reaches have implications for the persistence of extraction pits. Pits excavated from reaches with a high trapping rate and low stream power are *less* likely to fill, because vegetation locks the streambed in place. For example, in Bryan Creek, not all of the extraction pits have refilled, despite extraction ceasing approximately 30 years ago. Several pits excavated in the township reach, where *Phragmites* have established, remain in place, despite pits in upstream and downstream reaches refilling. In less sensitive reaches, such as the Glenelg River, pits quickly refill. For example, the Claybanks pit has refilled multiple times, even though this pit is surrounded by beds of *Phragmites*.

The Aggradation Tendency model is useful for systems like the Glenelg River and its tributaries., where coarse, uniform sand is the dominant grain size and channel complexity is controlled by vegetation (not larger grain sizes or LWD).

9.5.2.2 How managers can use the model to increase reach-scale complexity

Larger rivers, or rivers that perform more work over time, require a higher trapping rate to increase sensitivity (and therefore complexity) than small rivers, which perform less work over time. To increase the sensitivity of a river, managers can either increase the trapping rate, or decease stream power.

Interventions that increase the trapping rate include increasing the length of rivers treated with stock exclusion, to modify *L*. Alternatively, managers could increase river sensitivity by constructing in-stream structures that slow the flow, reduce stream power, and allow vegetation to take hold. The interventions are suitable when managers want to increase channel complexity by storing more sediment in the channel.

When managers are faced with a reach that has too much sediment stored in the bed (point C in Figure 9.2), they can reduce the aggradation tendency of the reach by either increasing excess flow energy, or increasing stream power. In practice, managers can decrease sediment supply (via extraction), which decreases the sediment transport rate, which then increases excess flow energy. Alternatively, managers could use 'crash grazing' (Rutherfurd *et al.*, 2000) or intermittent grazing of the stream bed to remove some vegetation, decreasing the trapping rate.

Environmental flows can be used to alter the trap efficiency and integrated stream power of a reach. Larger, more frequent flows will increase stream power, remove stored sediment and lower aggradational tendency. Environmental flows can also decrease trap efficiency by increasing the depth and duration of waterlogging experienced by vegetation in the channel (Hudon *et al.*, 2005; Miller *et al.*, 2013). If the vegetation is especially sensitive to prolonged, deep waterlogging (such as *Phragmites*) patches will recede and overall storage will decrease. Alternatively, periodic environmental flows may have the opposite effect and increase trap efficiency. More frequent flows prevent vegetation from drying out, which increases vegetation growth. Whether environmental flows increase or decrease aggradation tendency depends on the species of vegetation in the channel, the magnitude of flows released and the frequency of inundation.

9.6 Implications of this thesis for the use of in-stream extraction in the Glenelg River catchment

In the Glenelg River in-stream extraction was implemented to accelerate recovery. The commercial return generated by selling the clean, well-sorted sand extracted from the Glenelg River incentivises commercial extraction. Extraction royalties are paid to the state government, *not* the Glenelg Hopkins Catchment Management Authority (who issue the Work Authority that permit extraction from the streambed). This arrangement ensures that the sand extraction operation funds itself, and that the river recovery incentives of the Glenelg Hopkins Catchment Management Authority are not swayed by financial returns. Under this model of 'managed extraction', exractors are incentivised to work with the catchment management authority to improve river health. This arrangement incentivises extractors to use 'environmentally sensitive' extraction techniques rather than removing as much sediment as possible as quickly and cheaply as possible. The extraction program has been implemented since ~2001 and now supports a sizeable aggregate industry in the region. This section examines the ongoing management of extraction in the Glenelg River in light of the findings of this thesis. I consider the implications of this thesis for in-stream extraction in the Glenelg River by asking a series of questions.

9.6.1 Has the original model and purpose been supported/fulfilled?

In-stream extraction was implemented in the Glenelg River to protect downstream reaches from sand-ingress. Management plans identified that in addition to protecting downstream pools, the reduction in sediment supply from extraction could accelerate the channel adjustments typically associated with recovery: re-emergence of a well-defined low-flow channel, re-scour of pools on the outside of meander bends, increase in bed relief and channel contraction (Rutherfurd and Budahazy, 1996). The reach adjacent to Casterton (the study reach in Chapters 6 and 7) was identified as a priority extraction site. More detailed investigations by Brizga *et al.*, (2000b) and Brizga *et al.,*

(2003) argued against extracting from the Casterton reach, noting that the lack of in-channel forcing elements (LWD removed during de-snagging in the 1960s and 1970s) would prevent pools from re-scouring in the reach.

The Rutherfurd and Budahazy (1996) model of accelerated recovery has been partially fulfilled in the Glenelg River. Pools within the study reach (other than the extraction pits) have not filled with sand. A low-flow channel is evident along the entire study reach and bed relief has increased downstream of the extraction pits. However, I found no evidence that new pools had scoured on the outside of meander bends throughout the study reach, and meaningful increases in channel complexity only emerged in the part of the study reach in which stock were also excluded. Overall, extraction has protected pools in the 8 km of river downstream of the pits.

9.6.2 Is extraction occurring in the right places?

Priority sand extraction sites were identified by Rutherfurd and Budahazy (1996), Brizga *et al.* (2000a) and Brizga *et al*. (2003) based on the following criteria:

1. Extraction from those reaches would reduce the volume of sand moving into downstream reaches, where it would fill remaining pools.
2. Extraction from those reaches would slow the migration of the bedload pulses into the Heritage River reach (the Glenelg River estuary, downstream of Dartmoor).
3. Extraction pits would create habitat for fish, and swimming holes for the community.

