Sociogeomorphic evolution of an Australian upland river:

A physical-and-social basis for rehabilitation

Simon Mould

Department of Environmental Sciences

Faculty of Science and Engineering

Macquarie University

Submitted 9th October 2015

MACQUARIE University

Declaration

I hereby declare that this thesis has not been previously submitted to any other institution or university for a higher degree. Except where otherwise acknowledged, this thesis is comprised entirely of my own work. Ethical aspects of this thesis have been approved by the Macquarie University Human Research Ethics Committee (Reference No. 5201500083).

Simon Mould

October 9th 2015

Acknowledgments

First I'd like to thank my supervisor, Kirstie Fryirs, for the guidance and mentorship she provided throughout this research project. I've learned a lot from her work ethic and passion for rivers. My co-supervisor, Richie Howitt, was a great source of wisdom and encouragement and I'd like to thank him for sharing some of his vast experience with me.

To the MRes office crew, thanks for all the high quality comradery, advice and baked goods. That means you, Zacc Larkin, Jamie Lobb, Luke Stone, Kat Macsween and Shaun Grumley.

Thanks to all the kind people who were tricked into helping me with fieldwork: Luke Stone, Rory Williams, Peyton Lisenby, Anna Mould, Lani Barnes and Loretta Visintin. Thanks to the tiger snakes for leaving us alone.

For sharing their insights with me, I'd like to thank the research participants from the Pejar Local Aboriginal Land Council, NSW Local Land Services Southeast and Veolia Environmental Services, as well as David Pockley, for helping me to understand Crisp's Creek through their diverse experiences. Local Land Services and Veolia both provided resources that made this research possible. Thanks also to Uncle Lexodious Dadd, Elder-in-Residence at Macquarie University, who provided guidance in my first research engagement with Indigenous people.

Finally I'd like to thank my family for their support throughout this thesis, for patiently enduring and even feigning interest on occasion when all I could think or talk about was my thesis.

This research was made possible by a linkage grant from the Australian Research Council (LP130100120; CIs K. Fryirs and G. Hose) and funding from the Department of Environmental Sciences, Macquarie University.

Contents

Abstract

In many Australian river management settings there is a need to broaden and deepen participation and knowledge integration, particularly between physical and social sciences and with Indigenous knowledges. Recent developments in geomorphological thinking that promote place-based and reflexive practice in studying emergent landscapes may provide a basis for connecting geomorphology with diverse ways of knowing. In this thesis, a sociogeomorphological view of a chain of ponds river system provides a social-and-physical historical context for river management, revealing physical and social constraints on achievement of sustainable river management. Recognising the need for more appropriate engagement with Indigenous voices, this thesis established the beginnings of cross-cultural dialogue using ethnogeomorphological principles in a reconfiguration of relationships between people and between people and place. By re-making these relationships, the river was re-made for research participants and the researcher in a way that constitutes river rehabilitation in its own right. This conceptualisation of river rehabilitation as concerning physical-and-social relationships has implications for recognition of the political work of geomorphology, alongside other ways of knowing, in achieving sustainable river management.

1 Introduction, literature review and thesis aims

1.1 Introduction

We live now in a time that many are referring to as the *Anthropocene* because of the great and unprecedented extent to which human activities and structures now constitute the physicality of the Earth and influence environmental processes (Castree 2014, Steffen et al. 2011). Although technically problematic (e.g. Lewin and Macklin 2014, Gale and Hoare 2012), this term and its proliferation in public discourse does usefully draw attention to widespread questioning of how humans 'fit' in the world and how we as societies will respond to a rapidly changing physical-and-social environment (Head 2015, 2014). In a context of global environmental change, the challenges faced by societies are multifaceted, interconnected and uncertain, requiring that institutions of knowledge creation work across and outside of disciplinary boundaries to develop more holistic understandings of environments and their trajectories of change (Castree et al. 2014). At more local scales, too, there is a need for research that recognises the potential for connectivity between knowledges to improve our ability to manage human activities and needs within environments; to some degree, this need is being addressed by researchers grounded in geomorphology (Church 2010). Fluvial geomorphology in particular is well positioned to advance transdisciplinary thinking because of its increasingly prominent role in river management (Grabowski et al. 2014, Fryirs and Brierley 2013, Thorne et al. 1997, Kondolf 1995). Furthermore, fluvial environments provide fertile ground for necessary conversations on changing human - place relationships because they are sites of close interaction between people and the physical earth. This is due to the direct dependency of human (and non-human) life on fresh water and because of the cultural and spiritual significance of rivers (Kingsley et al. 2009, Weir 2009, Humphries 2007, Dudgeon et al. 2006, Jackson et al. 2005, Jackson et al. 2001).

Recognising the need for environmental research philosophies and methodologies that are capable of meeting the challenges of environmental change in complex physical-and-social systems, this chapter will focus on literature from geomorphology and river management, reviewing approaches to research that engage with social as well as physical dimensions of river evolution and management. First, this chapter will examine shifts in river management toward integrated, sustainability-focused approaches, outlining some significant opportunities and challenges in such work. Second, this chapter will review recent directions in geomorphology that promote understandings of landscapes with recognition of the importance of people, place and history in making and re-making geomorphic landscapes. This includes geomorphology's treatment of emergence and contingency and applications of critical theory in repositioning the role of humans (including researchers) in landscape evolution. The potential for this thinking to influence river management will then be considered.

Third, this chapter will put forth the iconic Australian *chain of ponds* as a river course often neglected in research and policy, which, with its history of heavy modification following the onset of European land use practices, provides a suitable 'testing ground' for geomorphological research that works with people, place and history in the development of knowledge suitable for guiding sustainable river management and rehabilitation. Finally, this chapter will present key research questions and aims and outline how this thesis will address these in the study of one particular chain of ponds system in southeast Australia.

1.2 Sustainable river management

River management in Australia, as in many other parts of the world, is undergoing a transformation whereby hard engineering and top-down approaches are being superseded by a more ecologically and socially sensitive paradigm; this new paradigm has been termed the Era of River Repair (Brierley and Fryirs 2008). The Era of River Repair is characterised by a focus on sustainable river management, principles of which include: **(i)** ecosystem-based approaches; **(ii)** participatory approaches; and, **(iii)** adaptive management (Gregory et al. 2011, Hillman 2009, Brierley and Fryirs 2008). In these approaches the catchment is often the fundamental scalar frame within which river management **planning** occurs because it frames connectivity between landscape units and reaches in a way that is spatially bounded and ecologically meaningful (Brierley et al. 2006, Brierley and Fryirs 2005, Frissell et al. 1986). Although many river management **activities** often occur at scales smaller than the catchment (e.g. reach scale), they are often prioritised and planned with consideration of their position in a catchment (Brierley and Fryirs 2005, Bohn and Kershner 2002, Snelder and Biggs 2002, Naiman et al. 1992). An ecosystem-based approach encourages managers to work with the inherent dynamic variability of river systems, both in physical and social dimensions (Brierley and Fryirs 2009, Hillman 2005). Integration of knowledges (both discipline-bounded and unbounded) is vital to developing a whole-of-ecosystem vision for river management (Wohl et al. 2014, Hillman et al. 2008). However, this vision should not only be based on expert analysis of the social and physical system; active participation from a wide range of interested community members is important for ensuring appropriateness and longevity of management strategies (Hillman 2005). Finally, adaptive management ensures that a process of deliberate learning is built into a flexible river management system in a way that is iterative so that strategies can be evaluated and continually improved (Clark 2002, Walters 1986).

This new paradigm of river management has been the focus of a significant body of literature; however, there remain challenges to realising sustainable river management in many settings. These challenges are common in many areas of environmental science and include: developing common language with which to communicate and understand physical-and-social systems (Bracken and Oughton 2006), limited integration of knowledges across and outside of disciplines (Elliott 2001), problems in communicating science with diverse groups of people and applying that science in management (Ryder et al. 2010, Benda et al. 2002). Fryirs et al. (2013) reported that publications from major Australian river management conferences remain skewed toward those that are discipline-bound (46%) or cross-disciplinary (defined as integration of biophysical sciences; 36%), with very few publications being trans-disciplinary (defined as merging of physical science with social and economic perspectives; 17%) and even fewer applying adaptive management (2%). Hillman (2009) also reviewed a number of cases and found that ingrained institutional conditions meant that integration was limited between knowledge types (technical practice, scientific knowledge and practical, value-based wisdom) and also between these knowledge types and the core principles of sustainable river management. This analysis indicated that insufficient integration in one area could limit effectiveness in other areas, reinforcing the need for each component principle of sustainable river management to be strengthened. Amongst other recommendations, Hillman (2009) argued that improvements were needed in science communication (content and methods), understanding of different forms of learning that connect people with their environment and recognition of the importance of place. These points for improvement intersect with recent directions in geomorphology, which will be discussed below.

1.3 Place, history and people in geomorphology

Geomorphology has much to contribute to the kind of grounded ecosystem understandings required for sustainable river management. Recent directions in geomorphology signal a turn toward emphasis on place and stronger integration with ways of seeing human-environment relations from the social sciences. These frontiers of geomorphological thinking and practice include an emerging sense of place and history as well as recognition of the roles of human agency and social processes in shaping landscape morphology and their implications for management that is adaptive to both ecological and socio-cultural processes (Ashmore 2015, Church 2010, Brierley et al. 2006).

1.3.1 A sense of place and history

The importance of place and history in explaining landscape evolution has been a significant focus for research in recent years as the specificity and unpredictability of geomorphic landscapes necessitates a more-than-theoretical understanding that recognises emergence and contingency (Phillips 2015, Murray et al. 2014, Brierley et al. 2013, Church 2010, Phillips 2007, 2006a, b, Harrison 2001). Phillips (2007) elegantly explains contingency and emergence thinking in his description of all landscapes as 'Perfect Landscapes',

> "Recognition of the perfection of landscapes leads away from a worldview holding that landforms and landscapes are the inevitable outcomes of deterministic laws, such that only one outcome is possible for a given set of laws and particular conditions. A perfect landscape perspective leads toward a worldview that landforms and landscapes are circumstantial, contingent results of deterministic laws operating in a specific environmental context, such that multiple outcomes are possible" (Phillips 2007, p.160).

Making sense of contingent landscape evolution requires an interpretive approach that is sensitive to the specificities of place whilst not neglecting the theoretical process underpinnings of geomorphology. Such an approach is promoted by Brierley et al. (2013) in *Reading the Landscape*, which provides an open-ended but structured framework for constructivist interpretation thus allowing 'non-conformist' characteristics (Phillips 2015) to be understood with reference to theory. Historical understandings of geomorphic landscapes provide a place-specific context within which larger scale processes and laws interact, making history a vital part of explaining contingent landscape evolution (Phillips 2007). Landscape history across a range of temporal scales (geological to human living memory) sets the boundary conditions that limit the possible range of river trajectories in ways that are meaningful for river management (Brierley 2010). For example, river rehabilitation goals that aim to restore a human-modified system to a previous state are often inappropriate as boundary conditions may have been altered so as to prevent a restoration of process or form (Allan 2015, Fryirs and Brierley 2009, Brierley and Fryirs 2008). Rates of river evolution can be used to contextualise contemporary river condition and to distinguish between adjustment, behaviour and change, with implications for the style of rehabilitation to be adopted in a particular setting (Fryirs and Brierley 2013, Brierley et al. 2006, Brierley and Fryirs 2005, Schumm 1977). 'Knowing your place', therefore, is a fundamental requirement for sustainable river management (Brierley et al. 2006).

1.3.2 Critical geomorphologies

An important part of understanding the contingent evolution of geomorphic landscapes is accounting for the effects of human actions and broader social processes. Geomorphology has long been concerned with uncovering the 'natural' processes of landscape evolution in isolation of social dimensions of the landscape, except where human actions can be seen as 'impacts' or 'disruption' of the natural system (Ashmore 2015, Head 2008). The hyper-separation of the human from the natural is problematic because it places human and non-human dimensions of the landscape in opposition, where one is active and so the other is passive or one is dominant and the other dominated (Plumwood 2002). This binary positioning of the human fails to recognise complexity and nuance in human and non-human relationships (Ashmore 2015, Tadaki et al. 2015, Head 2014, 2011, 2008). However, more recently, critical approaches in the environmental sciences have sought to 'put people back' in the landscape and within a broader concept of 'agency' (human and non-human), which acknowledges humans and social processes as landscape forming from within the system rather than as external disruptors (Ashmore 2015, Lane 2014, Linton and Budds 2014, Head 2008, Castree 2002).

Methodologically, some have suggested that stronger integration of physical and human geography is required to develop a field of critical physical geography that would apply social theory with a strong biophysical foundation (Lave et al. 2014), similar to the concept of coupled human and natural systems (e.g. Vogel et al. 2015, Liu et al. 2007). Alternatively, a less formal practice of being critical within physical geography has been proposed, wherein attention is given to the political, social and institutional context in which geographers work (Tadaki et al. 2015). With the recognition of different styles of critical physical geography, some exciting recent developments in geomorphology have emerged that provide opportunities both for allowing more complete and ecologically meaningful explanations of the role of humans in landscape evolution and for engaging with diverse knowledges through geomorphology. Two such examples are *sociogeomorphology* (Ashmore 2015) and *ethnogeomorphology* (Wilcock et al. 2013, Wilcock and Brierley 2012).

Sociogeomorphology has been promoted by Ashmore (2015) as a conceptual repositioning of humans in geomorphic landscapes that sees rivers as co-productions, or hybrids, of social and physical processes. In this repositioning, humans and social processes are seen as operating within socio-natural systems, rather than as external disruptors. This also questions the way we see the role of science and scientists in shaping rivers (materially and conceptually) through their epistemological frameworks (Ashmore 2015, Lane 2014, Tadaki et al. 2014), in effect, seeing the geomorphologist as a 'geomorphic agent'. Sociogeomorphology provides an opportunity to review and respect the roles of humans in ecosystems through deeper analysis of local and global social processes as relevant for river evolution in the past and also into the future, i.e. in reconstructing environmental change and imagining river futures or what is achievable in river management (Brierley and Fryirs 2015, Surian et al. 2009). Moving beyond 'human impacts' discourse allows closer analysis of the specific ways that river morphology and behaviour are influenced by social processes, these processes being an important consideration in river rehabilitation design.

A related, but distinct, critical geomorphology is ethnogeomorphology (Wilcock et al. 2013). Ethnogeomorphology proposes that there are multiple ways of knowing and understanding landscape processes and their meanings, with profound implications for environmental management as a process in intercultural settings. Ethnogeomorphology considers that landscapes are simultaneously biophysical-and-cultural, challenging the conventional separation of 'physical' and 'human' domains. From this position, ethnogeomorphology aims to use conversations on geomorphic landscapes and their evolution as a foundation for dialogue across cultures (Wilcock et al. 2013). This relational approach to geomorphology draws on concepts from the social sciences, such as situated engagement (Suchet 2002) and ontological pluralism (Howitt and Suchet-Pearson 2006, Howitt and Suchet-Pearson 2003), to develop shared understandings of landscapes built on multiple knowledges (Wilcock et al. 2013). Ethnogeomorphology also has an explicitly political motivation, using conversations on place as a way to empower people who are often sidelined in environmental decision making, particularly Indigenous people, in an "ethically and culturally engaged practice" (Wilcock 2013, p.470). In river management, ethnogeomorphology may provide a necessary re-framing of knowledges and political positions in order to improve communication between those involved in management.

1.3.2.1 Applications for river rehabilitation

Whilst ethnogeomorphology proposes a more radical engagement of geomorphology than does sociogeomorphology, the two ways of framing how we learn about landscapes may be complimentary and both can inform research practice in geomorphology in ways that are relevant for river rehabilitation. Sociogeomorphology's positioning of the human in socio-natures encourages more in-depth, critical analysis of the specific ways that social and physical processes interact in landscape evolution, beyond an oversimplified 'human impacts' explanation. This framing supports whole-of-ecosystem approaches to river rehabilitation that are realistic in terms of hybrid boundary conditions, echoing thinking in ecology that recognises the need to move beyond retrospective restoration agendas (e.g. Hobbs et al. 2009, Head 2008). Examining more closely the agency of humans as part of the landscape, a sociogeomorphic evolutionary understanding also may broaden the scope of river rehabilitation beyond the physical, creating discussion space for sources of knowledge beyond the technical. Ethnogeomorphology may be used to capitalise on this opening and expand conversations on rehabilitation to promote plural understandings of place in the framing of management goals and processes (Howitt and Suchet-Pearson 2003, Suchet 2002). This engenders opportunities for developing processes and outcomes that are environmentally just (Hillman 2006, 2005, Suchet 2002).

In order to test the opportunities presented by critical geomorphologies for improving river management processes, this thinking needs to be applied in case studies with different histories of human - river relationships. Australian rivers may provide a suitable testing ground because embodied in these landscapes are relatively recent histories of major changes to the ways humans have lived with rivers, with observable morphological results. Because the majority of changes to river morphology that can be attributed to human agency occurred in the last two centuries, these changes are generally well accounted for in historical records. The Australian river management setting, being formed around a largely middle-ground approach that is sensitive to place (Gregory et al. 2011) also makes this a suitable environment for testing the application of place-based geomorphologies. In a place-sensitive river management setting, there are opportunities to address diversity both in environmental knowledges and in the range of fluvial environments. Australia is home to a wide range of fluvial forms, many of which occur only in Australia. There is a need for river management to better address this diversity with greater attention to the less 'typical' river systems. In southeastern Australia, chains of ponds are a river type that were ubiquitous prior to European arrival but have in many cases undergone major adjustment (Eyles 1977b) or have been lost following the onset of European land use practices (Fryirs and Brierley 1998). Despite this, they are under-represented in the literature and in environmental legislation (Taylor and Stokes 2005), making them a priority for research. The next section will review the available literature on this increasingly rare river type in order to establish a basis for further research that could apply sociogeomorphology and ethnogeomorphology principles in case studies to examine the potential for their application in river rehabilitation.