In addition to the above criteria, locations in the river where commercially viable extraction could take place was also constrained by three other factors:

1. A large volume of sand was stored in the channel.
2. The extraction reach was easily accessible by road, and there was sufficient space nearby for machinery to screen sand and load trucks.
3. The reach had sufficient sediment supply to ensure pits would refill, and extraction could be repeated at the site (to justify the cost of constructing access tracks and the lease of adjacent land for machinery).

Extraction has since been undertaken at 14 different sites along the Glenelg River. The extraction program implemented since 2003 has largely followed the original recommendations of Rutherfurd and Budahazy (1996), Brizga *et al.* (2000a) and Brizga *et al*. (2003). Extraction sites are clustered in two reaches of the Glenelg River: the Pigeon Ponds-Chetwynd River junction complex (Chapter 4) (the 'Burkes Bridge area' in Brizga *et al.*, (2003)), and the Wando River junction to Wannon River junction reach. Two sites have also been extracted further downstream, where the Glenelg River becomes more confined and the dominant land use changes from agricultural to reservation or blue gum plantation.

This thesis supported the earlier contention of Rutherfurd and Budahazy (1996) and Brizga *et al*. (2003) that the Pigeon Ponds-Chetwynd River junction complex is the right area to extract sand. These areas are sedimentation zones that are regularly re-supplied with sediment. However, the aim of extracting from these sites was to limit the volume of sediment supplied to pools downstream of the second gorge. In reality, constrictions between the junction complex and these pools exert a stronger control on bedload pulse movement than the volume of sediment stored in the reaches immediately upstream.

Extraction from the reach between the Wando River junction and the Wannon River seems to have achieved its original aim, of protecting downstream pools, but continued removal of sand risks undermining the improvement in condition in the reach downstream of Casterton (see section 9.6.2).

Extraction sites further downstream (the Wannon River junction, Bahgallah and Heatherlie Road sites) are good locations for two reason: (1) the banks in these reaches are heavily vegetated, and (2) extraction from these reaches should reduce the supply of sediment to the leading edge of the bedload pulse, slowing its migration into the Heritage River reach.

9.6.3 What have been the consequences of extraction so far?

So far, the consequences of extraction have been to increase channel complexity—a proxy for bed relief and recovery—in reaches downstream of extraction sites. Extraction has caused the thalweg to erode and the depth of thalweg erosion to increase in a downstream direction. However, the magnitude of the increase in channel complexity does not steadily increase in a downstream direction. The *increase* (between 2005 and 2018) in complexity is slightly greater in the upstream part of the study reach, but the *absolute* values are much higher in the downstream part of the study reach (where in-stream vegetation has established).

In reaches where stock can access the bed (the upstream part of the study reach), a wide, relatively flat-bottomed low-flow channel cuts through unvegetated bars and benches. Extraction has caused this low-flow channel to become deeper and wider than it was in 2005, but it has not become more sinuous. The head and tails of many point bars have eroded at the same time that the point bars have migrated outwards. Bank erosion is visible on the outside of some meander bends but has not increased in frequency or intensity since 2005.

In reaches where stock have been excluded *Phragmites* have colonised the streambed and a more variable morphology has developed. A deep, narrow low-flow channel cuts between the vegetated bars and benches. Bed relief is much higher than the unvegetated reach upstream. However, several of the *Phragmites*-covered features have started to erode. Cut-off channel have formed between the benches and the banks they were once attached to. Several of the bars and benches have also developed scour holes. Some bank erosion is evident on the outside of meander bends, but this erosion has not caused the channel to widen overall.

Erosion of the streambed has re-exposed logs that were buried by the bedload pulse several decades ago. Exposure of in-situ wood on the bed suggest the bed has returned to (or is quickly approaching) its pre-pulse elevation. Further extraction risks shifting erosion from the overlying pulse to the underlying streambed.

Another aim of extraction was that the extraction pits would serve as habitat for fish and swimming holes for the community. This thesis found that extraction pits in unvegetated reaches are unlikely to serve as habitat because they quickly re-fill, their beds are mobile, and they are free of in-stream wood. Pits excavated in reaches where stock have also been excluded (e.g. the Claybanks pit, pits in the township reach of Bryan Creek) remain in the bed for longer than in unvegetated reaches. In some cases (the Claybanks pit) these pits still require periodic extraction (especially after high flows) to remain an asset to the community. While the extraction of upstream pits lowers the sediment supply to the Claybanks pit at Casterton, it does not totally prevent infilling. Most of the sediment that fills the Claybanks pit is sourced from the intervening streambed during high flows. A more targeted approach of excavating the Claybanks pit after high flows will ensure the asset is maintained without over-extraction risking degradation of the surrounding reach.

9.6.4 Is the rate appropriate?

A conclusion of this thesis is that the extraction rate (22,000 m^3 yr^{-1}) is approximately equal to the annual sediment supply (22,500 m^3 yr^{-1}). Removing sediment at the rate of supply has caused the Glenelg River to erode sediment from its bed at rate of 3 m^3 per river metre. The erosion downstream of the extraction sites has removed part of the bedload pulse, not the underlying clay bed channel. However, this zone of bed erosion likely extends up to 50 km downstream of Casterton, which is much further downstream than the length of the study reach. This adjustment zone is 45 km longer than the 5 km long monitoring zone, where cross-sections can be surveyed to monitor degradation, originally suggested by Rutherfurd and Budahazy (1996).

The main risk of extracting at a rate greater than sediment supply is that more intense erosion will impact a greater length of river, and that this erosion might cause degradation, not recovery. The absence of severe bank erosion, rapid meander migration and the fact that thalweg erosion in the upstream part of the study reach is relatively mild indicate that the current rate of extraction has not caused excessive degradation of the channel banks. However, the re-exposure of LWD in the streambed indicates that the cumulative erosion has removed most of the overlying bedload pulse in this reach and that further extraction could cause scour of the original channel. While the rate of extraction has been appropriate, the duration of extraction is approaching its upper limit in this part of the Glenelg River.

However, vegetated bars and benches in the downstream part of the study reach have started to erode. Erosion occurs at the head and tail of bars, as cut-off channels along benches and point bars, and as elongated scour holes on the surface of benches. Erosion of these stable features is undesirable because they increase channel complexity and are an indicator of recovery. Therefore, extraction should be phased out in the Casterton reach to prevent further erosion of channel landforms.

9.6.5 How the results of this thesis should be used to inform management future extraction in the Glenelg River

With the exception of the Casterton reach, many of the current extraction sites are located in high storage, high-supply parts of the catchment, such as the Chetwynd junction complex. Extracting sand at the rate of sediment supply from these reaches is unlikely to have detrimental impacts on the river, but without stock exclusion measures, extraction is unlikely to generate meaningful improvements in stream condition. Therefore, extraction from these reaches can continue, but stock should also be excluded from the reaches downstream of the extraction pits to maximise the benefits of extraction.

Extraction from existing sites of the Glenelg River between the Wando River junction and the downstream limit of the study reach should be phased out. Further extraction from these sites risks undermining the vegetated bars and benches that have formed in the reach adjacent to Casterton. The formation of a low-flow channel in the unvegetated streambed in this part of the Glenelg River goes some way to improving river condition. Managers could exploit the decrease in sediment storage and promote further recovery by excluding stock from this reach.

Excluding stock would allow vegetation to establish (*Phragmites* at first, and eventually eucalyptus seedlings) on the streambed, which would lock sediment into storage, increase channel complexity and promote recovery. Managers should select several existing pools spaced along the reach and monitor them for sand ingress. If pools in the reach started to fill with sand, managers could consider a more limited rate of extraction from a site located at the upstream end of the reach (at the Section Road bridge, where no sand is currently extracted form) to prevent aggradation of the downstream reach. The extraction rate should be kept at half of annual sediment supply (~10,000 m^3 yr^{-1}), so that downstream channel adjustments will be slow, and the vegetated benches adjacent to Casterton are unlikely to be impacted by more erosion.

Extraction can continue, at the same rate as annual sediment supply, at the extraction sites downstream of Casterton.

Preventing filling of a series of long, deep pools between the outlet of the gorge downstream of Burkes Bridge and the Wando River junction was a major reason for extracting sediment upstream, in the Pigeon Ponds Chetwynd River junction complex. This thesis found that floods deposited sand upstream of constrictions at the head of the gorge and within the gorge. The decrease in frequency of bankfull flows caused by regulation means that these deposits are not then dispersed downstream by lower flows. Managers can alter this flow regime by releasing environmental flows from Rocklands Reservoir. Although environmental flow releases have significant benefits for river health (such as filling empty pools, turning over stagnant water to reduce salinity, and watering in-stream vegetation) (SKM, 2003; Clark *et al*., 2013; Miller *et al*., 2013), they also risk increasing dispersion of the bed wave. As the bed wave is dispersed downstream sand will begin to fill the pools downstream of the gorge. When weighing the benefits of higher environmental flows against the potential for pool filling, managers could consider other interventions that limit sand movement but do not impede flow. For example, by using stock exclusion to encourage vegetation growth in reaches already prone to storage.

9.7 Implications of this thesis for models of river recovery

The paradigm of river restoration has moved from implementing hard engineering structures that maintain a fixed, 'stable' channel form to soft engineering approaches that accelerate a rivers recovery along some natural recovery trajectory (e.g. Spink *et al.*, 2009). Recognising that some rivers will never return to their pre-disturbance state, the literature has focused on ways to identify the sequence of channel changes a reach will pass through, and how the river can be guided through certain states so that they best serve human needs (Muhar *et al.*, 1995; Dufour and Piegay, 2009). Managers can use these recovery trajectories, which may be conceptual (Brierley and Fryirs, 2000; Fryirs and Brierley, 2000; Brierley and Fryirs, 2009; Fryirs *et al.*, 2012; Fryirs and Brierley, 2016), or defined in terms of a metric such as stream power (Brierley and Fryirs, 2016; Mould and Fryirs, 2018) to guide this process of accelerated recovery.

The findings of this thesis relate to the specific type of interventions a manger can use to accelerate recovery in rivers impacted by pulses of bedload sediment, and where in a catchment these interventions should be used. The bedload pulse dynamics model (Chapter 4) and the reach-scale aggradational tendency model (this chapter) can now be incorporated into existing methods for managing interventions. Managers could use these models in the following way: adopt a model of bedload pulse dynamics, map out possible recovery trajectories using tools such as a river evolution diagram (Brierley and Fryirs, 2016), estimate the unit stream power of the reach (to set realistic timeframes, and to understand sediment transport capacity) (Fryirs *et al.,* 2012; Brierley and Fryirs, 2016; Mould and Fryirs, 2018), calculate the reaches aggradational tendency, and then make a decision about if and how to intervene to change this aggradation tendency.

9.8 Future research

In addressing the research questions posed in Chapter 1, this thesis has proposed a new way of conceptualising bedload pulse dynamics at the catchment scale, and at the same time, identified the importance of in-stream vegetation in shaping channel recovery. In doing so, this thesis has identified four further questions to guide future research.

9.8.1 How are standing wave deposits removed from a catchment?

Chapter 4 predicted that as sediment supply from the catchment declined, the standing waves would be 'removed' (the deposits eroded) one after another, from upstream to downstream. This pattern of wave removal assumes that during a flood, when most pulse movement occurs, the river is transport limited upstream of constrictions and supply limited downstream of constrictions. A standing wave will start to be removed when the segment immediately upstream of the constrictions becomes supply limited during a flood. Constrictions become supply limited when the supplying segment is either empty, or when sediment within the compartment has entered long term storage on the floodplain. A key question is: how long will this process take?