1.4 Chains of ponds

Chains of ponds are one subset within a range of discontinuous river courses found throughout Australia. In humid and temperate environments, discontinuous river courses include *dells* (Young 1986) and *upland peat swamps* and *mires* (Fryirs et al. 2014a, Fryirs et al. 2014b, Nanson and Cohen 2014, Nanson 2009, Dodson 1987). In Australian alpine environments, *sphagnum peatlands* and *mountain mires* occur though are not common (Whinam et al. 2003, Hope 2002). In arid or semi-arid environments discontinuous rivers called *floodouts* occur where flow is insufficient to transport sediment loads and drainage breaks down (Ralph and Hesse 2010, Tooth and McCarthy 2007). Many of these river types have overlapping characteristics and indeed the term *chain of ponds* has been used historically to describe a range of fluvial forms. Mactaggart et al. (2008) review the various uses of this term, ranging from discrete scour pools formed in intact valley fill and separated by grassy, saturated flow paths (Hazell et al. 2003, Fryirs and Brierley 1998, Prosser 1991, Eyles 1977a); to historical accounts of pools and riffles disconnected in periods of low flow (Mactaggart et al. 2007); and even large-scale scour pools in an anastomosing dryland river (Knighton and Nanson 2000). Mactaggart et al. (2008) constructed a decision key in an attempt to normalise descriptive terms, which defines chains of ponds as being pools formed by scour, sediment build-up or biological accumulation, irregularly spaced and of variable size with hydrologic and geomorphic conditions suitable for development of swampy vegetation. These pools are usually part of a linear (but not channelised) drainage line on a valley floor, often consisting of multiple preferential flow paths

(Mactaggart et al. 2008, Hazell et al. 2003, Prosser 1991, Eyles 1977a). According to Mactaggart et al. (2008), chains of ponds are a subset of the *swampy meadows* river type, which typically consists of flow paths on an alluvial valley fill without scour pools.

1.4.1 Holocene formation and evolution

Chains of ponds are typically set into broad, low-gradient valleys of alluvial fill (Eyles 1977b). In the Southern Tablelands and Southern Highlands of New South Wales (NSW), where the majority of chain of ponds research has been conducted, these alluvial fills commenced accumulation in the early Holocene, coinciding with transitions to a climate more similar to that of the present (Johnston and Brierley 2006, Prosser et al. 1994). In Wangrah Creek in the NSW Southern Highlands, three swampy sedimentary units have been identified, dated to around 13-8 ka, 5-3 ka and 2.9 ka to historical times (Prosser et al. 1994). These units accumulated with the aid of swampy vegetation able to survive in the warmer Holocene climate relative to the Pleistocene. However, within the Holocene, Prosser et al. (1994) argue that the influence of climate on aggradation and erosion has been less pronounced than more local factors, including bedrock control and establishment and disturbance of vegetation. Valley fills in the Southern Tablelands and Highlands region tend to follow a general pattern of increasing sediment size with depth. In swampy meadows at Wangrah Creek and in the upper Mulwaree River (which is the trunk stream to the study catchment in this thesis, Crisp's Creek), organic-rich, fine swampy meadows deposits overlie gravels, sands and bedrock (Rustomji and Pietsch 2007, Prosser et al. 1994). In floodplain pockets on Mulloon Creek (approximately 24 km to the west of the study catchment), finer sedimentary layers of organics, organic clays and silts, floodplain deposits and channel fills overlie a basal gravel lag (Johnston and Brierley 2006). Both these sequences indicate decreasing stream energy over evolutionary time.

Sedimentary evidence indicates that episodic incision of swampy valley fills was not uncommon in the pre-European record. Prosser (1991) found that although incision was more widespread and of a greater magnitude following European land use change than at any other time in the record, episodic incision and subsequent longer-term aggradation was a characteristic process of valley fill environments in southern NSW prior to European arrival (see also Zierholz et al. 2001, Prosser and Winchester 1996). Similarly, Fryirs and Brierley (1998) describe cut-and-fill landscapes characterised by incision and aggradation in pre-European periods. Triggering of changes between periods of incision and aggradation at the local scale in chains of ponds and swampy meadows has been attributed to localised vegetation and ground surface disturbance occurring in combination with proximity to a threshold of valley fill thickness increasing the slope of valley floors over time (Prosser and Slade 1994, Prosser 1991). Drivers of returns to periods of aggradation are less well understood, but appear to be closely related to colonisation of sediments by swampy vegetation (Prosser and Slade 1994, Prosser 1991).

1.4.2 Post-European changes

Many valley fills in the Southern Tablelands and Highlands of NSW have experienced significant incision since the onset of European land use in the region, around the 1820s, such that intact chains of ponds, which were once widespread, are now largely degraded (Johnston and Brierley 2006, Wasson et al. 1998, Eyles 1977a). Removal of vegetation and disturbance of the floodplain surface have been cited as triggers, specifically land clearing, grazing by sheep, cattle and rabbits, road building and drain construction (Mactaggart et al. 2008, Prosser 1991, Prosser 1990, Eyles 1977b). This incision produced a significant spike in catchment sediment yields in the Southern Tablelands and Highlands region between the early nineteenth and twentieth centuries, now reflected in ubiquitous sandy or loamy surface deposits variously termed *post-European material* (PEM) or *post-incision alluvium* (PIA) (Rustomji and Pietsch 2007, Johnston and Brierley 2006, Zierholz et al. 2001, Wasson et al. 1998, Prosser 1991).

Where incision lengthens ponds by knickpoint retreat and joins them to form continuous channels, contrast between pond and intermediate environments and associated habitats are lost (Hazell et al. 2003). Dewatering of ponds and swampy terrain also occurs with incision. In an intact system, water runs off the surface more readily and maintains wet conditions in the superficial sedimentary layers, whereas incision allows rain water to infiltrate through the floodplain and be evacuated by the channel, desiccating floodplain sediments (Prosser 1991). Such a hydrological change has significant implications for communities of sensitive organisms; for example, frog species rely on timely availability of surface water and vegetation to reproduce, and saturation of sediments to maintain body moisture when surface water is unavailable (Hazell et al. 2003). Changes to water quality, in addition to water quantity and seasonality, are also likely to be important factors affecting the aquatic ecology of these systems (Hazell et al. 2003).

Since widespread post-European incision, some possible signs of recovery have been observed. Sediment delivery rates, which peaked shortly after European arrival, have been declining since and now are somewhere between peak post-European rates and the inferred pre-European rates (Rustomji and Pietsch 2007, Wasson et al. 1998). In some locations, recent formation of ‘instream wetlands’ within previously incised channels may indicate processes of channel recovery as sediment begins to be stabilised and stored (Zierholz et al. 2001). However, it is unknown whether this represents a return toward something similar to a pre-European geomorphic state or a transition to a new condition, the distinction between river metamorphosis (Schumm 1977) or change (Brierley and Fryirs 2005) and dynamic variability being reliant on analysis of system form and behaviour within a longer term evolutionary context. The need is clear for more research that examines the longer term evolution of chains of ponds and uses this information to frame the development of management strategies specific to this river type and sensitive to its particular range of behaviours (Brierley et al. 2006).

1.5 Aims of this thesis

Despite river management theory in Australia having undergone major changes from 'command and control' (Holling and Meffe 1996) to 'river repair' (Brierley and Fryirs 2008), there remain challenges in practice that prevent realisation of what might be called sustainable river management (Gregory et al. 2011, Hillman 2009, Brierley and Fryirs 2008). Some recent developments in geomorphology, such as sociogeomorphology and ethnogeomorphology, may present an opportunity to develop better practice in learning about rivers from different perspectives and bringing those perspectives together for better cooperation in river management. However, this potential needs to be explored with further research in a range of case studies. Analysis of the current literature in these areas highlights some important questions for investigation:

- Can a sociogeomorphic perspective on river evolution improve the depth of our understandings of the shared histories of humans and rivers in a way that can inform sustainable river management?
- Can principles from ethnogeomorphology be used alongside a sociogeomorphic framing to enhance opportunities for participation and integration with diverse knowledges?
- How can these critical geomorphologies be enacted within geomorphology and what kinds of methodologies might be required?

Addressing these research questions will advance the potential for geomorphology to play an even greater role in river management. Given these questions, this thesis aims to:

(i) Understand how the studied chain of ponds river has formed and changed over time as a simultaneously physical-and-social landscape

(ii) Connect this understanding with characterisation of the contemporary management setting and identify opportunities for this to contribute to improved management practices

(iii) Apply principles from sociogeomorphology and ethnogeomorphology in a socially engaged geomorphological research project to explore ways of opening geomorphology to diverse ways of understanding simultaneously physical-and-social landscapes

2 Regional setting and methods

2.1 Regional setting

2.1.1 Geology and climate

Crisp's Creek is a headwater chain of ponds river system and a tributary to the Mulwaree River. Crisp's Creek joins with the trunk stream at the town of Tarago in the Southern Tablelands of NSW (Figure 2.1). The Mulwaree River forms part of the Hawkesbury-Nepean Catchment, which flows north-east to the Pacific Ocean via the Hawkesbury River. The Crisp's Creek subcatchment is approximately 30 km^2 in area and has a stream length of approximately 3 km at 740 m elevation above sea level. No flow gauges exist on the Mulwaree River, the nearest being where the Mulwaree joins the Wollondilly River at Goulburn. Crisp's Creek flows along an alluvial valley fill surrounded by bedrock ridges of Woodlawn Volcanics, consisting of Late Silurian rhyolite, ignimbrite, breccia and acid tuff (Felton and Huleatt 1975), these ridges forming part of the Great Dividing Range. Mean annual rainfall measured at the nearby town of Lake Bathurst (83-year record) is 683.4 mm with a slight spring and summer bias (Bureau of Meteorology 2015d). Mean monthly maximum and minimum temperatures measured at Goulburn Airport (26-year record) are 19.6 °C and 6.0 °C respectively (Bureau of Meteorology 2015b, c). Vegetation structure consists of grassland on valley floors and low open woodland with grasses on ridges. Historical accounts suggest that the treeless state of valley floors was typical at the time of European arrival in the region in the early 1800s (Eyles 1977b).

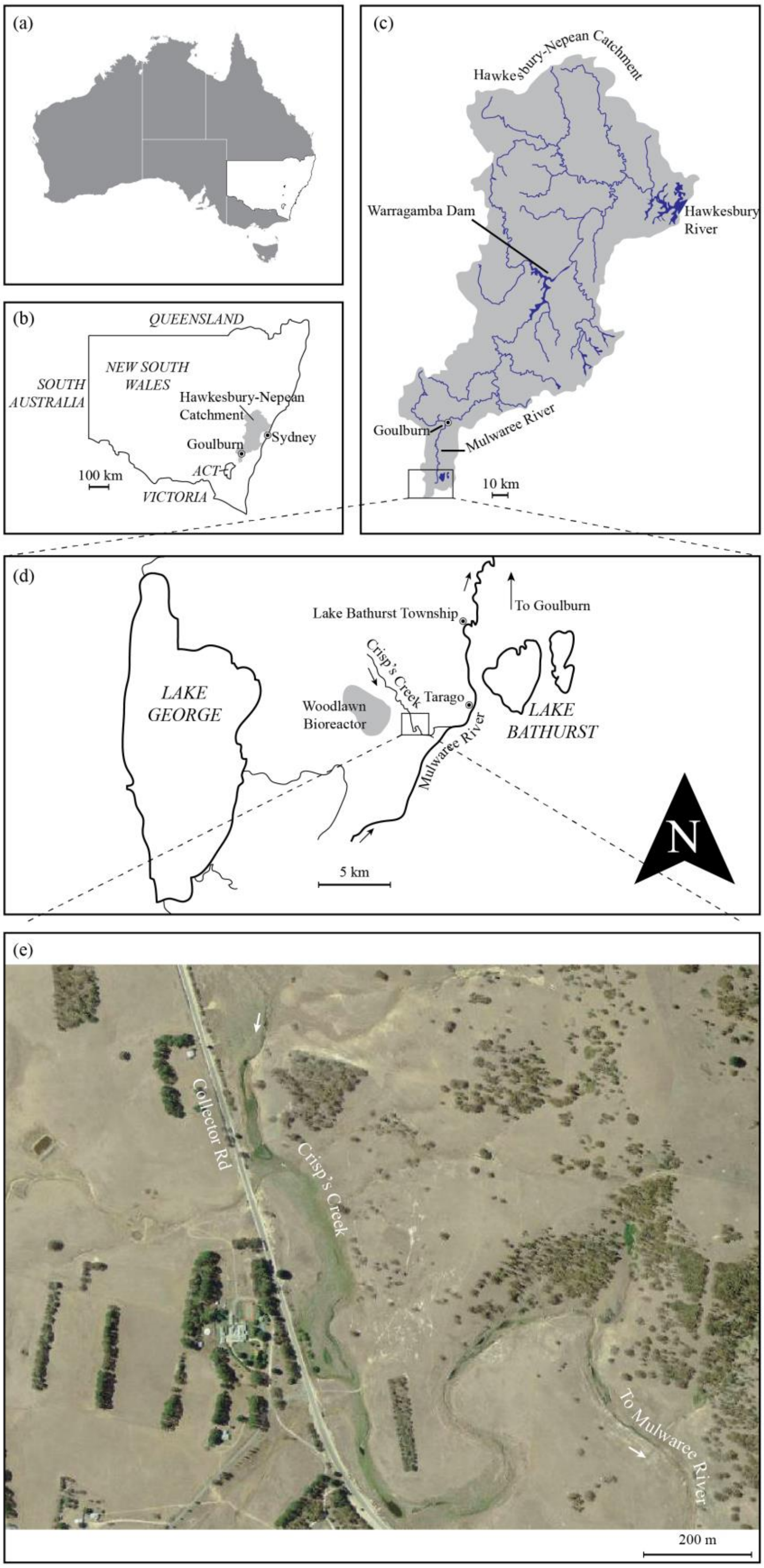

Figure 2.1: Location of study site. **(a)** Map of Australia showing state of New South Wales (NSW); **(b)** State of NSW; **(c)** Hawkesbury-Nepean Catchment; **(d)** Crisp's Creek and Mulwaree River; **(e)** Study site at Crisp's Creek (satellite imagery source: http://six.nsw.gov.au).

2.1.2 Key actors in river management

Veolia Environmental Services ('Veolia' hereafter) are the current landowners responsible for the majority of the Crisp's Creek subcatchment. Veolia is an international organisation with a range of interests, primarily in waste management. This research project concerns in part a river rehabilitation project undertaken by Veolia and NSW Local Land Services Southeast (LLS hereafter), which is the State agency responsible for land and river management in NSW. Prior to 2014, LLS offices throughout the state were known as Catchment Management Authorities and played a largely regulatory role in river management. Following a change in government, this agency adopted its current name and a new remit. Covering eleven regions, LLS now "delivers quality, customer-focussed services to farmers, landholders and the community across rural and regional New South Wales. LLS brings together agricultural production advice, biosecurity, natural resource management and emergency management into a single organisation" (Local Land Services 2015).

The Pejar Local Aboriginal Land Council is another important environmental management organisation in the area surrounding Crisp's Creek. It is part of the network of LALCs established under the NSW *Aboriginal Land Rights Act 1983*, with the NSW Aboriginal Land Council (NSWALC) as its peak body. The role of the LALC is partly established in the legislation as involving acquisition of vacant crown land by claim or purchase, establishment of Aboriginal commercial enterprises and maintenance and enhancement of Aboriginal culture, identity and heritage (NSW Aboriginal Land Council 2009). It is also contingent on particular local community and environmental relations. For example, when developments are proposed, including river rehabilitation works undertaken by LLS, LALCs are required to attend if the development site has previously unearthed Aboriginal artefacts or is a site recognised by the Aboriginal Heritage Information Management System. The LALC then is responsible for negotiating the protection of Aboriginal heritage at that site (LALC participant 2015, LLS participant 2015). The capacity of a LALC to respond to such demands inevitably depends on particular resources, individuals and circumstances.

2.1.3 Rehabilitation work at Crisp's Creek

A portion of Crisp's Creek is now under a management agreement in partnership between Veolia Environmental Services and LLS. The agreement is designed to protect from degradation a relatively intact section of Crisp's Creek, which is an example of the chain of ponds river type that is relatively rare and unique. The rehabilitation approach is largely passive, comprising new perimeter fencing to exclude livestock and the planting of approximately 3000 indigenous trees on hillslopes adjacent to the watercourse. The agreement was struck in 2014 with fencing and tree planting taking place early in 2015.

2.2 Geomorphology

Geomorphological interpretation of the site was undertaken using a combination of desktop and field-based analysis. Initially, contemporary satellite photographs were used to undertake geomorphic mapping using GIS (Esri ArcMap v10.2). Identification of geomorphic units was then confirmed with observations made in the field over a number of site visits in order to construct an accurate representation of the system's morphology. Interpretation of the geomorphic unit assemblage was informed by the approach, 'Reading the Landscape' (Fryirs and Brierley 2013) whereby catchment position, boundary conditions and an understanding of the site's history all provided context for analysis at the reach scale. Geomorphic units were identified according to Fryirs and Brierley (2013).

2.3 Topographic surveys

Augers, cores and bank exposures were correlated with topographic surveys undertaken in the field. A Leica ScanStation C10 terrestrial laser scanner (TLS) was used to survey the study reach with a point density of one point every 20 cm at 100 m range. The survey consisted of 19 scans using 37 targets with at least three targets constant in adjoining scans covering an area of approximately 0.24 square kilometres. Further cross-sectional surveys were undertaken using a Leica TCR-705 Total Station for the purposes of verifying TLS data and filling the areas where the TLS could not penetrate, for example amongst dense vegetation or beneath the water surface. TLS data were processed first in Leica Cyclone software to remove points that were far above the ground surface, for example power lines and trees. The trimmed data were then processed in LAStools software in order to extract an inferred ground surface and thin the data to a density suitable for conversion to a digital elevation model (DEM). This process preserved the single lowest point within each cell of a 1 m^2 grid. The output from this process was then combined with total station point data in ArcMap 10.2 and a DEM was produced from these datasets. The DEM assisted in detailed geomorphic mapping and was used to interpolate cross-sectional and longitudinal profiles additional to those completed with the total station.