Predictions of how long a bedload pulse takes to evacuate a catchment are in the order of centuries. To estimate the remaining lifespan of a standing wave, research should focus on quantifying the volume of sediment that can pass through a constriction during a typical flood, and the volume that is placed into long term storage on the floodplain. This transport-storage ratio could be calculated using combined hydraulic and sediment transport modelling (using Delft3D or similar software). The modelling would identify the discharge under which backwaters develop at constrictions, the sediment flux through constrictions at each discharge, and the volume of sediment deposited on the floodplain at each discharge. This relationship between discharge, transport and storage could then be coupled with a Monte Carlo simulation of future flow scenarios to estimate the lifespan of each standing wave and the long-term sediment flux of the river. By estimating the longer-term sediment flux of the river, managers can predict when the crest of standing waves will begin to erode, and duration of the overall Aggradation Degradation Episode currently impacting the catchment.

9.8.2 What type of channel changes accompany sediment storage at the peak of standing waves and at the trough of standing waves?

Within each segment there is a gradient in sediment storage. Sediment storage increases from upstream to downstream. This makes the segments in the Glenelg River a good place to investigate how variations in the relationship between sediment flux and sediment storage translate into shifts in channel morphology and planform. For example, does the increasing tendency for sediment to be stored in the streambed upstream of constrictions increase the frequency of channel avulsions? This problem could be addressed by using the existing LiDAR data to map avulsion channels, and then use their relative width and elevation to estimate their age in the sequence. If in-stream wood has been buried by the deposits in the avulsion channels, then radiocarbon dating could be used to distinguish modern (post-bedload pulse) channels from much older (pre-pulse) channels.

9.8.3 How do stochastic flows impact the filling of single extraction pits?

The finding in this thesis, that the process of pit infill is discharge-dependent, needs to be investigated further. The next step in refining models of pit behaviour in natural channels is to better understand not just the transport dynamics at constant discharges, but how the shape of the hydrograph impacts the rate and pattern of pit infill. Better understanding of how pits fill and change shape under a more variable discharge regime is especially important for unregulated rivers. A more detailed understanding of how infill rate changes with discharge, and how pit shape evolves over time, means that equations that predict pit depth, and pit migration distance (Lee *et al*., 1993; Lee and Chen, 1996; Barman *et al*., 2018) can be updated. More refined models should parameterise the infill processes identified in this thesis: the formation and then growth of the narrow scour zone downstream of extraction pits, the re-building of point bars, and the point at which extraction pit trap efficiency begins to fall below 100 %.

These processes could be investigated in natural channels by monitoring the infill of extraction pits more closely, frequently surveying pit dimensions as the pit fills, and by using an acoustic doppler current profiler (ADCP) to measure the depth, velocity, and suspended sediment transport rate within the filling pit. The ADCP data can then be used to calibrate and verify the results predicted by two-dimensional hydraulic modelling.

9.8.4 How stands of *Phragmites australis* induce deposition and under what hydraulic conditions?

The association between *Phragmites* and deposition in natural channels needs to be explored. At the moment, sediment transport and deposition processes within patches of emergent vegetation are investigated using scaled-down flume studies. By necessity flume studies are only able to investigate a limited number of channel configurations, discharges, and sediment supply rates. Field based studies are needed and should focus on taking measurements of deposition rate, flow velocity, turbulence and sediment transport rates both within patches of *Phragmites* and in the streambed surrounding patches of *Phragmites* (such as in the lee of patches, or in the low-flow channel adjacent to patches). These empirical measurements are needed across a range of flows, a range of channel shapes, and under naturally variable sediment supply and transport rates. The empirical data these studies generate will complement flume studies.

The aim of these studies should be to identify the net effect on natural channels of the many case-specific patterns of erosion and deposition observed in flumes. Field measurements should focus on 'continuous' (or at least multiple events of different magnitude) measurements of the flow field (using ADCP profiles, or velocity metres suspended from structures that overhang the vegetation patch) and sediment transport rate in and around the vegetation. Suspended sediment could be measured by grab samplers, or with a 'winged' automatic suspended sediment sampler (e.g. Gettel *et al.*, 2011). Bedload could be inferred by the passage of bedforms measured by load cells or sensitive piezometers buried within the vegetation patch, or using a more traditional Helley-Smith bedload sampler. Alternatively, detailed pre-and post-event surveys using total station surveys could capture net change in sediment storage.

The final step is to couple these process-based measurements and model with vegetation growth models, many of which already exist (e.g. Asaeda and Karunaratne (2000)).

9.9 Conclusion

This chapter has related the findings of this thesis to the body of literature concerned with river recovery. I have related the model of catchment-scale bedload pulse dynamics I developed in Chapter 4 to the notion of river recovery potential and considered the implications this model has for the sequencing of interventions across a catchment. The behaviour of extraction pits in vegetated and unvegetated reaches was considered as a management tool. This chapter also related the surprising local-scale improvements in stream condition observed in Bryan Creek (Chapter 8) to existing models of channel recovery, and to the literature describing rivers as connected networks.

A major focus of this chapter was the impact in-stream vegetation (*Phragmites australis*) has on channel complexity. I have developed a conceptual model that describes how rivers of different sizes and stream power respond to the presence of in-stream vegetation. This model is used to calculate the aggradational tendency of a reach. I propose that the aggradation tendency of a reach is related to channel complexity via a two end-member model. At very low values of aggradational tendency (simple, erosive channel with low storage) and very high values of aggradational tendency (homogenous channel filled with sediment) a reach has low geomorphic complexity. At intermediate values of aggradational tendency, erosion and deposition are more balanced and geomorphic complexity is higher. Managers can use the components of the model, stream power and trap efficiency to evaluate the kinds of interventions that will increase or decrease aggradation tendency, depending on the initial stream condition.

I then considered the implications the findings of this thesis have for the management of sand extraction in the Glenelg River catchment. This thesis recommends that the extraction rate is limited to the sediment supply rate at all extraction sites. Most extraction sites in the Glenelg River are still an appropriate place for sand removal, but extraction should be phased out in the segment of the Glenelg River between the Wando River junction and the Wannon River junction. Further extraction from this segment risk eroding the stable landforms that have emerged in the downstream half of the reach. Wherever possible, managers should undertake extraction from reaches that have also had stock excluded. Using extraction and stock exclusion together, in the same reach leads to larger increases in geomorphic complexity than extraction alone.

Chapter 10: Conclusion

10.1 Introduction

Pulses of bedload sediment, which are generated by natural and anthropogenic sources, can completely transform river channel networks. Bedload pulses fill pools, simplify the channel bed, reduce channel capacity and can lead to widening, avulsions and a switch from meandering to a braided planform. Much research has focused on describing these impacts in different rivers and on developing conceptual models of how bedload pulses migrate downstream. Much less has been written about what can be done to accelerate the recovery of a river degraded by a bedload pulse. This thesis has focused on the recovery of sand-bed rivers impacted by pulses of bedload sediment.

The over-arching aim of this study was to assess whether in-stream sediment extraction can be used to accelerate the recovery of sand-bed rivers impacted by pulses of bedload sediment. I have explored this question by first reviewing the ways managers can respond to pulses of bedload sediment, and how management interventions can be sequenced in a catchment. I then developed, and then tested, conceptual models at three scales:

4. A conceptual model of bedload pulse dynamics at the catchment scale (Chapter 4)
5. A conceptual model of reach-scale response of a river to a sequence of extraction pits (Chapters 6 and 7)
6. A conceptual model of how a river responds to multiple interacting interventions at the tail of a bedload pulse (Chapter 8)

These conceptual models were tested in the Glenelg River, SE Australia, a sand-bed river recovering from multiple bedload pulses. Finally, I drew the insights generated by the conceptual models together and considered their implications for the use of in-stream extraction to accelerate recovery in sand-bed rivers impacted by pulses of bedload sediment (Chapter 9). In doing so this thesis has made three fundamental contributions:

1) Advanced our understanding of how bedload pulses of sand migrate through a sand-bed river with cohesive banks at the catchment scale.

2) Advanced our understanding of how sand-bed reaches impacted by a bedload pulse respond to in-stream extraction.

3) Advanced our understanding of how in-stream vegetation influences the pattern of bed adjustment, drives localised recovery, and disconnects reaches.

This chapter summarises the major conclusions from this research. I do this by listing my findings for each of the four research questions posed in Chapter 1. For each research question, I describe how my findings have refined the conceptual models I developed from the literature.

10.2 Findings of the thesis

10.2.1 How do multiple interacting bedload pulses delivered by tributaries spaced along the length of a sand-bed river migrate through a catchment?

Conceptual models of pulse dynamics are the basis of the 'do nothing' approach to managing bedload pulses (Sims and Rutherfurd, 2017). Managers use an understanding of pulse dynamics to evaluate the recovery potential of reaches and to identify the most appropriate interventions to accelerate that recovery (Brierley and Fryirs, 2000; Abernethy et al., 2004a; Brooks and Brierley, 2004; Wohl et al., 2005; Brierley and Fryirs, 2016).

Bedload pulse dynamics are usually conceptualised as a migrating wave (Gilbert, 1917; Pickup *et al*., 1983; Meade, 1985; James and Lecce, 2013). James (1989; 2006; 2010) interrogated this analogy and identified two types of wave: bed waves moving along the channel, and secular sediment waves, which interact with the floodplain and take decades to centuries to pass downstream. At the catchment scale, bed waves become discontinuous along the river: sediment is stored in sedimentation zones but rapidly passes through transport reaches (Church, 1983; Macklin and Lewin, 1989; Nicholas et al., 1995; James, 2006b; Gran and Czuba, 2017). When studying bedload pulse dynamics at the reach scale researchers rely on the Eulerian approach: sequential bed elevation observations over time, taken at a limited number of points in the network. When studying bedload pulse dynamics at the catchment scale, researchers take a Lagrangian view: map sediment storage over larger areas, but at a snapshot in time and at low spatial resolution. This thesis bridges the gap between the Eulerian and Lagrangian viewpoint of pulse dynamics by mapping in-channel sediment storage over 235 km of the Glenelg River.

A major contribution of this thesis has been to propose an alternative to the migrating wave model of pulse dynamics: the standing wave model. The standing wave model is an appropriate way to conceptualise bedload pulse dynamics in catchments where extrinsic controls dominate pulse movement, and most pulse movement occurs during floods. The peaks of the standing waves remain stationary, but sediment is exchanged between them. The peak of the standing waves lies upstream of valley constrictions and the trough lies immediately downstream of constrictions. Bedload pulse movement is driven by floods, which maintain standing waves by depositing sediment in backwaters that form upstream of the constrictions. By limiting sediment movement at particular points in the river, constrictions break the Glenelg River into a series of compartments. Floods quickly flush sediment that lies within each compartment towards the next constriction downstream.