2.4 Sedimentology

Nine transects were established to investigate the sedimentary structure of the alluvial valley fill, covering sections containing ponds, intact flow paths and incised channels. Along these transects nine cores, seven hand augers and five bank exposures were used to analyse sedimentology. At two transects a total of three piezometers were installed so that subsurface water samples could be collected at a later date. Piezometers were made from PVC pipe with 50 mm diameter and with 3 mm horizontal slots to allow seepage of water into the pipe cavity. The tops of piezometers were capped and soil mounded around the surface of the core hole to prevent capture of rainwater or surface runoff into the piezometer. Coring was undertaken for detailed analyses using a GeoProbe® 54LT direct push mobile coring system. The probe used the DT22 sampling system with a 57 mm outer case and lightweight centre rods to minimise infill between pushes. Cores were retrieved inside PVC liners with integrated core catchers to ensure recovery in soft sediments. Hand augers were then used to correlate sedimentary layers between cores. Bank exposures were used, where available, to observe and sample sediments in-situ. Core samples were described and characterised in the laboratory. Grain size, sorting, rounding and mineralogy were determined using a hand lens, colour determined using a Munsell colour chart and facies descriptions completed according to Miall (1999). Augers were analysed in the field for grain size and characteristics, field texture and colour. Bank exposures were either analysed in the field or samples taken for analysis in the laboratory using the same techniques.

2.5 Organic matter content

Sub-samples from all cores and one bank exposure (H_BE1) were taken for measurement of organic content using the loss on ignition method (LOI). LOI was performed on 115 samples using a Lindberg Blue furnace. Samples weighing between 8 and 20 g (wet) were dried, weighed and crushed prior to ignition in 50 mL porcelain crucibles. Samples undergoing LOI were heated from 25 °C to 550 °C over 2 hours, held at 550 °C for 4 hours and then cooled to 105 °C over 2 hours. This approach has been used in peat forming swamp systems elsewhere in southeastern Australia (e.g. Fryirs et al. 2014a). Samples were then weighed immediately after removal from the furnace at 105 °C. Use of a desiccator was trialled; however, there was found to be no significant difference between weighing after removal at 105 °C and weighing after one hour in a desiccator. One batch of 24 samples was subjected to a second cycle of LOI to determine if the temperature and duration were appropriate to achieve complete removal of organic material. The difference in weight between a single cycle and two cycles was insignificant so a single ignition cycle was used for all samples.

2.6 Radiocarbon dating

Three charcoal and two bulk sediment samples were taken from bank exposure H_BE1 for AMS radiocarbon dating by Beta Analytic in the USA. Bulk sediment dating was used to date two sedimentary units because charcoal recovery was very low. Beta Analytic are a professional laboratory accredited under ISO/IEC 17025:2005. Samples were subjected to Acid/Alkali/Acid (AAA) and acid wash pre-treatments (Table 2.1). Charcoal samples were extracted by floating and dispersing in deionised water. At Beta Analytic, the samples were then washed with hot HCl acid to remove carbonates and then with NaOH to remove secondary organic acids. A final acid wash was used to neutralise samples before drying. Bulk sediment samples were dated using the bulk organic fraction. These samples were sieved to <180 µm to remove any roots or macrofossils and then neutralised using an HCl acid wash. Calibration of radiocarbon ages was completed by Beta Analytic using the 'SHCal13' database (Hogg et al. 2013) and the mathematical method of Talma and Vogel (1993).

Table 2.1: Summary of samples and treatments used for radiocarbon dating.

Sample	Depth from surface	Material type	Pre-treatment
CR_26	26 cm depth	Charcoal fragment (3.2 g)	Acid/alkali/acid
CR_38	38 cm depth	Charcoal fragment (2.2 g)	Acid/alkali/acid
CR_46	46 cm depth	Charcoal fragment (0.123 g)	Acid/alkali/acid
CR_70	70 cm depth	Bulk sediment (2.0 g)	Acid washes
CR_120	120 cm depth	Bulk sediment (2.0 g)	Acid washes

2.7 Surface and subsurface hydrology

Water samples from surface sources (ponds and incised channels) and from below the ground surface (using piezometers, see Section 2.4) were compared with rain water using analysis of stable isotopes $\delta^{18/16}O$ and $\delta^{2}H$ to determine relative roles of surface water and groundwater in contributing to flow. Surface water samples were collected using a 60 mL syringe mounted to a length of PVC conduit. Water samples were taken from a range of depths, always including one surface sample and one sample from directly above the pond floor. A total of 23 samples were taken from 11 locations. Subsurface water samples were taken from piezometers using the same syringe method as used in ponds. A total of 5 samples were taken from 3 piezometers. Water samples were analysed by the Australian Nuclear Science and Technology Organisation (ANSTO) using the Cavity Ring-Down Spectroscopy (CRDS) technique, which measures the rate of light decay in a mirrored cavity filled with the vaporised water sample (1.85 µL sample size pre-vaporisation). Quality control results for $\delta^{18/16}O$ and $\delta^{2}H$ were within one standard deviation of certified values for ANSTO standard reference materials (SRM) 'AILS-003' and 'AILS-012'.

2.8 Historical, archival research

Historical data were collected and analysed in order to construct an environmental history of land use dating from the arrival of Europeans in the region in the 1800s. Library searches were undertaken at the National Library of Australia, the Mitchell State Library of NSW, ACT Heritage Library in Canberra and the Goulburn-Mulwaree Library in Goulburn. Secondary accounts of local history were used along with first-hand accounts of the landscape made by early 'explorers'. Telephone conversations with a former landowner of Crisp's Creek, David Pockley, were also drawn on. Parish and county maps were obtained for years covering 1904 to 1933. These were used to identify changes in drainage line position and morphology where possible. Historical aerial photographs covering the study subcatchment from 1941, 1960, 1967 and 1998 were obtained from the National Library of Australia and NSW Local Land Services Southeast offices in Braidwood, NSW for the purposes of identifying river planform change over time. Contemporary (2014) aerial photographs were accessed via the NSW Land and Property Information portal, Spatial Information Exchange (http://six.nsw.gov.au). Aerial photographs were georeferenced in Esri ArcMap v10.2 and geomorphic mapping was undertaken for each timeslice in this software (n = 6).

2.9 Social research

Rehabilitation work undertaken at Crisp's Creek in partnership between Veolia and LLS provided an opportunity to examine an example of how management of a chain of ponds is enacted and to understand the human context of this system in addition to its physical morphology and history. Two telephone interviews were carried out with employees from these two relevant organisations (ethics approval reference no. 5201500083) in order to understand: **(i)** their knowledge and interest in chains of ponds; **(ii)** their role in the management and rehabilitation of the chain of pond under study; **(iii)** their motivations for undertaking rehabilitation; and, **(iv)** the wider organisational context within which river management occurs in this setting. One participant from each organisation was interviewed by telephone for 30-45 minutes in a semi-structured fashion. These interviews built on a longer personal engagement over a period of approximately 10 months prior to the interviews taking place. In this time, the researcher had been in contact with these participants throughout the implementation of the rehabilitation and undertaking of environmental monitoring at the study site. LLS were involved in this research as industry partners on the Australian Research Council (ARC) grant that partially funded this research (ARC Linkage Grant LP130100120; CIs K. Fryirs and G. Hose, Macquarie University).

Board members of the Pejar LALC, responsible for the area under study, were also engaged in order to understand: **(i)** their role in and conception of river management and environmental management more broadly; **(ii)** their understandings of chains of ponds as a river type; **(iii)** their knowledge of and interest in the specific site as well as the wider regional landscape; and, **(iv)** their perspectives on the way that environmental management decisions are made within their region of responsibility. Although the LALC had not been engaged by LLS or Veolia, they were asked to participate in this research so that a wider range of perspectives on river management more generally could be heard.

The social research approach taken in this thesis borrowed from work in ethnogeomorphology a focus on establishing dialogue through conversations on the geomorphic landscape as a way to build relationships between researchers and Indigenous participants (Wilcock and Brierley 2012). Principles of good Indigenous social impact assessment (SIA) research were adopted as an ethical benchmark because of their relevance in a situation where the process of research could have real social impacts on the people involved. These principles included: *intervention*, *empowerment*, *participation* and *negotiation* (O'Faircheallaigh 1999, Howitt 1993). Intervention refers to the consciously political work of this social research having an intention to improve relationships between the Indigenous participants and other environmental managers. This meant going beyond documentation of perspectives by seeking opportunities to assert these perspectives in a way that could affect change in management practice. Empowerment of participants in this research meant creating space for participants to decide how the research would proceed. This was done through participation and negotiation in and of the methodological approach.

The LALC were approached initially through the Elder-in-Residence at Macquarie University and then by telephone in order to request their involvement in the research. A face-to-face meeting at the LALC offices in Goulburn, NSW was then undertaken between the researcher and the Chief Executive Officer (CEO), Pejar LALC to negotiate how the research might proceed. An application to the Macquarie University Human Research Ethics Committee (MQHREC) was then submitted and approved (Reference No. 5201500083; details in Appendix). Research with the LALC first involved an informal site visit with two researchers and two members of the LALC board. This informal research approach was inspired by the process of 'talking whilst walking' (Anderson 2004) whereby talking on place is done in place and the act of walking together aims to both unsettle unequal power relations that may be present in a formal interview setting and to inspire conversation as participants and researchers see, hear and feel in the landscape together. The on-site conversations were guided by a schedule of themes developed in consultation with supervisors, the Elder-in-Residence and LALC members. Materials such as historical aerial photographs and sediment cores were also taken into the field to enhance and stimulate discussion. Following the site visit, the researcher followed up with one participant from the LALC through one semi-structured telephone interview, similar to those undertaken with participants from Veolia and LLS. This interview was able to take a more focused structure because it built on the personal relationship that had been established during the site visit and allowed the researcher to determine how participants had reflected on the field experience. All telephone interviews and conversations on the site visit were recorded and transcribed with permission from participants and copies of material provided to participants for correction and confirmation prior to publication.

Responses from all social research were analysed qualitatively to construct an understanding of the relationships between actors in management, including between participants and the physical environment they work in. This involved the researcher reviewing interview transcripts, identifying key themes from responses and reflecting on these responses as part of an emerging understanding of the social context. The approach was not designed to be statistically verifiable nor to represent the institutions or communities to which participants belonged. Rather, the aim was to ensure that the right individual people were being consulted, who had a personal involvement in the study site and its management, could assist the researcher in understanding some of the social context in which river management occurs and were interested in participating in the research. The historical circumstances of the Crisp's Creek sub-catchment produced a particular set of institutional interests and the approach adopted to understanding the social and cultural dimensions of the management system aimed to ensure the research engaged with these interests. The purpose was to ensure the scientific research on the geomorphic landscape was sensitive to critical cultural and economic dynamics in the system. This required engagement with questions of meaning rather than measurement and required engagement with qualitative reflective methods rather than quantitative analytical approaches. For the researcher, engaging with this reflexive approach was consistent with the expectations of critical geomorphic studies in sociogeomorphology and ethnogeomorphology, pursuing the understanding of more-than-human relationships in the sub-catchment to engage deeply with entwined human and natural (and more-than-human) relationships and processes.

3 Results

3.1 Contemporary morphology and hydrology

3.1.1 Morphology

Crisp's Creek is a chain of ponds inset into alluvial valley fill with discontinuous incision (Figure 3.1). The study site can be separated into three broad morphological sections. The upstream section had a relatively broad valley width (e.g. 101 m at Transect A; Figure 3.2b, Table 3.1) and incised channels that flow adjacent to swampy preferential flow paths. The mid-section (Transects B to C) largely comprised intact alluvial fill with a moderate valley width (e.g. 30 m at Transect E; Figure 3.2b, Table 3.1) and swampy preferential flow paths intermediate to occasional disconnected ponds. The downstream section (Transects C to I) had a narrow valley width (e.g. 18 m at Transect I; Figure 3.2b, Table 3.1) with very steep surrounding hillslopes. Here ponds were separated by either swampy preferential flow paths or incised channels, but rarely both. Valley width generally decreased downstream, from 101 m at Transect A to 18 m at Transect I. However, notable exceptions to this trend include Transects B and H, where bedrock spur and ridge orientation influence patterns of valley fill deposition. The longitudinal profile of the area surveyed with the Terrestrial Laser Scanner (TLS; Figure 3.2c) produced a valley slope value of 0.005 (measured over 956 m). In comparison, valley slope measured from a 1:25000 topographic map was 0.010 (measured over 1962 m, closest available contour markers). Although these slope values are both very low, the difference is significant. Given the high level of accuracy of the TLS and the greater measurement distance of the topographic map, the most likely explanation for this discrepancy is that the section of river surveyed with TLS may be a section of particularly low slope within a valley of generally greater slope as the watercourse nears its confluence with the Mulwaree River 3.3 km downstream of the study reach.

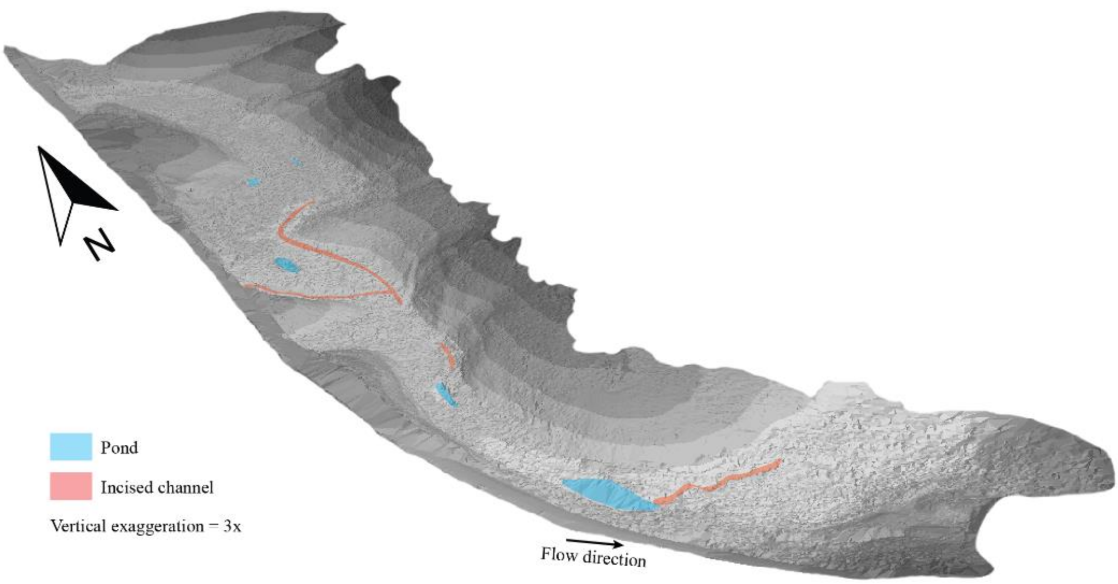

Figure 3.1: Annotated DEM generated from TLS data shows valley morphology and major geomorphic units.

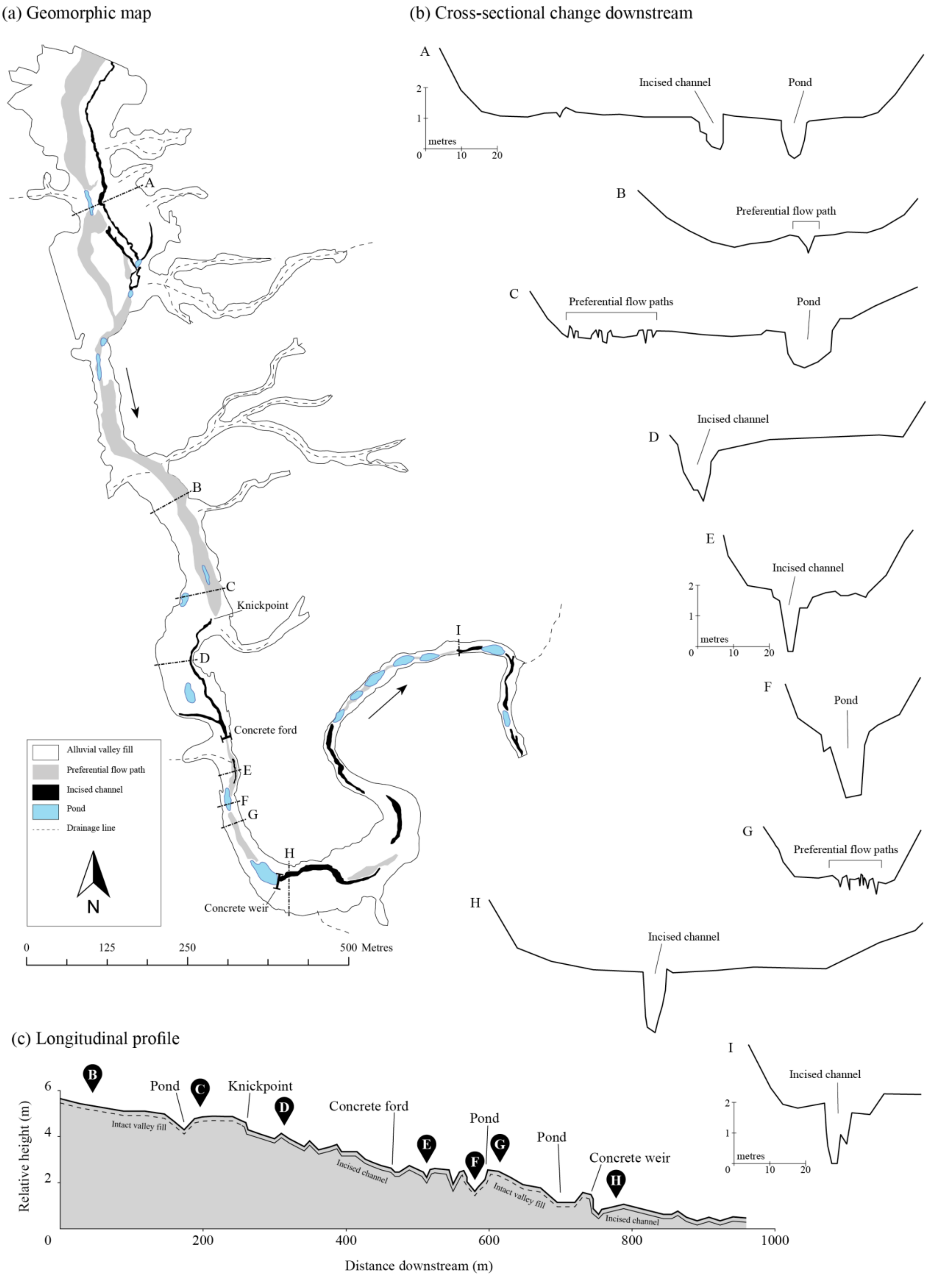

Figure 3.2: Valley morphology in Crisp's Creek. **(a)** Geomorphic map shows major geomorphic units: alluvial valley fill, preferential flow paths, ponds and incised channels; **(b)** Change in cross-sectional profile downstream shows a general narrowing trend in valley width with distance downstream; **(c)** High-resolution longitudinal profile of a portion of the study reach shows locations of transects, major morphological and structural features and qualitative assessment of geomorphic condition (intact vs incised valley fill). Valley slope was 0.005.