By conceptualising bedload pulse dynamics as a series of standing waves, rather than a series of migrating waves emanating from tributaries, managers can better evaluate the recovery potential of reaches in the Glenelg River. The standing wave model suggests that in-stream extraction should be focused in reaches immediately upstream of constrictions, and revegetation should be focused downstream of constrictions, at the upstream section of a compartment. The standing wave model can also be used to understand how sediment moves between storage zones in a catchment and to predict the residence time of sediment in those storage zones (at the wave crests). The standing crests are akin to the stationary peaks in sediment storage described by Church (1983) and Macklin and Lewin (1989) and to the pattern of catchment-scale sediment storage modelled by Nicholas *et al*. (1995). The key difference is that unlike these earlier studies, the amplitude of waves in the Glenelg River does not change over a timescale of several decades (but the amplitude will decrease over many decades to centuries)

10.2.2 How do extraction pits in straight sections and on meander bends refill with sediment?

Extraction pit infill has been studied by engineers seeking to understand channel stability, and by geomorphologists trying to understand how the sediment deficit that pits create impacts upstream and downstream reaches. Using flume experiments (Lee *et al.*, 1993; Lee and Chen, 1996; Neyshabouri *et al*., 2002; Barman *et al* 2018a), numerical modelling (Cao and Pender, 2004; Chen, 2005; Gill, 1994) and more recently, field studies in natural channels (Owen *et al*., 2012; Yuill *et al*., 2016) researchers have concluded that extraction pits fill by migration of the pit head in a downstream direction. Migration is driven by bedload falling down the avalanche face at the pit head, while the tail of the pit rotates in a downstream direction. As the head migrates sediment accumulates at the upstream end of the pit. Sediment does not transit through the middle of the pit, between the advancing head and the tail of the pit. Once the head of the pit migrates past the original position of the pit tail, the pit begins to shallow (fill from the base upwards) and move downstream at the same time (Lee *et al.*, 1993; Lee and Chen, 1996; Chen *et al*., 2010). Studies of point bar scraping have found that point bars rebuild slowly, and scour is concentrated at the downstream end of the bar. A clear gap in the existing literature was studies of pit infill and point bar rebuilding in natural sand-bed channels subject to stochastic flows.

This thesis found that the pattern of infill is discharge dependent. At high discharges (bankfull and above) a zone of bedload transport develops on the bed of the pit, between the advancing head and the rotating tail. At the same time, a lobe of suspended sediment intrudes into the pit, depositing sediment in front of the advancing avalanche face. Together these processes cause the head of the pit to migrate downstream, a scour zone to develop on the bed of the pit, and for sand to be deposited along the pit margins. At lower discharges, no bedload transport occurs in the middle of the pit: settling of suspended sediment and the slow collapse of sand down the avalanche face are the only processes delivering sediment to the pit. At lower discharges the pit head migrates more slowly.

These results contrast with the earlier view of pit infill in straight channel segments in four main ways: (1) the way pits refill is discharge dependent, they do not refill at a constant rate, (2) at bankfull discharge, bedload transport occurs along the bed of the pit, between the advancing head and the rotating tail, (3) a scour channel forms on the bed of the pit, (4) infill is not by bedload deposition at the avalanche face alone, a lobe of suspended sediment deposits sediment at the head of the pit *and* along the pit margins.

This thesis also found that in-stream vegetation limited the width of the active channel upstream and downstream of the extraction pit. By limiting local sand supply, vegetation patches decreased the rate of pit infill at low discharges, when bedload steadily migrates into the pit. Vegetation had little impact on pit infill at higher discharges, when suspended sediment passes over vegetation and settles in the pit.

Finally, this thesis found no evidence for a migrating nickpoint upstream of any of the pits. However, hydraulic modelling did predict that pits would increase bed shear stress and the total sediment transport rate upstream of the pit. Therefore while nickpoint migration was a key feature of many of the earlier models of pit evolution, this thesis supports the contention of Wishart *et al*. (2008) that nickpoints are not generated in all cases.

The pattern of pit infill has four implications for the use of extraction in river restoration in medium-sized sand-bed rivers: (1) excavating long, deep, narrow pits does not generate a nickpoint that migrates upstream, (2) the width of the scour zone downstream of extraction pits is influenced by the pre-existing bed topography. Bars and benches already in the channel confine the scour channel that develops at the tail of the pit, preventing the scour channel from expanding across the width of the channel, and (4) in-stream vegetation only limits pit infill at low discharges.

Point bars removed by extraction rebuild in two ways, depending on whether the point bar was excavated on a low angle meander or a sharp meander. Point bars on low angle meanders rebuild from upstream to downstream, from inside the meander towards the outside of the meander, and from the base upwards, all at the same time. The head of the point bar does not migrate uniformly, instead hugging the inside of the meander. The pattern of rebuilding is controlled by the secondary circulation cells that usually maintain point bars. Point bars excavated on sharp meanders rebuild from the base upwards, from the centre of the channel towards the inside of the meander, and from downstream to upstream, at the same time. This pattern of rebuilding is controlled by the formation of a recirculating eddy on the inside of the meander, which entrains sediment from the main body of flow and deposits it within the low-velocity eddy.

The growth of point bars around a shallow meander bend and the deposition of sediment inside a recirculating eddy both contrast with earlier models of point bar rebuilding, which were based on a small number of field observations after points bars were scraped (not completely removed). These earlier models imply that a point bar would rebuild according to the distribution of shear stress across the bar surface during discharges that mobilised the median particle diameter. This thesis has shown that it is secondary circulation and the presence of recirculating eddies that control point bar rebuilding following their complete removal.

10.2.3 Does a sequence of extraction pits accelerate reach-scale recovery from a bedload pulse?

The premise of using in-stream extraction to accelerate recovery has been proposed (Rutherfurd and Budahazy, 1996; Brizga et al., 2000a; Wilkinson et al., 2006) but never tested. The man aim of using extraction in a sand-bed river is to prevent sand ingress to downstream pools (i.e. preserve intact habitat). Additionally, reducing sediment supply to downstream reaches may cause pools to re-scour on the outside of meander bends faster than without extraction. Together these two aims are conceptualised as accelerating river recovery.

The conceptual model developed in this thesis predicted that pits in a sequence will all begin to refill at the same time (Gill, 1994). When pits are close together, upstream pits interact with downstream pits, and the sequence is coupled. When the space between pits is large, pits behave independently. As additional pits are added to the sequence, the sediment deficit imposed on downstream reaches also increases. As the sediment deficit grows in a downstream direction, so too will the depth of thalweg erosion and the degree of channel adjustment. Channel adjustments that signify recovery include: return of a well-defined low-flow channel (Hoyle *et al.*, 2008; Fryirs and Brierley, 2016; Mould and Fryirs, 2018), an increase in bed relief (Erskine, 1996) and the re-emergence of pools on the outside of meander bends (Madej, 2001; Zunka *et a*l., 2015).

This thesis found that thalweg scour did increase in a downstream direction following the extraction of a sequence of extraction pits. The low-flow channel, which was present when extraction began, deepened and widened in the upstream part of the reach. The channel contracted in the downstream section, where vegetation had established on the streambed. Pools present on the outside of meander bends at the start of the study period did not fill with sand or increase in size. No new pools were scoured on the outside of meander bends. Bed relief and channel complexity increased along the entire study reach, but the upstream, unvegetated part of the reach showed a greater increase in complexity than the downstream half. However, the absolute level of complexity was much higher in the downstream, vegetated part of the reach before and after extraction. The pattern of bed shear stress explained the pattern of thalweg erosion and volume change at each cross-section, regardless of whether vegetation had established.

The river did not overcome the sediment deficit caused by extraction within the 8 km study reach. I predict that a further 50 km of river downstream from the study reach has been impacted by extraction to date.

Another major contribution of this thesis was to identify that the benefits of in-stream extraction only materialise once stock are excluded from the reach. In reaches where stock were excluded *Phragmites australis* colonised the streambed and caused an abrupt increase in channel complexity. The increase in complexity driven by in-stream vegetation was larger than the increase in complexity driven by in-stream extraction.

Overall, extraction alone has modest impact on the pattern and rate of recovery and is not likely to cause new pools to scour in downstream reaches (which was the original intent). The absence of forcing elements in the channel (such as LWD and erosion resistant bars) means that bed erosion produces a wide, shallow and flat-bottomed low-flow channel set between low relief benches. This morphology is only slightly more complex than the pre-extraction sand sheet and appears to provide little more habitat.

When extraction and stock exclusion are implemented in a reach, channel complexity will increase, and recovery can be accelerated. Stock exclusion is the more powerful of the two interventions. Continuing to extract sediment will cause these vegetated landforms to erode. Eroding these stable landforms risks undermining the improvements that have already been realised.

10.2.4 Do multiple, interacting local-scale interventions accelerate recovery at the tail of a bedload pulse?

A key premise of river restoration is that catchment scale drivers of degradation must be addressed before the reach-scale symptoms of degradation (Hillman and Brierley, 2005; Wohl *et al*., 2005; Meyer *et al*., 2007). This thesis examined a river where the catchment scale drivers of degradation (increased erosion) have been treated, and then a series of local-scale interventions have been implemented in the trunk stream (Bryan Creek).

In-stream sand extraction is one such local-scale intervention, implemented over hundreds of metres of river at a time. Assessing the response of a river to extraction is complicated when other local-scale interventions, such as stock exclusion and bank revegetation, are also implemented in extraction reaches. Stock exclusion and re-vegetation interrupt sediment continuity by either locking sediment into storage or removing sediment from storage, which causes reaches to interact. Interaction between reaches should produce gradual changes in morphology along the river.

This thesis developed a conceptual model to predict the impact that a set of local-scale interventions would have on the degrading tail of a bedload pulse. The key finding of this part of the thesis was that once the catchment scale drivers of degradation have been addressed, local-scale interventions can profoundly alter morphology. Reach-scale changes are highly localised, reaches did not interact, and the boundary between the different reach morphologies was sharp (in this case defined by fences). Stock exclusion, which allowed *Phragmites* to establish on the bed, rapidly transformed a flat sheet of sand to a sequence of deep pools. The sequence of pools developed by the simultaneous scour of pools and the aggradation of the intervening streambed. Once extraction had ceased, transformation to a sequence of pools occurred in only eight years.

Reaches treated with extraction only, and reaches where stock exclusion fencing was not maintained, showed no similar improvement in stream morphological condition. Instead, spiny rush colonised the bed of these reaches and a network of low-flow channels developed. This dissected morphology increased cross-section variability but had little impact on thalweg variability or overall stream condition.

The ability for vegetation (in this case *Phragmites*) to alter morphology so dramatically in such a short time has important implications for the use of local-scale interventions to accelerate recovery. This research shows that local scale interventions can be undertaken in reaches where drivers of degradation are controlled, and stock exclusion should be prioritised above other interventions. The research also shows the potential for in-stream extraction to be used to generate deep, narrow channels in downstream reaches. The deep low-flow channel can serve as a starting point for pool development. When extraction ceases, and stock are excluded, vegetation begins trapping sediment and pinching-off the low-flow channel. In this way, extraction causes a sequence of pools to form faster than if the sediment supply was left to decline at a natural rate.

This thesis has also demonstrated that rivers previously degraded by historic over-extraction are able to have their condition locally improved. By immobilising sand in the reaches surrounding extraction pits, stock exclusion preserves the pits in the bed so they can continue to serve as habitat. By immobilising sand, vegetation heals the reach, balancing the erosion of some parts of the streambed with aggradation in others. The outcome is a more complex channel. Managers could work with landholders to improve condition in selected reaches, and then work to link these improved reaches into a single corridor.