Table 3.1: Valley width and geomorphic unit geometry in each transect. Preferential flow paths width includes entire extent covered by flow paths, not individual threads. * denotes the dominant flow-carrying geomorphic unit.

Transect	Geomorphic units present	Valley width (m)	Preferential flow path width x depth (m) and area (m^2)	Pond width x depth (m) and area (m^2)	Incised channel width x depth (m) and area (m^2)
A	Incised channel* Pond	101	N/A	7.0 x 0.9 m **6.3 m^2**	6.3 x 1.0 m **6.3 m^2**
B	Preferential flow paths*	40	20.5 x 0.5 m **10.3 m^2**	N/A	N/A
C	Preferential flow paths* Pond	72	22.7 x 0.4 m **9.1 m^2**	14.0 x 1.1 m **15.4 m^2**	N/A
D	Incised channel*	58	N/A	N/A	10.5 x 1.5 m **15.8 m^2**
E	Incised channel*	30	N/A	N/A	10.0 x 1.4 m **14.0 m^2**
F	Pond*	15	N/A	12.5 x 1.8 m **22.5 m^2**	N/A
G	Preferential flow paths*	26	13.7 x 0.4 m **5.5 m^2**	N/A	N/A
H	Incised channel*	70	N/A	N/A	7.6 x 1.8 m **13.7 m^2**
I	Incised channel*	18	N/A	N/A	7.0 x 1.5 m **10.5 m^2**

The most common geomorphic units identified in Crisp's Creek were **(i)** alluvial valley fill; **(ii)** preferential flow paths; **(iii)** ponds; and, **(iv)** incised channels. Preferential flow paths are depressions in the alluvial valley fill, which may cover a large or small proportion of the valley floor but were typically very shallow (0.4-0.5 m; Table 3.1). Within the preferential flow path zone, flow was split into multiple threads around tussock grasses, producing a hummocky surface profile (Figure 3.3). During times of low flow, these multiple threads were either saturated at the surface or contained small amounts of standing water. Surface sediments were typically organic-rich fines combined with decaying organic matter. In intact sections of alluvial valley fill, preferential flow paths were intermediate to ponds, which were disconnected in low flow and connected by flow paths in high flow. Ponds were observed to retain surface water even in dry periods when connecting flow paths held no water (observations by researcher). Ponds were typically elliptical and elongate in shape with bed depths of between 0.9 and 1.8 m measured in cross-section (Table 3.1), or between 0.5 and 1.5 m lower in elevation than the base of connecting preferential flow paths (longitudinal section). Where intermediate sections featured incised channels rather than preferential flow paths the channel bed was typically at a similar elevation to pond beds (1.0-1.8 m; Table 3.1), ponds appearing as marginally deeper depressions within the channel bed or in some cases almost indistinguishable from the channel bed. Where ponds were connected by incised channels, they appeared unable to retain surface water, reflecting the more efficient flow path of the incised channel. Although incised channels had similar cross-sectional areas to ponds (ponds averaging 14.7 m^2 and incised channels averaging 12.1 m^2; Table 3.1), the continuity of the incised channels made them more efficient flow carriers than ponds. In many cases, the beds of incised channels were mostly bare except for some minor exotic grass cover. However, in some locations reed beds had formed instream, suggesting some degree of recovery from incision (see analysis of aerial photographs, section 3.3).

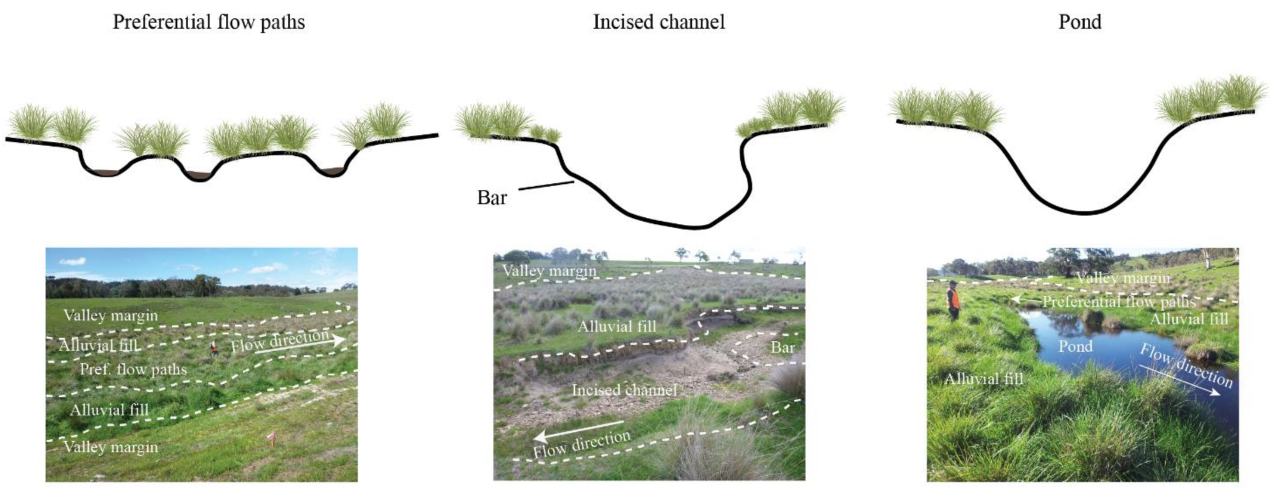

Figure 3.3: Schematic cross-section comparison with corresponding photos of preferential flow paths, incised channel and pond at Crisp's Creek.

3.1.2 Isotopic analysis of water

In the upstream section of the site, stable isotope ratios $\delta^{18/16}$O and δ^{2}H revealed no clear difference between samples from surface water sources (ponds and channels) and those from piezometers (sample points 1-7; Figure 3.4). These samples all fell near to the Local Meteoric Water Line (LMWL) for Canberra (Jacobsen et al. 1991), which is approximately 50 km southwest of the site. Similarity to the LMWL suggests little evaporation has taken place since the last flushing rainfall event, which was 15 days previous with 9 mm falling at Goulburn (Bureau of Meteorology 2015a). Although not clear enough to determine a pattern, the piezometer sample points 2 and 4 being further enriched along the LMWL than piezometer point 1 may have been influenced by valley position. Points 2 and 4 were located farther from the primary flow path and would be more likely to receive hillslope subsurface flows, whereas point 1 was located in the centre of a flow path and may receive more surface water flows, making this point appear more isotopically similar to the pond and incised channel sample points.

Some difference was apparent between samples from incised channels and those from ponds, with incised channels (sample points 5 and 6) showing greater variation within each sample point. Within incised channels the samples taken at depth (100 and 150 cm respectively) were in both cases more enriched than the samples from the surface (0 cm). This may indicate some degree of stratification, which may prevent more recent rainfall from reaching the deeper parts of the channel; however, a more targeted sampling program would be required to verify this difference and to determine its cause.

Samples from the more downstream section (sample points 8-14) followed a trend with R^2 = 0.99, distinct from the LMWL and increasing in enrichment with distance downstream. This suggests that the downstream-most water bodies are more evaporated, which may reflect length of time in residence and exposed to the atmosphere as surface water moves slowly between ponds in periods of low flow. The concrete weir below sample point 8 may have influenced this trend by inhibiting flow; however, again, the preliminary nature of this sampling program limits determination of cause.

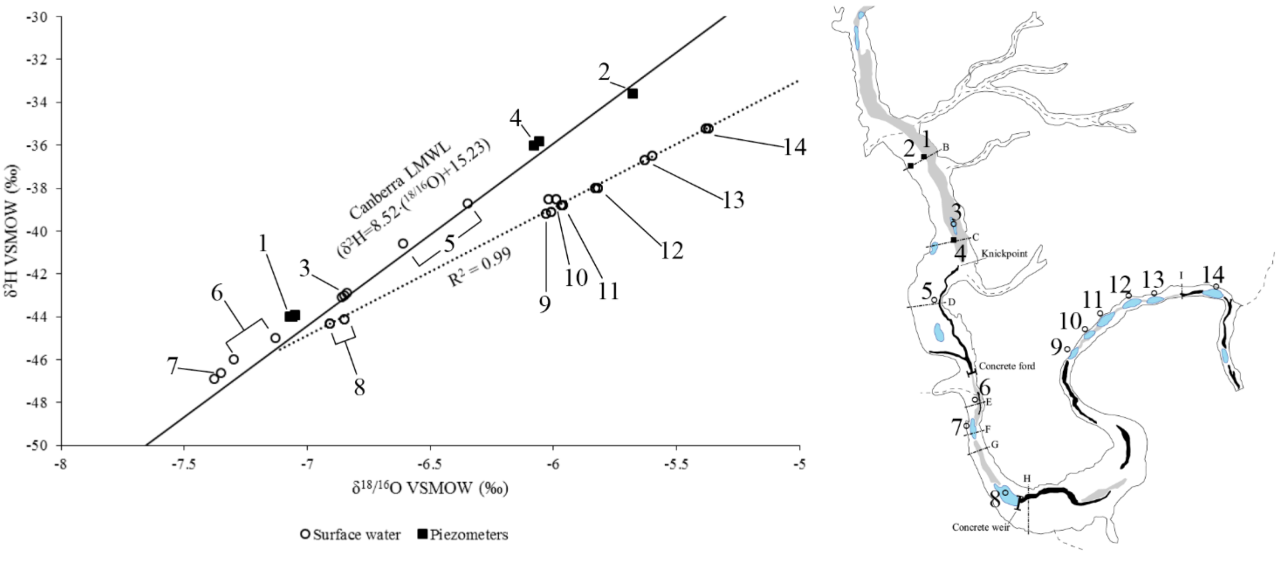

Figure 3.4: Stable isotopes $\delta^{18/16}O$ and δ^2H from surface water sources and piezometers reveal differing hydrology in the upstream vs downstream section (1-7 vs 8-14), the former being more similar to the LMWL (rainfall samples) and the latter becoming more enriched with distance downstream. Greater variability within locations at incised channels (5 and 6) compared with ponds suggests differences in hydrology due to geomorphology.

3.2 Sedimentology and age structure

3.2.1 Major sedimentary units

Sedimentological investigation reveals a relatively consistent sedimentary architecture throughout the study site, with some local variation in unit thickness and presence or absence of certain sedimentary units. Examples of the most common sedimentary classes appear in Figure 3.5 and Table 3.2. In the majority of transects, surface sediments were either organic-rich, dark coloured clays with decaying organics (average 13% LOI), or a buff-coloured sandy loam with lower levels of organics (average 6-13% LOI, lower value excludes samples with living organics at 0 cm depth). Whether surface sediments were organic-rich clays of buff-coloured sandy loams depended on contemporary process zone and location relative to incised channels. Organic-rich, swampy sediments containing decaying organic matter were common in cores taken within preferential flow paths where surface sediments were commonly saturated. Surface samples from areas with incised channels and an absence of intact preferential flow paths were more commonly buff-coloured loams or sandy loams. These buff-coloured loams typically overlayed organic-rich clays, which contained pedal structures and signs of bioturbation. The organic-rich clays graded into massive, grey-brown clays with a lower organic content (average 5 % LOI) or occasionally a layer of interbedded clays and sands followed by the massive, grey-brown clays. Massive, grey-brown clays commonly graded into red/yellow-mottled clays, which were similar but for prominent reddish or yellowish mottling. These fine sediments tended to overlay angular gravels of variable size; however, alternating clay, sand or gravel units were also common. Bedrock or saprolite, where reached by coring, was between 2 and 3.2 m below the surface.

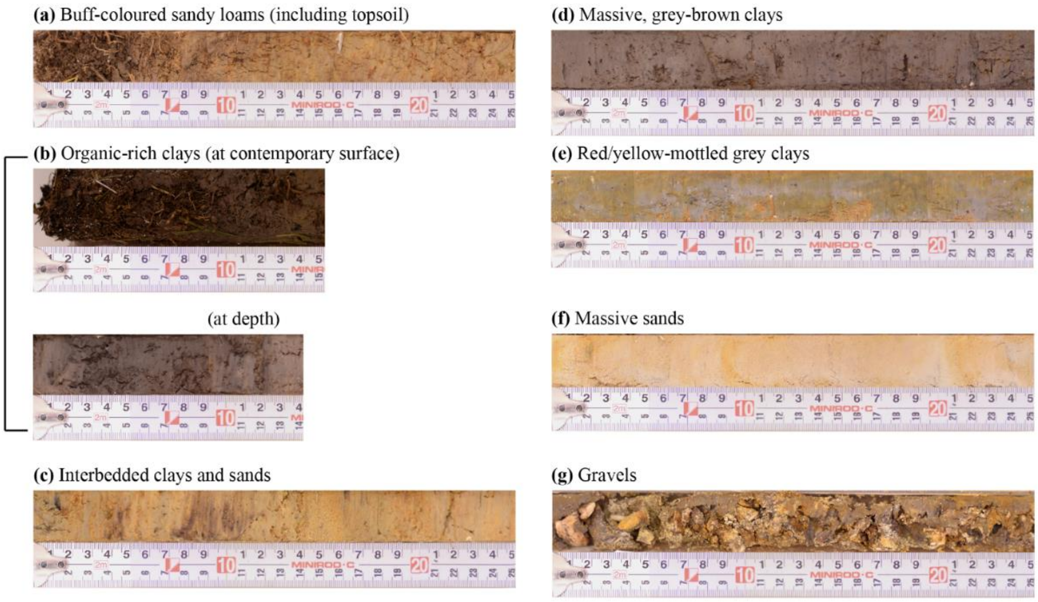

Figure 3.5: Photographs of sediment classes from representative sections of core. 'Organic-rich clays' includes those at the contemporary surface and at depth. Scale is in centimetres.

Table 3.2: Characteristics of sedimentary classes found at Crisp's Creek. Where there was more than one colour, both are given. *Organic content for buff-coloured sandy loams may be over-estimated due to inclusion of living organic material at surface. Lower value of 6% excludes all surface LOI samples.

Sediment Class	Average grain size (± range)	Facies code	Average % organics	Munsell colour
(a) Buff-coloured sandy loams	<4 Phi (<4 Phi-vcL)	Fine massive (Fm)	6-13 %*	10YR 4/4 "Dark yellowish brown"
(b) Organic-rich clays	<4 Phi (<4 Phi-mU)	Fine massive (Fm)	13 %	10YR 2/1 "Black"
(c) Interbedded clays and sands	<4 Phi (<4 Phi-mU)	Fine laminations/Sand massive (Fl/Sm)	3 %	Clay: 10YR 5/8 "Yellowish brown" Sand: 10YR 7/6 "Yellow"
(d) Massive, grey-brown clays	<4 Phi (<4 Phi - >50 mm)	Fine massive (Fm)	5 %	10YR 4/2 "Dark greyish brown"
(e) Red/yellow-mottled grey clays	<4 Phi (<4 Phi-100 mm)	Fine massive (Fm)	5 %	Matrix: 10YR 4/2 "Dark brownish grey" Mottling: 10YR 6/8 "Brownish yellow"
(f) Massive sands	mU (<4 Phi-30 mm)	Sand massive (Sm)	2 %	10YR 6/8 "Brownish yellow"
(g) Gravels	27 mm (<4 Phi-150 mm)	Gravel matrix supported (Gms)	3 %	Matrix: 10YR 5/2 "Greyish brown" Gravel: 10YR 6/8 "Brownish yellow"

3.2.2 Age structure of valley fill

Five AMS radiocarbon dates were processed from a single bank exposure in the lower section of the study reach (H_BE1 on Transect H; Figure 3.6). A sample from the base of the exposure (120 cm depth, immediately above water level in the incised channel) returned an age of 3680-3480 Cal. BP (Table 3.3). This sample was taken from a red/yellow-mottled grey clay unit found consistently throughout the study site. The unit above (at 70 cm depth), which was a massive, grey-brown clay unit, returned an age of 1430-1315 Cal. BP. The organic-rich clay unit above this (at 46 cm depth) returned an age of 275 to Modern Cal. BP and two samples from the buff-coloured sandy loam unit above (at 38 and 26 cm) returned ages of 265-Modern and 295-Modern Cal. BP respectively, potentially placing these units within the period following European arrival in the region around 1820 AD. The distribution of ages with depth was linear, except for the uppermost two samples, CR_26 and CR_38, for which calibrated ages overlapped (Figure 3.6). This may have been due to modern reworking at the surface.

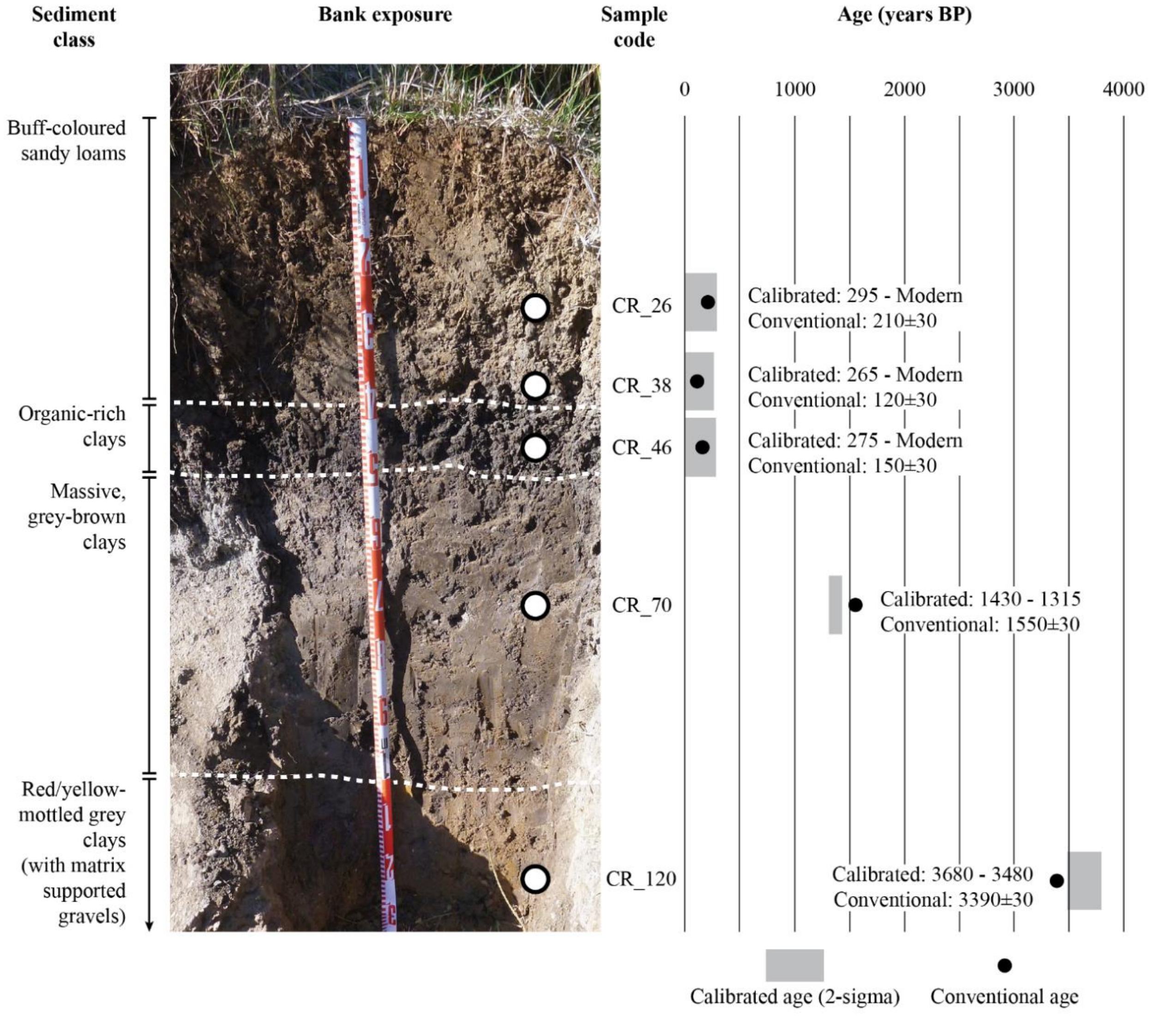

Figure 3.6: Five samples from bank exposure H_BE1 were dated using radiocarbon. Boundaries between sediment classes are shown along with locations of samples. Scale in photograph shows depth in centimetres (20 cm per red or white bar). Ages are distributed linearly with depth, except for the uppermost two (CR_26 and CR_38); however conventional ages for these samples overlap. Detailed analysis of profile sedimentology appears in Figures 3.7h and 3.8i.

Table 3.3: Ages obtained from bank exposure H_BE1.

Sample ID	Depth from surface	Material type	Sediment class	2-σ calibrated age (yrs)	Conventional age (yrs)
CR_26	26 cm	Charcoal	Buff-coloured sandy loam	295-Modern	210±30 BP
CR_38	38 cm	Charcoal	Buff-coloured sandy loam	265-Modern	120±30 BP
CR_46	46 cm	Bulk sediment	Organic-rich clays	275-Modern	150±30 BP
CR_70	70 cm	Bulk sediment	Massive, grey-brown clays	1430-1315 BP	1550±30 BP
CR_120	120 cm	Bulk sediment	Red/yellow-mottled grey clays with matrix-supported gravels (inferred transition to basal gravel)	3680-3480 BP	3390±30 BP

3.2.3 Detailed sedimentology by transect

3.2.3.1 Transect A

Transect A featured a pond near the right valley margin and an incised channel nearer the centre of the valley (Figures 3.7a and 3.8b). This transect contained a sequence of sediment classes typical for Crisp's Creek. Surface sediments were buff-coloured sandy loams, which ranged from 25 to 75 cm thickness, thinning toward the right valley margin. Beneath this layer was an organic-rich clay layer that extended across the majority of the valley width but was absent on the right side of the valley, where the pond bank instead revealed two prominent matrix-supported gravel layers with b-axes 2-100 mm in the uppermost layer and 5 mm in the lower layer. The matrix for the upper gravel layer in A_BE1 was a massive, grey-brown clay unit, whereas the lower gravel layer marked the boundary between these massive, grey-brown clays and red/yellow-mottled grey clays. These clay units, most prominently the massive, grey-brown clays, extended across the valley floor in a layer approximately 80 cm thick and into which the incised channel and pond were set. Underneath the clays were basal gravels with dominant b-axes of 20 mm. On the far left margin massive, grey-brown clays and basal gravels were separated by a thin (20 cm) unit of medium sands containing minor gravels to 30 mm. Bedrock could not be reached in this transect.

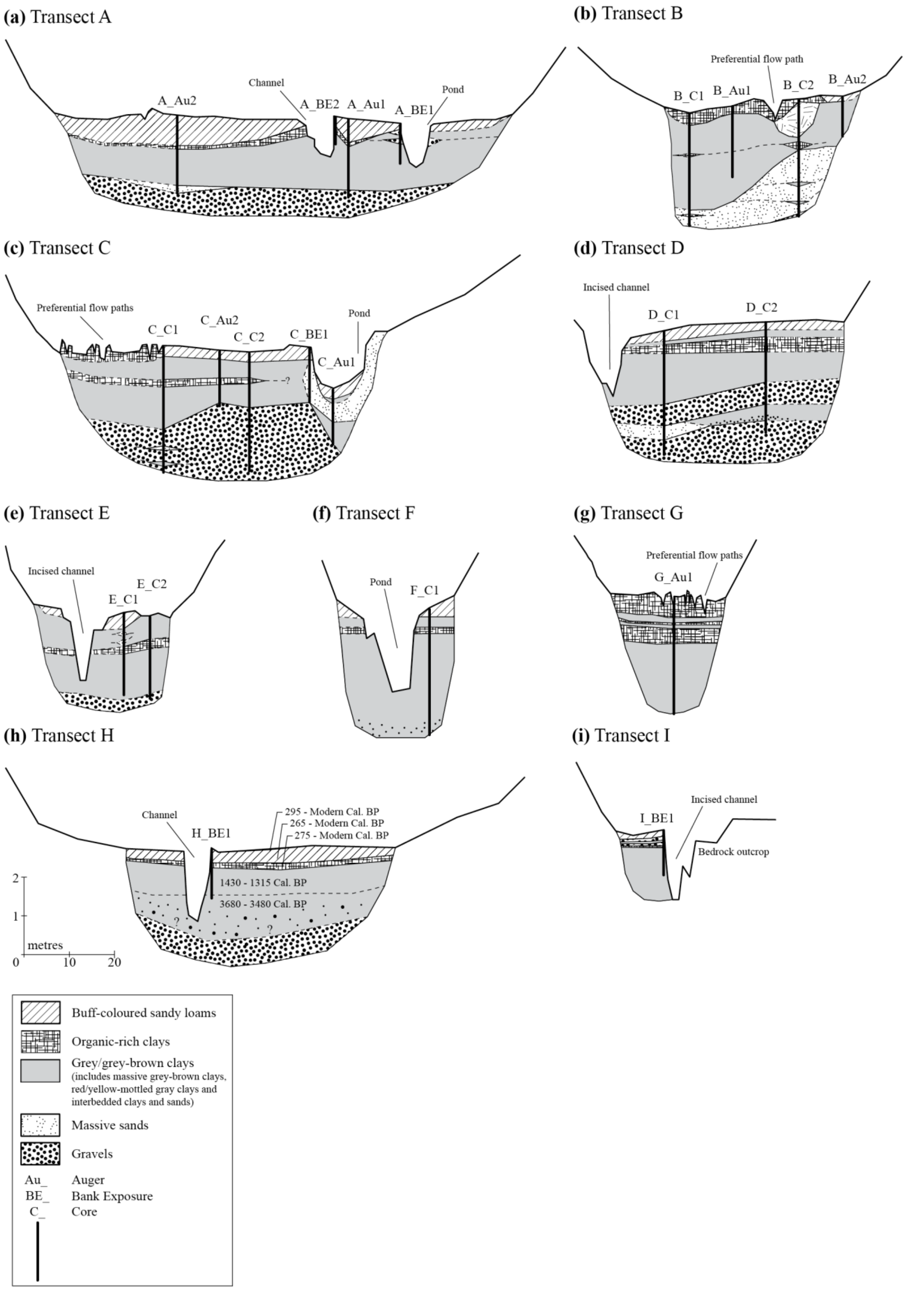

Figure 3.7: Correlated sedimentological cross-sections. Detailed sediment columns appear in Figure 3.8.

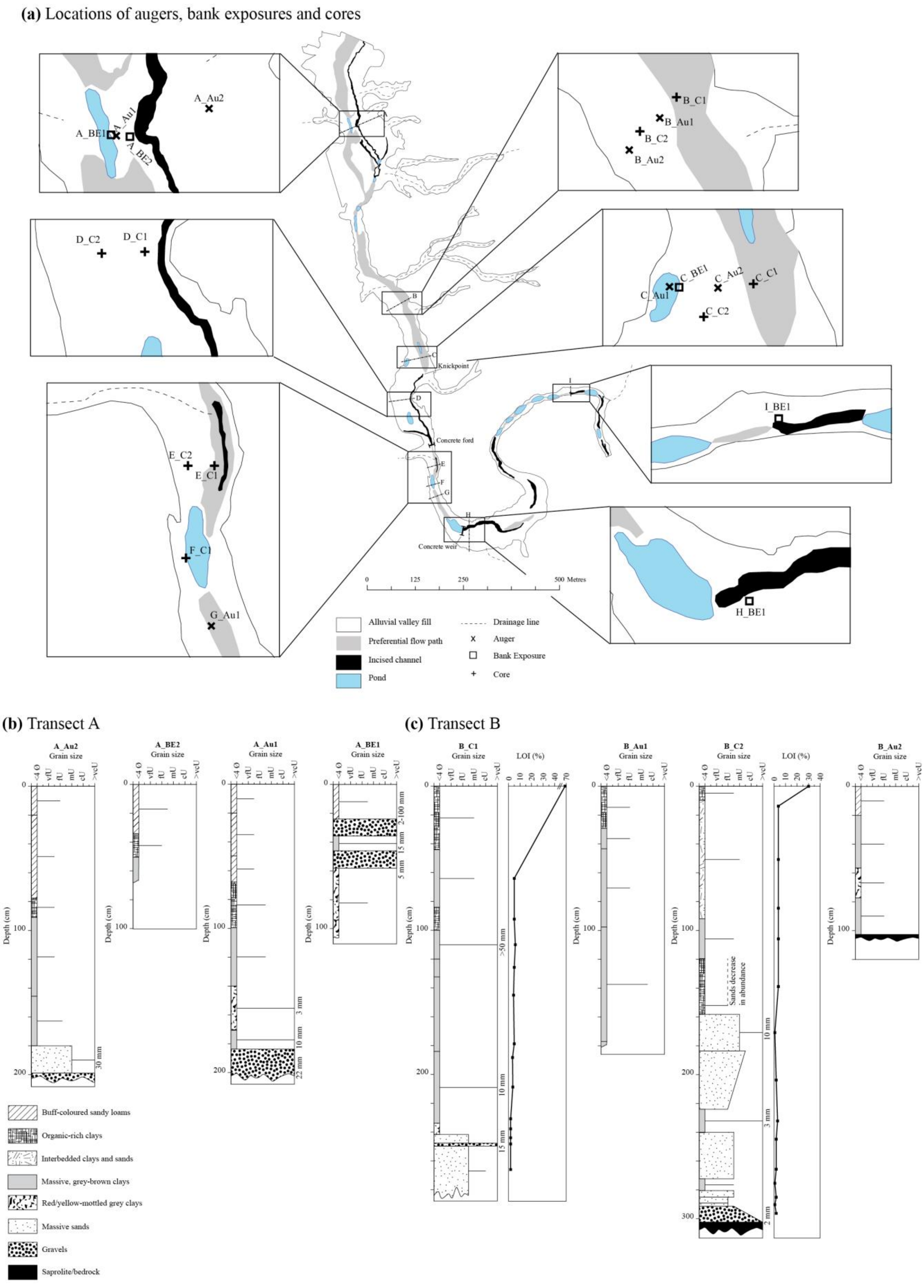

Figure 3.8: Detailed sediment columns for bank exposures, augers and cores, including LOI results where applicable.

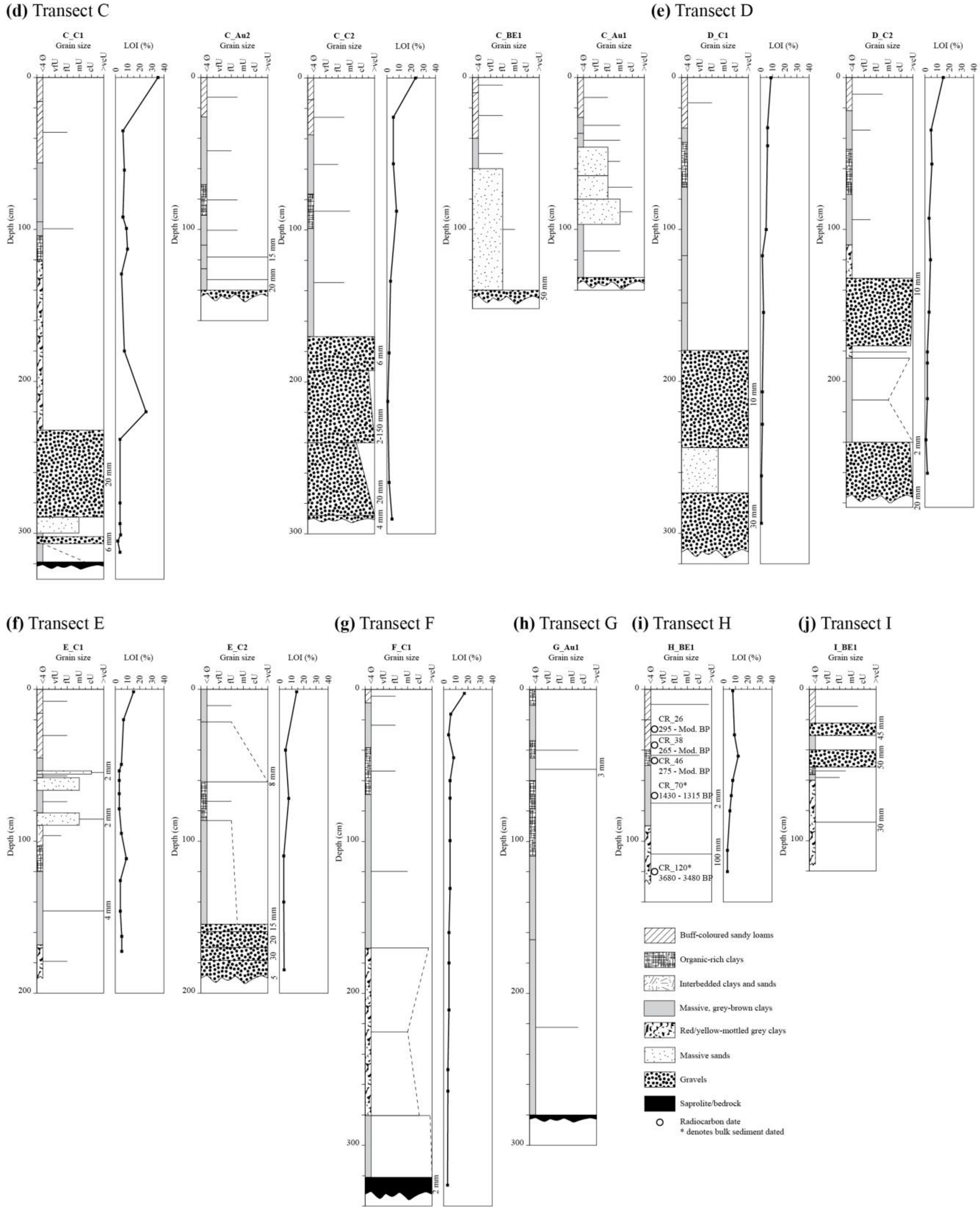

Figure 3.8: (continued over from previous page)

3.2.3.2 Transect B

Transect B featured preferential flow paths, which covered the majority of the alluvial valley floor (Figure 3.7b). Surface sediments were organic-rich clays (30-70% organics) to a thickness of between 10 and 45 cm, thickening around the centre and left side of the alluvial fill surface. Organic content dropped sharply to <10% below the surface of the profile. Underneath the organic-rich clays were massive, grey-brown clays toward the left margin and interbedded clays and sands toward the right margin, 40 and 80 cm thick respectively. Underneath these layers was another organic-rich clay layer (although <10% organic content this layer was heavily stained), which was found across the valley but not towards the centre; however, textures here were similar (Figure 3.8c) and hand augering may have destroyed evidence of the colour change in B_Au1. Massive, grey-brown clays that underlaid the second organic-rich clay layer were asymmetrical in thickness, being 130 cm thick on the left margin and absent on the right margin. This difference appeared to be due to a stacked sequence of massive sands with some massive, grey-brown clays, which was 140 cm thick on the right margin and only 40 cm on the left margin. Basal gravels with b-axes of 2 mm (10 cm thick) directly overlayed bedrock at 300 cm depth.

3.2.3.3 Transect C

Transect C featured preferential flow paths covering the left margin of the alluvial valley fill surface and a pond on the right margin, separated by alluvial valley fill (Figure 3.7c). The pond at Transect C was not connected to any prominent flow path and was observed to be dry on a number of occasions. A 25-55 cm thick layer of buff-coloured sandy loam dominated the valley surface between the flow path and pond although this layer was not observed at the surface of the preferential flow path or on the right bank of the pond. Underneath these surface layers were massive, grey-brown clays, which extended across the majority of the valley and were underlain by an organic-rich clay layer (7-9% organics) of approximately 20 cm thickness. Massive, grey-brown clays and red/yellow-mottled grey clays extended underneath this layer with a thickness of 50-110 cm, beneath which were basal gravels with b-axes of 4-150 mm and mixed with thin massive sandy and massive, grey-brown clay layers toward the left margin. Bedrock was reached at 320 cm. Sedimentary layers surrounding the pond (C_BE1 and C_Au1; Figure 3.8d) did not correspond well with the majority of the valley, comprising mostly massive sandy units above which some massive, grey-brown clays and buff-coloured sandy loams had infilled. Underneath the massive sands (50 cm thickness, ranging fine to coarse) were massive, grey-brown clays (35 cm thickness) followed by basal gravels.