10.2.5 A model for reach-scale aggradational tendency

This thesis developed a model to conceptualise the aggradational tendency of different sized rivers (Chapter 9), and a function to relate that relates aggradational tendency to reach-scale geomorphic complexity. The model conceptualises aggradation tendency, the tendency of a reach to trap and store sediment when colonised by vegetation, as the ratio of driving forces (which erode sediment from storage) and resisting forces (which store sediment in the channel). Driving forces are quantified using the integral of stream power over some time period. Resisting forces are quantified via the metric of the trap efficiency, which is the product of excess flow energy and a constant representing vegetation patch density and growth dynamics.

Aggradation tendency is related to reach-scale geomorphic complexity by an inverted parabola, with each end member of the parabola corresponding to low geomorphic complexity. The model implies that to maximise geomorphic complexity, managers must steer a reach away from either very low storage (such as a simple, eroding gully) or away from very high storage (such as a homogenous, aggraded channel).

Complexity is maximised between the two end members, where the processes of erosion and storage are balanced, and the bed is re-arranged into a more variable morphology. The downstream part of the study reach in the Glenelg River, and the reach adjacent Coleraine in Bryan Creek are examples of reaches where a combination of extraction and sediment trapping by *Phragmites* have led to an overall increase in reach-scale geomorphic complexity.

10.3 Can in-stream extraction be used to accelerate the recovery of rivers degraded by a bedload pulse?

The answer to the over-arching research question investigated by this thesis is a qualified yes. The qualifying condition is that stock should also be excluded from extraction reaches so that vegetation can establish on the streambed.

By exploring bedload pulse dynamics at the catchment scale, this thesis has developed a conceptual model that can be used to decide where extraction, or other interventions, are most likely to accelerate recovery. By exploring how individual extraction pits refill and change shape, this thesis has found that deep, narrow extraction pits minimise channel disturbance in medium-sized sand-bed rivers. By examining how a sequence of extraction pits impact upstream and downstream reaches, I found that pairing extraction with stock exclusion can lead to a substantial increase in channel complexity. Importantly, most of the channel complexity that develops downstream of extraction sites can be attributed to the presence of in-stream vegetation, and not extraction alone. Finally, this thesis examined how in-stream extraction interacts with other local-scale interventions at the tail of a bedload pulse. When the catchment-scale drivers of degradation have been addressed, local-scale interventions, and stock exclusion in particular, are the dominant control of reach-scale recovery. Local scale interventions disconnect reaches and cause them to behave independently.

10.4 Summary of the contribution of this thesis

This thesis makes several fundamental contributions to knowledge. This thesis has improved understanding of bedload pulse dynamics and the use of extraction in sand-bed rivers recovering from bedload pulses in a number of ways (see Table 10.1 for a summary).

Table 10.1: A summary of the key contributions of this thesis, detailing what we knew about bedload pulse dynamics in sand-bed rivers and the impact of extraction before the thesis and what we now know.

What we knew before this thesis	**What we know now**
Bedload pulses migrate through a catchment as a migrating wave, or series of smaller waves that emanate from tributaries.	Bedload pulses do not move through this catchment as a series of migrating waves. Instead, bedload pulses in the bed of the Glenelg River are broken into smaller compartments by valley constrictions. When extrinsic controls dominate the catchment-scale movement of sediment, and when most bedload pulse movement is driven by floods, bedload pulse dynamics can be conceptualised as a series of standing waves. The peaks of standing waves (areas of high sediment storage) are stationary, but sediment is exchanged between peaks.
Extraction pits in straight channels fill from their upstream end. The head of the pit slowly migrates downstream while the tail of the pit rotates in a downstream direction. Sediment does not along the bed of the pit, between the advancing pit head and the rotating pit tail A scour profile develops downstream of the extraction pit. Over time the scour channel expands across the width of the channel.	The process of pit infill is discharge dependent. At high discharges (bankfull and above) a bedload transport zone forms within the pit and a lobe of suspended sediment intrudes into the pit. At lower discharges (0.5 x bankfull) there is no bedload transport within the pit, and the lobe of suspended sediment entering the upstream end of the pit does not intrude as far into the pit. A scour channel forms at the downstream end of the pit but does not expand across the width of the channel. Extracted point bars can rebuild in two ways: by secondary circulation or by eddy recirculation. Point bars extracted from low angle meander bends re-build from upstream to downstream, from the inside of the meander to the outside of the meander and from the base upwards, all at the same time. Secondary circulation currents, which sweep sediment along the streambed towards the inside of the bend, control the rebuilding process. Recirculating eddies control rebuilding of point bars extracted on sharp meander bends. Point bars grow from the centre of the channel towards the inside of the meander, from upstream to downstream, and from the base upwards at the same time.

Extraction will lower bed levels downstream and accelerate recovery. Extraction will generate a nickpoint that migrates upstream.	Extraction interacts with the complexity of the natural channel. The existing sediment transport pattern and in-stream vegetation shape channel recovery. Improvements in condition are not realised until stock are excluded and vegetation establishes. Nickpoint were not generated upstream of the extraction pits studied.
Extraction will interact with other interventions in a river to gradually increase geomorphic complexity from upstream to downstream.	When the drivers of degradation have been addressed, local-scale interventions are dominant. The river becomes disconnected. There is little interaction between reaches and the transition between different morphologies is sharp. Stock exclusion, which allows vegetation to establish on the streambed, is associated with pool development and a dramatic transformation in morphology. Extraction alone produces little to no improvement in stream condition. Geomorphic complexity can be conceptualised as a two end-member model, with very low sediment storage (low aggradational tendency) at one end, and very high sediment storage at the other end (high aggradational tendency). Managers can alter reach-scale stream power, or the trapping rate of vegetation (by excluding stock, or changing excess flow energy) to shift a reach away from either end of the curve, towards a more complex configuration.

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