3.2.3.4 Transect D

Transect D was located at a bedrock spur that alters the orientation of the valley fill (Figure 3.7d). At the left bank an incised channel abutted the bedrock spur. Sedimentary units were consistent across the valley, the surface of which consisted of buff-coloured sandy loams 20-35 cm thick, thickening toward the incised channel. A thin massive, grey-brown clay layer separated the loams from a 20 cm thick organic-rich clay layer (5-6% organics), underneath which was a thicker layer of massive, grey-brown clays and red/yellow-mottled grey clays (55-110 cm thick). Gravels with b-axes of 10 mm underlaid the clays to a thickness of 40-60 cm, underneath which were fine massive sands on the left side of the valley grading to sand-and-gravel-rich red/yellow-mottled grey clays and massive, grey-brown clays toward the right valley margin. Gravels with b-axes of 20-30 mm and 40 cm thick prevented cores from reaching bedrock.

3.2.3.5 Transect E

Transect E was located immediately downstream of a small concrete ford (date of construction unknown). A deeply incised channel flowed along the left side of the valley fill (Figure 3.7e). Buff-coloured sandy loams covered the surface of the alluvial valley fill closer to the incised channel, whereas the right side of the valley fill surface consisted of massive, grey-brown clays, which extended to 60 cm depth and included small gravels (b-axis 8 mm) toward the base of the unit. Loams at the surface closer to the incised channel were underlain by a complex set of massive, grey-brown clays and massive sandy sediments, followed by interbedded clays and sands. A valley-wide organic-rich clay layer (7-9% organics) underlaid these sediments with a thickness of 15 to 25 cm. Massive, grey-brown clays and red/yellow-mottled clays underneath the organic-rich clays extended 70 cm before reaching basal gravels (30 cm thick, 5-30 mm b-axes) on the right side of the valley. Basal gravels were not reached closer to the incised channel and bedrock could not be reached with either core.

3.2.3.6 Transect F

Transect F featured a two-metre deep pond inset near to the centre of the valley (Figure 3.7f). Buff-coloured sandy loams at the surface (8 cm thickness) were underlain by a thin layer (25 cm) of massive, grey-brown clays. These clays covered a 25 cm thick layer of organic-rich clays (5-8% organics), underneath which was a 100 cm thick layer of massive, grey-brown clays. Beneath this was a red/yellow-mottled grey clay layer, which was 110 cm thick and contained coarse sands. The basal unit was a massive, grey-brown clay unit, which graded to a gravel-rich (2 mm b-axis), grey-brown clay toward the base of the unit. Bedrock was reached at 320 cm.

3.2.3.7 Transect G

Transect G featured an intact preferential flow path comprising the majority of the alluvial valley fill surface (Figure 3.7g). The stratigraphy consisted of three separate layers of organic-rich clays in the top 110 cm, including a contemporary swampy surface, each separated by massive, grey-brown clays with occasional gravels (3 mm b-axis) included in the massive clays near the surface. A 170 cm thick massive, grey-brown clay unit extended to 280 cm, where bedrock was reached.

3.2.3.8 Transect H

Transect H was located immediately downstream of a concrete weir (constructed ca. 1990; D. Pockley 2015 *pers. comm.*), which impounded the largest pond in the study reach (Figure 3.7h). Deep incision had occurred downstream of the weir in the form of a continuous channel (7.6 m wide x 1.8 m deep), which was observed to hold some surface water in the lowest part of the channel. H_BE1 was exposed in the bank of this incised channel to a depth of 125 cm. The exposure comprised examples of the most common upper sedimentary units: superficial buff-coloured sandy loams (40 cm thick) followed by organic-rich clays (12% organics, 10 cm thick). Massive, grey-brown clays (40 cm thick) then overlaid red/yellow-mottled grey clays (35 cm thick). The lower unit (mottled clays) contained matrix-supported gravels of highly variable calibre (up to 100 mm b-axis) distributed throughout and increasing in abundance with depth. No clear clast size to depth relationship could be determined. The basal gravel lag in Figure 3.7a was inferred because of its presence in similar cross-sections and because of the increasing abundance of gravels in the lower section of this exposure.

3.2.3.9 Transect I

Transect I was located in the most downstream section of the study reach, which was confined by a very narrow bedrock valley (Figure 3.7i). I_BE1 was exposed in an incised channel (7 m wide x 1.5 m deep) immediately downstream of a bedrock outcrop. The channel featured a pool at the upstream end of the channel, likely the result of high energy flow from the bedrock step above and immediately upstream. Buff-coloured sandy loams at the surface (20 cm thick) were underlain by an 8 cm layer of matrix-supported gravels with b-axis 45 mm. This gravel layer was separated from a further, 10 cm thick gravel layer (b-axis 50 mm) by a thin (10 cm) layer of massive, grey-brown clays. Beneath the gravels were a very thin (5 cm) organic-rich clay layer followed by a 5 cm thick massive, grey-brown clay layer. These layers were underlain by a red/yellow-mottled grey clay layer that was 55 cm thick and contained gravels (up to 30 mm b-axis) increasing in abundance with depth, similarly to the pattern seen at Transect H. Water levels in the incised channel prevented this exposure from extending deeper.

3.3 Analysis of parish maps and aerial photographs

Geomorphic adjustment was mapped for six timeslices over 110 years provided by aerial photographs and parish maps covering the years 1904, 1941, 1960, 1967, 1998 and 2014 (Figure 3.9). The 1904 parish map indicated that the position of the reach’s overall primary flow path within the valley has not changed significantly since that time. Aerial photographs from 1941 provided more detail and demonstrated that the extent of geomorphic changes since this time have been minor, the study reach remaining a recognisable chain of ponds. Overall the time series depicted here suggests that the study reach has been recovering from an early period of discontinuous incision, eroded sediments now being stabilised by instream reed beds in sections of incised channel downstream of knickpoint heads. For example, in 1941 an incised channel can be seen connected to the upstream-most pond. However, by 1960 the two were disconnected and in 2014 the pond, which lies on Transect A, was situated in a shallow preferential flow path completely disconnected from the adjacent incised channel. The channel that previously connected the pond to the main incised channel had infilled to the extent that it was difficult to identify from the 2014 aerial photographs. A similar sequence appeared to have occurred approximately 200 m downstream of this point, where an incised channel seen connecting a pond in 1960 was replaced by a preferential flow path with no visible channel by 2014. These examples suggest some recovery from initial incision has occurred in the upper section of the reach.

In the lower half of the study reach the only significant geomorphic changes appeared to be associated with anthropogenic structures. First, a forked knickpoint that developed prior to 1941 has continued to retreat upstream towards an intact pond and section of preferential flow path near Transect C (Figure 3.10). Measurements made in GIS indicated that this knickpoint has retreated approximately 30 m since 1941 and appeared to have originated near the present position of a concrete ford. From the construction of the ford it appears that it was in place prior to the incised channel forming. Figure 3.11 shows the active head of the knickpoint in 2015, which appeared to be retreating up through multiple preferential flow paths. Immediately downstream of the knickpoint, tussock grasses could be seen, around which sediments had been eroded. In the distance, reeds were visible. Since 1941, dense reedy vegetation has colonised the bare gullies visible in Figure 3.10, suggesting that some degree of recovery has occurred with stabilisation of bare sediments. The road pictured in Figure 3.10 was realigned and upgraded sometime between 1967 and 1985. The new route encroached on the right-side (right bank) fork of the knickpoint gully and may have contributed to its arrest relative to the left fork. At present there is little evidence of the gully alongside the road, which was built up on the floodplain. Second, further downstream near Transect H a concrete weir was installed around 1990 (D. Pockley 2015 *pers. comm.*) in order to hold back water and sediments in the large pond upstream (Figure 3.12). Since that time, there has been further incision downstream of the weir and the incised channel directly below the weir now measures approximately 2 m deep. The weir consists of a horizontal slab of concrete at the base of the pond perpendicular to the direction of flow along with a concrete ramp running downstream in the direction of flow. Sediments surrounding the concrete ramp have eroded over time; however, as in other incised channels, reed beds have colonised sediments in-channel and appear to be playing a stabilising role (Figure 3.13).

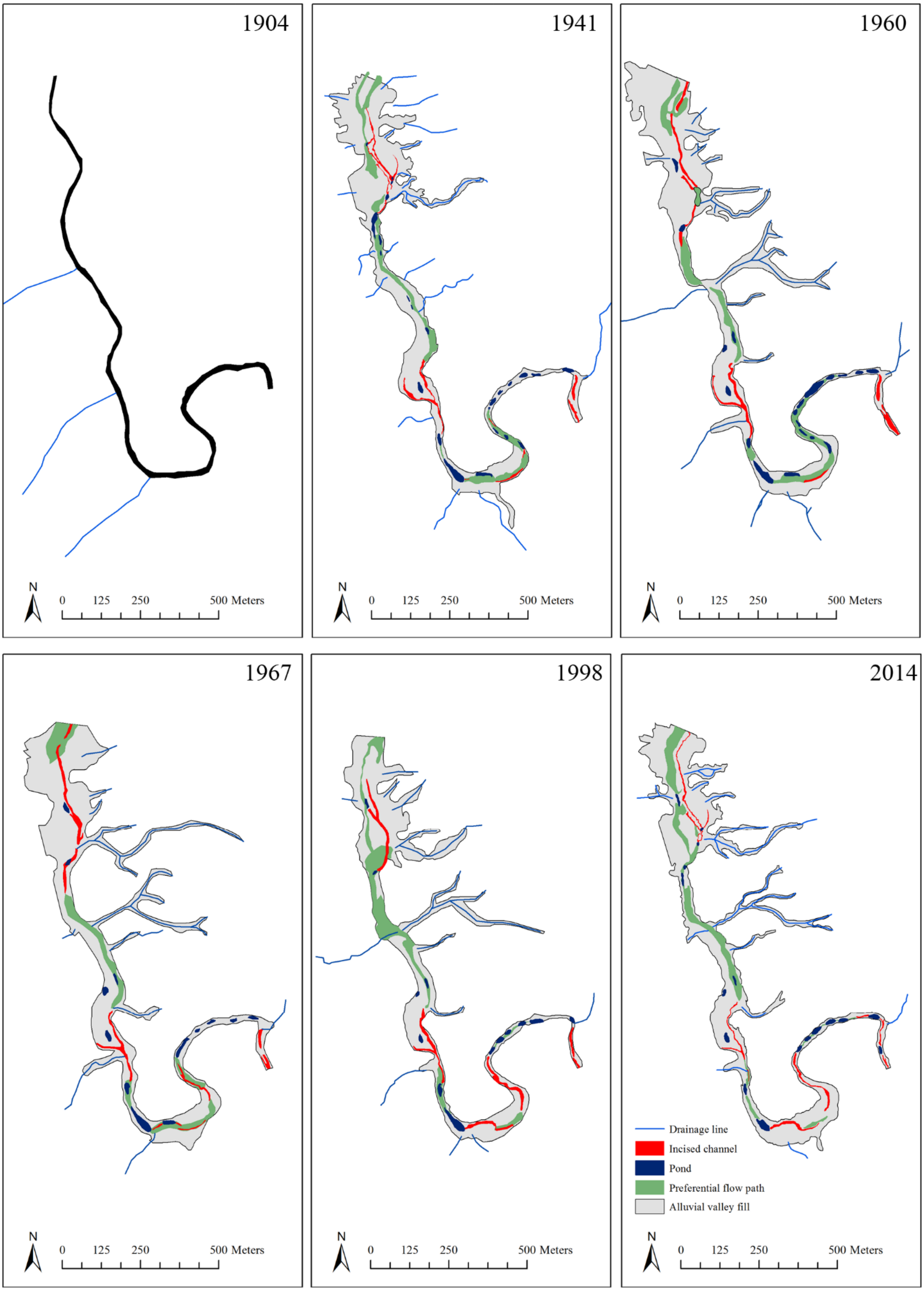

Figure 3.9: Geomorphic adjustments over six timeslices from 1904 to 2014. The majority of change appeared to be in condition, i.e. increasing incision and readjustment of flow path size and position, rather than large-scale planform change.

Figure 3.10: The knickpoint shown here remains active and has retreated approximately 30 m since 1941. Some stabilisation of sediments downstream of the knickpoint has also taken place with the appearance of reed beds.

Figure 3.11: In the upstream direction, the face of the knickpoint can be seen along with the preferential flow paths that are being eroded by the knickpoint. Downstream, tussock grasses can be seen, around which preferential flow paths have incised much deeper than in the intact flow paths upstream. In the distance, reeds can be seen, which appear to be stabilising older gullies.

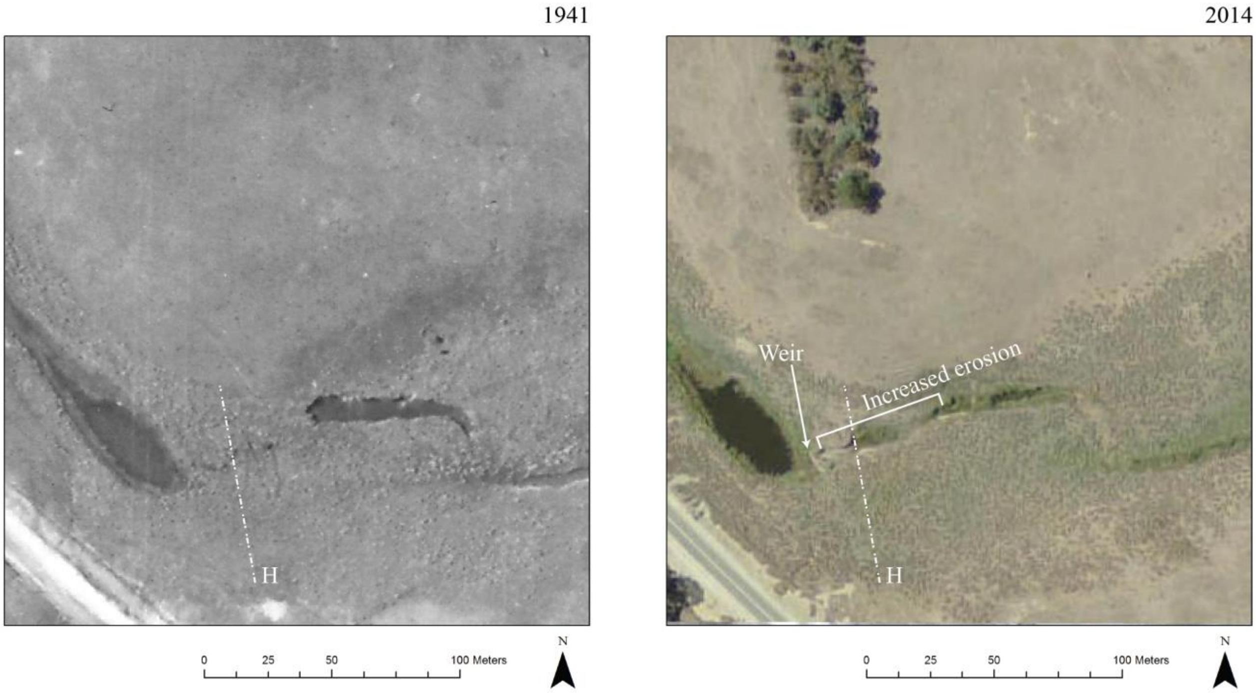

Figure 3.12: Since installation of a concrete weir around 1990, incision has continued downstream of the large pond pictured. However, some of the sediments eroded from this channel appear to have been stabilised by reed beds downstream.

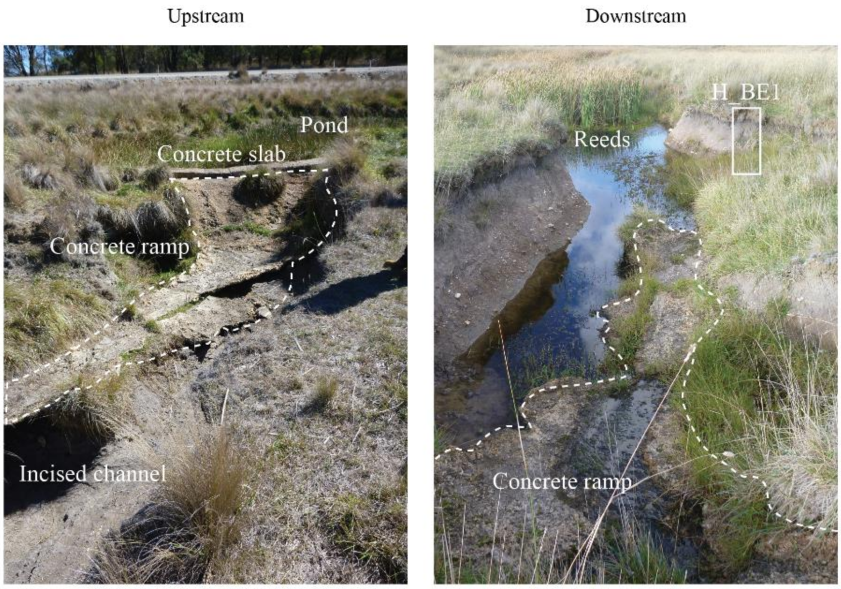

Figure 3.13: Concrete weir and concrete ramp viewed upstream and downstream. Sediments surrounding the ramp have eroded and incision has occurred downstream to approximately 2 m depth. Locations of H_BE1 and some instream reed beds can be seen in the downstream photograph.

3.4 Contemporary environmental management context

Social research was undertaken to understand the contemporary environmental management context for Crisp's Creek's rehabilitation. Responses have been organised into three main themes that are relevant to the management of Crisp's Creek: **(i)** participants' perceived roles in the management of rivers and the broader environment; **(ii)** participants' goals for the management of rivers and the broader environment; and, **(iii)** participants' knowledge of chains of ponds as a river type and how they came to develop that knowledge.

3.4.1 Role in river management as perceived by participants

The participant from LLS described their role as being primarily twofold: **(i)** delivering funding incentives to landowners for interventions aimed at improving the condition of the landscape, including fencing creeks, planting trees and controlling weeds in riparian zones and providing alternative sources of stock water, all with the goal of controlling erosion and improving ecological function; and, **(ii)** training and educating landowners in practices that can improve and/or protect the condition of the landscape, including provision of grazing management advice. The participant explained that, since 'Catchment Management Authorities' became 'Local Land Services',

> "We're still (more or less) doing exactly the same work as before, but we are trying to improve the way we connect with and increase the knowledge of the landholders. This will hopefully develop the relationships we have with our landholders, enable a knowledge sharing relationship and encourage them to utilise our services when needed" (LLS participant 2015).

The participant from Veolia (the landowners of Crisp's Creek) described their role as having responsibility for issues of environmental compliance (monitoring of water quality and other environmental indicators as required by the NSW Environmental Protection Authority (EPA) pollution licencing system), health and safety matters and operation of sustainability initiatives such as an on-site aquaculture facility. Coordination of the Crisp's Creek rehabilitation project, along with other native planting projects undertaken previously, was described as a non-core function reflecting a personal interest in environmental restoration,

> "The restoration sort of projects are just additional [to many other responsibilities] but are of personal interest to me and I try to fit it in with that [other work]. Also from the sustainability side of it, I was involved with a sustainability steering committee for NSW and that group's interested in undertaking restoration works on Veolia sites around NSW and therefore Woodlawn's a good option for that. It's a 16000 acre farm and there's plenty of opportunities around the place for that" (Veolia participant 2015).

In developing the Crisp's Creek rehabilitation project, the Veolia participant worked with the participant from LLS to identify potential sections of river for rehabilitation and to coordinate the project's implementation.

The participant from the LALC identified their role in land management as largely pertaining to the acquisition and management of vacant crown land as provided for by the *Aboriginal Land Rights Act 1983* (NSW). In the Pejar LALC area, the majority of land acquired is preserved,

> "Because it's natural bushland it just stays that way" (LALC participant 2015).

Another role of the LALC is to consult on matters of cultural heritage, particularly where physical artefacts have been found on a site of development. However, the LALC participant felt this was a narrow view of their responsibility, to 'care for Country',

> "We don't get called in. Like most of the time it's just for Aboriginal heritage … They [landowners, developers and government] see us as just there for the artefacts … But we're not, we're there for the whole Country. Caring for the whole of the Country, not just for our artefacts" (LALC participant 2015).

The LLS participant confirmed that LALCs are usually only engaged as part of a rehabilitation project where a search of the Aboriginal Heritage Information Management System (AHIMS) returns previous artefact finds within the specified area.

> "Whenever we start a project we conduct an AHIMS search. If the search returns results we contact the Local Aboriginal Land Council and ask if they would like to inspect the site further. Our Cultural Aboriginal Communities officers work a lot closer with the LALCs than I do" (LLS participant 2015).

Although the area managed by the LALC is not necessarily the traditional Country of those LALC members, the LALC participant described a sense of responsibility to care for all Country,

> "Whether it's my, you know, link, it's still part of the Country … it still has to be looked after" (LALC participant 2015).

The LALC participant expressed a desire to see more involvement of Indigenous people in environmental management,

> "For instance, they've got a group of people in Orange [a town in NSW] … doing the traditional burn offs so they can go around to people's land and get rid of the tussock [grass] … or whatever is growing there that is not natural, native, so that the native grasses can come back through … but we'd have to have the support from other organisations as well" (LALC participant 2015).

3.4.2 Goals for river management and rehabilitation

Participants from LLS and Veolia were asked about their goals for the rehabilitation project at Crisps Creek and all participants, including the LALC, were asked about their goals for river rehabilitation more generally. A common response was a desire to return landscapes to a more ‘natural’ condition, more similar to the landscape prior to the arrival of European people in the area in the 1800s. The LLS participant initially offered an idealistic pre-European condition but then settled on a more pragmatic position,

> “Repairing a riparian ecosystem that looked and functioned similar to that of pre-European settlement conditions would be my pie in the sky dream. But being realistic I guess having a healthy riparian buffer that is anywhere from 20-40 m wide would be great. It would have to include all levels of the ecosystem, tall storey, mid storey and native grasses so that it can actually improve the water that is entering and leaving the system. Having water that enters the buffer zone laden with sediment and nutrients and leaves as clean water, to me, is a riparian ecosystem that everyone should aim for. Having said this though, creating large buffer zones can be very unrealistic as farmers can potentially lose productive ground. Therefore, the healthiest landscape I would aim for (and have seen a few examples of) is one where the water which enters the riparian zone is already good quality” (LLS participant 2015).

The participant from Veolia identified improved vegetation cover and water quality as goals,

> “I recognised that that area had been farmed extensively and there isn’t really much vegetation in that area at all, and there’s quite a lot of potential there … downstream … for erosion and from the LLS point of view, that’s something they’re trying to control to improve water quality” (Veolia participant 2015).

On the goals of rehabilitation and management more generally, the LALC participant appealed to an idea of ‘naturalness’,

> “I think it’s just putting it back to its natural state … there used to be all different kinds of birds in Goulburn and they’ve just disappeared, like their habitats … It’s just basically putting it back to its natural state, like looking after… if you look after the land it’ll look after you … it’s basically preserving, or replanting trees where it’s eroded to stop more erosion” (LALC participant 2015).

3.4.3 Knowledge transfer and recognition of chains of ponds

In characterising the social and organisational context in which river rehabilitation occurs, it is important to understand how knowledge about rivers is transferred and used to bring about change. For all participants, personal communications helped participants to recognise the importance of chains of ponds. The LLS participant first became aware of chains of ponds as a distinct and significant river type due to their special designation in spatial datasets owned by the State Government and then through conversation with colleagues,

> "I was tasked with creating a rating sheet to allow us to rate each project so we had a benchmark to work to determine funding allocations for each project. I was using the River Condition Index and River Styles mapping layers to determine catchments with healthier ecosystems that we could focus on. During this I noticed 'chain of ponds' was the only specifically attributed river type. I asked my colleague, who had completed a River Styles[1] training course … and discovered that these were highly fragile ecosystems, which were few and far between. I used the chain of ponds river style as a rating factor. This ensured that if a landholder had these ecosystems on their property and wanted to protect them, they would receive a higher rating and have a greater chance of protecting these fragile and 'threatened' ecosystems" (LLS participant 2015).

Since then, the participant has undertaken geomorphological training including content on chains of ponds,

> "Since completing the River Styles course I learned about how variable these ecosystems are, of which [many] have been damaged across the landscape. There are still large knowledge gaps on how they actually formed (sediment movement and trapping) and how they exist [as] deep pools that can sometimes have variations of fish species between adjacent pools" (LLS participant 2015).

In turn, the participant from Veolia was alerted to the significance of chains of ponds by the LLS participant when they were undertaking an assessment of the study river and selecting potential sites for rehabilitation,

> "Originally I had [LLS participant] come out to look at another site … and there was a lot of stream bank erosion along the Mulwaree River, which Crisp's Creek flows into, and when I was driving back with [LLS participant] past the current site we've been working on [they] flagged that this could be a good potential site because of the chain of ponds" (Veolia participant 2015).

The participant from the LALC identified the site visit undertaken with the researcher as the point of recognition of the chain of ponds' significance,

> "Yeah it was really interesting. Because now I'd like to know, really, why the ponds are like that. You know, it's got me thinking why are they there? Little deep holes and then even when it's really, really dry they've still got water" (LALC participant 2015).

Since the site visit, the participant reported that they are able to recognise chains of ponds in the landscape and that their interest in the ponds has grown,

> "I had no idea about them. I just knew they were all just these little tiny ponds and I thought "Oh yeah", you know, a couple here and a couple there … But now they're sort of fascinating me … I'm looking for them now … I'm not meaning to, but it's like subconsciously I'm doing it. If I look at the river, then I'll look for little pondy things" (LALC participant 2015).

---

[1] 'River Styles' refers to a framework developed for the geomorphic characterisation and analysis of river. For more information see Fryirs and Brierley (2013).

The participant from LLS drew specific attention to the need for better understanding of chains of ponds, part of the participant's motivation for undertaking projects such as the Crisp's Creek,

> "Losing a 'threatened' ecosystem due to human disturbance, of which we have minimal understanding of, is not a good thing. Everyone needs to work together to stop this occurring" (LLS participant 2015).

This suggests that a lack of detailed understanding of chains of ponds is limiting the ability of practitioners to rehabilitate in ways that are particularly sensitive to the river type in need of rehabilitation. This was echoed by the Veolia participant,

> "I think [the project] ticked a few boxes from the LLS side so far as projects that integrate research and monitoring, which is often a factor that's missed out on in these sorts of projects … it's also a good blend because we don't have the people or the time to undertake the monitoring there … so we can't evaluate the project apart from visually [without support from research partners]" (Veolia participant 2015).

Responses from participants on their roles in river management, their goals for rehabilitation and their understandings of chains of ponds give insight into the social and political context in which river rehabilitation is undertaken. In a landscape like Crisp's Creek and its surrounds, where humans have interacted closely with the physical landscape over thousands of years, this social setting makes up an important part of the physical-and-social landscape and warrants analysis. This interaction between social and physical aspects of the landscape will form the focus of the following chapter.

4 Discussion

4.1 Introduction

This chapter will first reconstruct a sequence of geomorphic evolution for Crisp's Creek based on the morphological, sedimentological, archival and oral evidence. Second, this reconstruction will be discussed in terms of a sociogeomorphological history, recognising the roles of both physical and social processes in producing a simultaneously physical-and-social landscape. Third, responses from participants along with environmental management theory from physical and social sciences will form a characterisation of the river management setting of Crisp's Creek, identifying strengths and opportunities for improvement with particular reference to Indigenous participation. Finally, this chapter will evaluate the physical-and-social approach taken in this research as a basis for building interpersonal relationships capable of supporting cross-cultural dialogue in river research and management. This has implications not only for improving participation in river management but also for findings ways to situate geomorphological research within a social context and to create opportunities for a more socially engaged geomorphology.

4.2 Interpretation of Holocene evolution and post-European environmental history

Evidence from the sedimentary record, radiocarbon ages, archival history and oral history, as well as other studies that have been undertaken in adjacent catchments, provide the necessary information to reconstruct the physical-and-social evolution of the Crisp's Creek chain of ponds throughout the Holocene. The site's history is organised here into four key stages based on major sedimentological and historical changes: **(i)** Late Pleistocene; **(ii)** Late Holocene (3.7-1.3 ka); **(iii)** Post-European arrival (1820s-1980s AD); and, **(iv)** Present day. At the reach scale, these evolutionary stages are summarised in Figure 4.1 as a geomorphic conceptual model. Figure 4.2 shows the social and physical changes that occurred from the mid-Holocene to the present day at both the site scale and also in the wider Southern Tablelands region. Correlation between physical and social indicators of landscape change reveals relationships across spatial and temporal scales that provide vital historical context for the present-day morphology and efforts to rehabilitate Crisp's Creek.

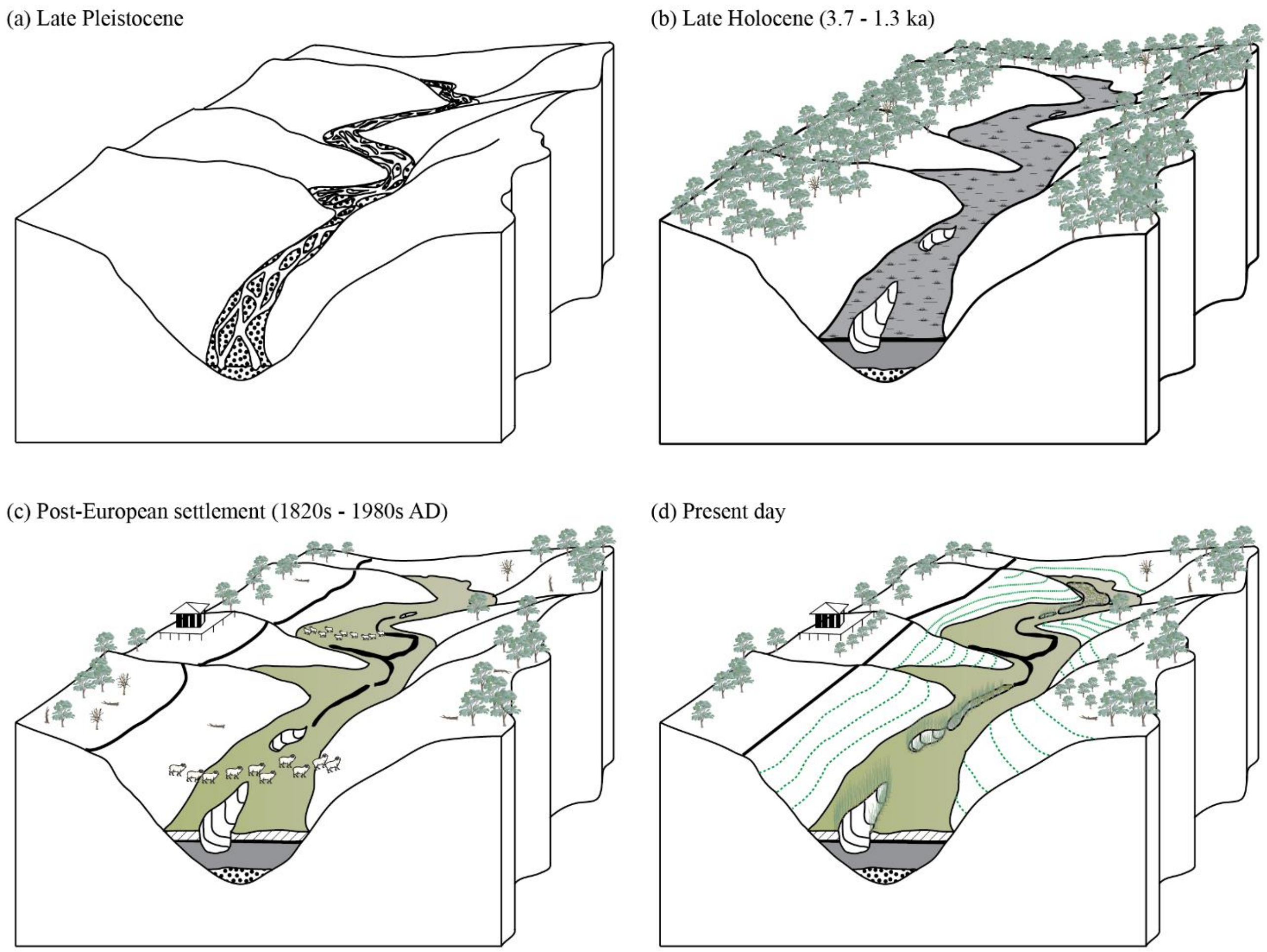

Figure 4.1: Evolutionary stages of Crisp's Creek throughout the Holocene and to present day. **(a)** Late Pleistocene: treeless hillslopes contribute gravels to river in valley fill; **(b)** Late Holocene: transition to suspended load system with assistance of swampy vegetation on valley floor. Aggradation of valley with accumulation of fine sediments (contemporary sediment classes: red/yellow mottled grey clays, massive, grey-brown clays and organic-rich clays) at surface. Primary sediment source is reworking of Pleistocene valley fill. Ponds scoured from valley fill, separated by preferential flow paths. Aboriginal subsistence land use including burning to maintain grassland; **(c)** Post-European settlement: widespread clearing of hillslopes making way for agriculture. Increased runoff and disturbance of valley fill surface results in incision of channels in some sections of valley fill. Products of incision deposited as post-incision alluvium (buff-coloured sandy loams). Fertilisers used to increase productivity in place of Aboriginal burning; **(d)** Present day: trees replanted on hillslopes starting in 1960s and continuing through 2015 as contoured plantings. Removal of sheep from section of creek as part of rehabilitation plan undertaken by Veolia Environmental Services and NSW Local Land Services. Incised channels begin to infill with instream sediments stabilised by reedy vegetation as sediment delivery declines in the catchment.

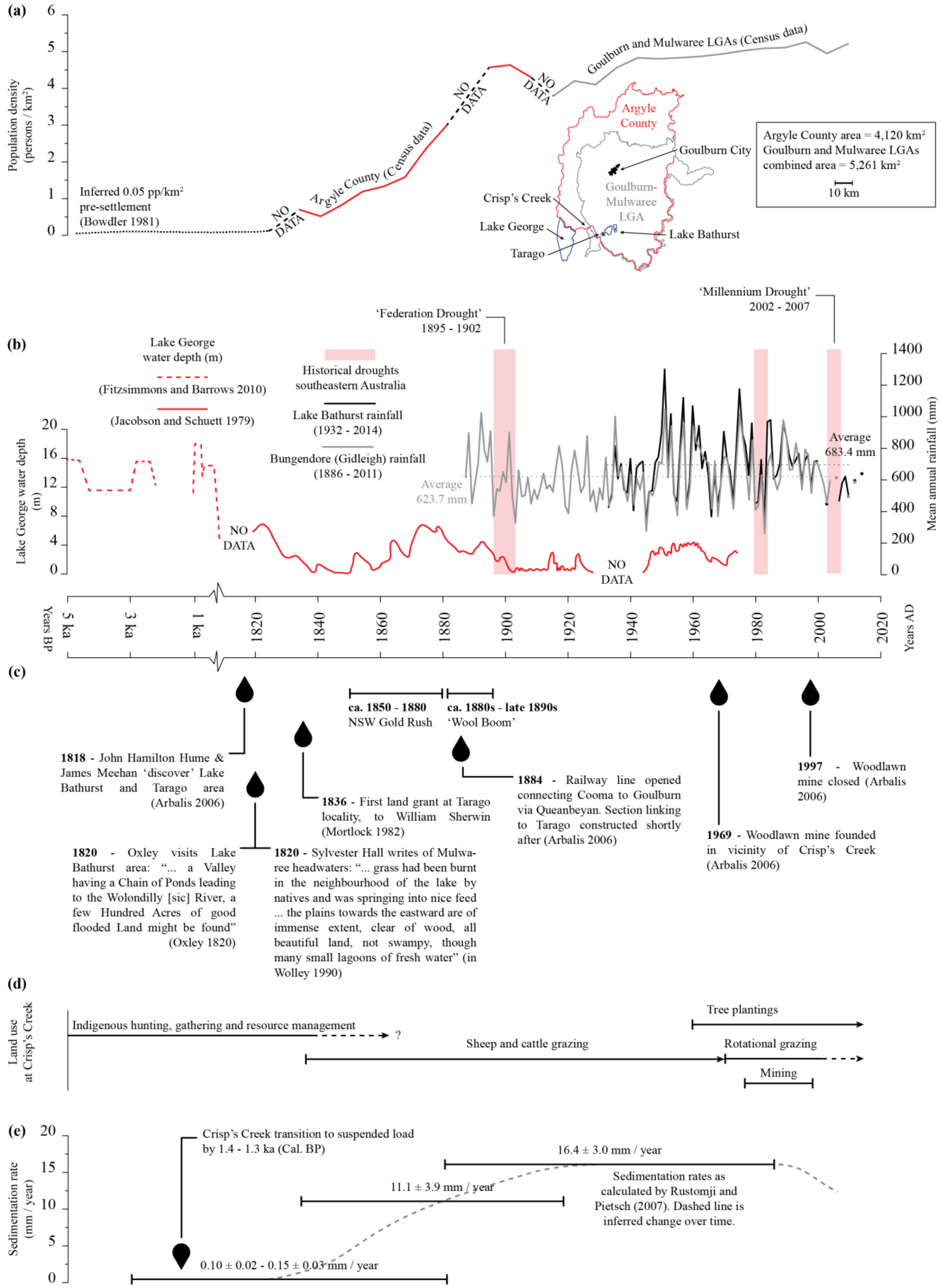

Figure 4.2: Major changes and events at the Crisp's Creek site as well as the wider Southern Tablelands region throughout the Holocene and to the present day. Note that Census data excluded Aboriginal people until 1966.

4.2.1 Late Pleistocene: A gravel bed river

The basal gravel unit found throughout the Crisp's Creek site reflects a past sediment transport environment vastly different to the present, most likely having been deposited in the Late Pleistocene. Although this unit was not dated in the present study, very similar units were dated by Rustomji and Pietsch (2007) at the confluence of Crisp's Creek and the Mulwaree River trunk stream using Optically Stimulated Luminescence (OSL). Their work returned an age of 21.3±2 ka, which is around the peak of the Last Glacial Maximum (LGM). Prosser et al. (1994) also attributed basal gravel deposits in nearby Wangrah Creek to Pleistocene denudation of treeless hillslopes (Figure 4.1a), the resulting sediments being reworked throughout the Holocene. Environmental conditions around the LGM included reduced vegetation cover and temperatures approximately 9 °C cooler than at present (Kershaw et al. 1991, Galloway 1965). This represents the most likely timing for the deposition of basal gravels in the Crisp's Creek valley.

4.2.2 Late Holocene: Transition to suspended load and chain of ponds

Radiocarbon ages from H_BE1 indicate that the transition from a gravel-bed river to a suspended load transport regime began at least as early as 3.7-3.5 ka (Figure 4.1b). Declining gravel abundance toward the surface relative to massive, grey-brown clays supports a transition stage between gravel bed load transport and suspended load transport with some reworking of basal gravels, similarly to descriptions by Prosser et al. (1994). This timing is also consistent with similar sedimentary units termed 'black and grey silts' at the Crisps-Mulwaree confluence dated at approximately 3 ka to late nineteenth century by Rustomji and Pietsch (2007) and interpreted as swampy meadow aggradation. The transition to a suspended load system at Crisp's Creek appears to have been mostly complete by 1.4-1.3 ka (Figure 4.2e), around which time only very occasional gravels to 2 mm (b-axis) were deposited. This period of aggradation, from approximately 3.7 to 1.3 ka, is consistent with a group of valley fill deposits identified by Coventry and Walker (1977) to have been deposited in the Lake George area 4.4-1.6 ka, approximately synchronous with high water levels in Lake George around 6-2.5 ka (Fitzsimmons and Barrows 2010; Figure 4.2b). Because Lake George has no outlet, its water levels provide a suitable proxy for rainfall (minus evaporation) throughout the Quaternary (Fitzsimmons and Barrows 2010). Wet conditions in the local area at this time could have contributed to vegetation growth, consistent with conditions required for valley fill aggradation and the formation of swampy surfaces (Prosser and Slade 1994).

The most prominent phase of swampy conditions is represented by a dark, organic-rich clay unit commonly observed at Crisp's Creek between 50 and 100 cm depth. This likely reflects a period of low energy in the system when decaying vegetation accumulated along with fine mineral sediments, similar to the contemporary conditions observed in sections with intact preferential flow paths (e.g. at Transects B, C and G). The clay units described and dated by Rustomji and Pietsch (2007) at the Crisp's-Mulwaree confluence also had a black surface, which was dated to the nineteenth century. Although the upper organic clay layers at Crisp's Creek were radiocarbon dated in the present study to 275-Modern Cal. BP, the black layers described by Rustomji and Pietsch (2007) were dated more precisely as pre-European using OSL. Because OSL directly dates the sediment rather than fragments included in the sediment, for these recent ages the OSL ages may be more accurate than the radiocarbon used in the present study (Blong and Gillespie 1978). Although the ages determined by Rustomji and Pietsch (2007) cannot be extrapolated directly to the black clays at Crisp's Creek, the more precise OSL ages from the Crisp's-Mulwaree confluence support the Crisp's Creek organic-rich clay unit being deposited in the earlier, pre-European part of the given age range. At transects B and G there was evidence of more than one phase of swampy accumulation in the form of multiple black 'surfaces', whereas in other transects only one was found. Transect G contained three of such units including the contemporary surface. At Transect B two were identified but did not appear to be continuous across the valley, the unit appearing in B_C1 and B_C2 but not the intervening B_Au1. These patches indicate that swampy accumulation may have been spatially variable in the valley, as it appears to be at the contemporary surface.

At all opportunities to undertake sedimentary investigation on site, water levels were too high to allow detailed analysis of most pond banks. The only ponds that could be examined were those on Transects A and C, both of which were dry the majority of the time. The bank exposure at the Transect A pond closely resembled the sedimentology of other bank exposures and augers on that transect and elsewhere throughout the site (e.g. F_C1). The ponds appeared to have been scoured into the valley fill sediments; however, the mechanism by which this occurs remains unknown (Fryirs and Brierley 2013). Eyles (1977a) provides one model for pond formation, whereby once the protective surface sediments are breached by disturbance, underlying dispersible clays are removed, creating an environment where banks may be undermined and collapse, producing the elliptical pools characteristic of the chain of ponds river type. This pre-European sequence of formation is also consistent with the historical accounts of chains of ponds in the area at the time of European arrival (Eyles 1977b, Oxley 1820).

Human interactions with the physical landscape prior to European arrival are not well understood. However, archaeological evidence indicates that Aboriginal people were in the Lake George area at least as early as 2.4 ka (Hughes et al. 2014). Increased fire frequency around 4-3 ka has been attributed to Aboriginal land management practices, in broad agreement with the minimum age given by Hughes et al. (2014) for Aboriginal activity. Population density in the pre-European period has been estimated to be approximately one person per 22 km^2 (Bowdler 1981), which is significantly lower than at present (Figure 4.2a). Presence of stone artefacts indicates that the flats and hills surrounding Crisp's Creek were used by Aboriginal people, although these deposits have not been dated (Navin Officer Heritage Consultants 1998).

4.2.3 Post-European arrival: Incision and sedimentation

The post-European period at Crisp's Creek was marked by increased sedimentation and incision of the valley fill with the formation of discontinuous channels (Figure 4.1c). In most profiles a surficial unit of buff-coloured or light brown loamy material overlays the black clays of the pre-European swampy surface. Two samples from this ubiquitous layer returned ages of 265 and 295 to Modern Cal. BP (1685 and 1655 AD to present), a period which contains the arrival of Europeans in the area, around 1820 AD (Figure 4.2c). Although this timing could include the pre-European period, comparison with the higher precision OSL ages obtained by Rustomji and Pietsch (2007) from equivalent units in a similar sedimentary sequence, combined with the sedimentary and historical evidence of increased sedimentation following European arrival, all suggest a post-European age for these surface deposits. Previous research in the Southern Tablelands has demonstrated that sedimentation rates and overall sediment delivery increased markedly following European arrival and have since decreased to a level between the pre- and post-European periods (Rustomji and Pietsch 2007, Wasson et al. 1998, Figure 4.2e). The source of this sediment is understood to have been the alluvial valley fills, which were incised, likely due to disturbance to ground cover (Rustomji and Pietsch 2007, Johnston and Brierley 2006, Wasson et al. 1998, Prosser 1991). At Crisp's Creek an active gully and incised channel network occurs upstream of the study site, supplying the buff-coloured loams that now lie above the swampy meadow units (massive, grey-brown clays and organic-rich clays). In most cases, these channels incised to the lower part of the Holocene fill or the upper part of the basal gravel units. However, in places channels incised to bedrock, for example, at Transect I, where confinement is high and a bedrock spur is near to the surface. When the products of incision were deposited on valley fill surfaces, it is likely that they also caused some infilling of ponds, which would have been flushed to some extent during high flows.

Although the direct cause of incision cannot be determined from the data gathered in the present study, previous research has highlighted some potential factors that may have directly or indirectly triggered erosion. These include removal of vegetation (land clearing), grazing by livestock and introduced animals, road building and drain construction, all of which either disturb surface sediments or the vegetation that holds sediment in place (Mactaggart et al. 2008, Fryirs and Brierley 1998, Prosser and Slade 1994, Prosser 1991, Eyles 1977a). At Crisp's Creek, the most likely cause was overgrazing, which reduced ground cover and valley floor resistance (Eyles 1977b). Oral evidence also indicates that the hillslopes, now sparsely covered with *Eucalyptus* and other trees, were more densely covered at the time of European arrival (D. Pockley 2015 *pers. comm.*), which would have impacted on runoff. River response to grazing and other landscape disturbances in the form of gullying and sedimentation would likely have lagged after the initial impacts (Wasson et al. 1998, Eyles 1977b). Although the population density of Argyle County shortly after settlement was fairly low (Figure 4.2a), in the 1836 NSW census 38% of the population (or 1282 people) were reported as being employed in agricultural industries, of which 61% were working with sheep. This reflects the significance of grazing to the local economy at this time. The region saw significant increases in population in the nineteenth century, population density increasing by a factor of 9 between 1836 and 1901 (Figure 4.2a) as the Gold Rush (ca. 1850-1880) brought miners to the region, followed by the Wool Boom of 1880s to late 1890s. However, the Federation Drought of 1895 to 1902 put significant pressure on agricultural industries and the exceptional rate of population growth came to an end (Figure 4.2a, b, c). Sedimentation rates as calculated by Rustomji and Pietsch (2007) increased significantly and concurrently with population growth (Figure 4.2a, e), reflecting the magnitude of land use change in this region.

4.2.4 Present day: River recovery and rehabilitation

The present period and recent history can largely be described as a phase of recovery and rehabilitation (Figure 4.1d). This began in the 1960s when the then land owner began planting trees on hillslopes with the intention of increasing infiltration of rainfall and improving productivity for pasture growth without use of superphosphates (D. Pockley 2015 *pers. comm.*). Since the land including Crisp's Creek was acquired by Veolia Environmental Services in 2001, this stewardship has continued with a number of tree planting projects and more recently the rehabilitation project undertaken in partnership with Local Land Services. Sheep stocking rates have been reduced across the site (Veolia participant 2015) and grazing altogether ceased within the study reach, where approximately 3000 indigenous trees were planted in early 2015. There has been a noticeable shift in ground cover and vegetation density since 1941 with once-bare gullies and hillslopes now well covered (visible in Figure 3.10). Although knickpoint retreat continues in the mid-section of the study reach (Figure 3.10), immediately downstream of the knickpoint and within other incised channels, sediments have been better stabilised by the regrowth of reedy vegetation (Figures 3.11 and 3.13).

Behaviourally, the chain of ponds is in a largely disconnected state in low flow and there is no noticeable flow between ponds. Isotopic evidence suggests long residence time of water in ponds during low flow. Water in ponds is still and retained largely by cohesive sediments in the banks and bed, which likely act as an aquitard. At this time some minor groundwater contributions may be made but isotope analysis suggests that these are largely surface water fed systems. When the bankfull stage is reached in ponds, water levels reach the lateral margins but only begin to flow in and out of the lower elevation upstream and downstream ends, which are approximately level with the beds of intact flow paths. This inflow and outflow likely produces some turbulence in the ponds capable of transporting fine material from the pond bed by entrainment and suspension and perhaps reworking or removal of larger bed material, 'flushing' the ponds. Entrainment of bed material over time in sequences of high-energy flow may lead to bank slumping and pond augmentation as noted in Eyles (1977a). Preferential flow paths in bankfull conditions appear as multiple channels flowing around clumped tussock grasses. In this stage, flow paths provide connection between ponds. Organic detritus and available mineral sediments are entrained and transported, some of which is likely deposited in the less turbulent ponds downstream. The persistence of clumped tussocks and their protected sediments, even downstream of knickpoints, indicates that these forms are highly resistant to erosion and that little of this material would be removed even in the bankfull stage. At overbank stage, the system is hydrologically connected. Preferential flow paths are most active and ponds are full. Fine-grained sediment accumulation occurs around the tussocks of the swampy surface, building the valley fill. In incised channels, sediments accumulate amongst instream reed beds, building up the channel bed.

4.3 Sociogeomorphology of Crisp's Creek

Crisp's Creek has changed physically and socially over time. Interactions between physical and social dimensions have also changed. Some of these changes are best accounted for by the physical forms of the landscape and others by anthropocentric historical records. When each source of evidence is considered as a selective record of a common sociogeomorphic history of physical-and-social evolution (Ashmore 2015), together they can form a contextual basis within which contemporary river morphology can be more fully explained and the contemporary river management setting can be historically situated. This sociogeomorphic context provides a way to understand how past and present political and social processes are manifest in the physical landscape and how a history of changing relationships between people and between people and places have shaped the way river management is done today.

The particular human actions that contributed to significant alteration of river morphology in the early nineteenth century can be seen partly as a product of the colonisation of the Australian continent by Great Britain and of the politics, values and attitudes that made up a colonial worldview (Fryirs et al. 2008). A colonial perception of the landscape as 'empty' and ripe for 'improvement', created by the legal invention of 'Terra Nullius' (Collis and Webb 2014, Banner 2005), enabled and indeed encouraged the actions of pioneers who, in the Southern Tablelands, cleared the hills, overgrazed the country and alienated Aboriginal people from their land and ways of life. This was a common perception of the Australian landscape that has to a large extent driven the development of water law and environmental management (Gibbs 2009). However, the landscape of the Southern Tablelands as Europeans found it was far from being a blank canvas; the landscape had already been co-evolving with human society for thousands of years. An example of this co-evolution can be found in the pollen record from Lake George and other sites, which suggests that burning of vegetation by Aboriginal people likely played a role, along with longer-term climatic changes, in the establishment of the present-day vegetation structure dominated by *Eucalyptus* trees and grassland (Kershaw et al. 1991). The practice of burning as maintenance is also supported by early accounts of the Lake George area, near Crisp's Creek,

> "The grass had been burnt in the neighbourhood of the lake [Lake George] by the natives and was springing into nice feed" (Sylvester Hall (1820) in Woolley 1990).

Human agency had, along with physical processes, produced a productive grassland that was seen by colonisers as a place of opportunity. The actions of early farmers in clearing and grazing the land, reflected in early accounts (Eyles 1977b) and in the sedimentary record (Rustomji and Pietsch 2007, Prosser 1991), were manifest at a localised subcatchment scale but also were implicated in global-scale geopolitical relationships that connected political and social processes in Great Britain with environmental change in the Southern Tablelands and at Crisp's Creek.

Whilst human action and broader social processes have resulted in significant changes in landscape character, so did the physical landscape impact on society. The productive condition of the landscape at the time of European arrival enabled expansion of the colony from Sydney (Butzer and Helgren 2005, Dodson 1986, Oxley 1820). The Southern Tablelands area was grazed heavily from early in the nineteenth century and the Goulburn area became a centre for fine wool production (even today Goulburn is home to a tourist attraction called 'The Big Merino'). This productive landscape supported the 'wool boom' of the 1880s and 1890s, which, along with the preceding gold rush, resulted in significant human population growth in the region (Figure 4.2). The common saying in Australia, that this country's early development 'rode on the sheep's back', reflects the extent to which pastoralism contributed to a sense of national identity (Taylor 1990). The physical-and-social landscape was re-made in this time of agricultural prosperity, as the city of Goulburn grew large, national identity was crafted and the product was exported internationally, and as the pursuit of economic growth became measurable in the rivers' sedimentary response to grazing pressure (Rustomji and Pietsch 2007, Wasson et al. 1998, Figure 4.2e). As the wool industry's growth was tied to landscape condition so too was its decline, the end of the wool boom coinciding with the Federation Drought at the turn of the century. Population in this time declined and never again grew at such a rate (Figure 4.2a).

Increased sedimentation caused by overgrazing produced 'hybrid morphologies' (Ashmore 2015), reflecting interaction between physical and human-driven processes. Instream reed beds described by Zierholz et al. (2001) and present in the study area are likely novel geomorphic units having only formed following the unprecedented gullying and incision that occurred with European farming practices and likely also influenced by drought. Importantly, it is unlikely that the river will 'return' to a former morphological state; rather, these novel hybrid forms reflect a particular, contingent history of human - river interaction (Hobbs et al. 2009, Phillips 2007, Zierholz et al. 2001). Although there may be some return of geomorphic process in the swampy aggradation, this can only be considered as a new, hybrid river condition with a trajectory constrained by the emergent physical and social conditions (Brierley and Fryirs 2005).

Human agency is also reflected in structures that limit the movement and organisation of sediments in Crisp's Creek. Concrete weirs installed in the early 1990s to trap sediment and reduce peak flow (D. Pockley 2015 *pers. comm.*) act as controls on morphology, as intended, and these structures are now so much a part of the river's morphology that they are analogous to geology. Their removal would likely be catastrophic, resulting in significant erosion and loss of characteristic ponds that have so far been protected from knickpoint retreat. The design of these concrete structures reflects the river management paradigms of the time they were installed, when a 'command and control' approach focused on hard engineering solutions to erosion problems (Fryirs et al. 2013, Gregory et al. 2011, Brierley and Fryirs 2008, Holling and Meffe 1996). This kind of intervention contrasts dramatically with the rehabilitation works undertaken more recently as part of the collaboration between Veolia and LLS. The goals of rehabilitation have shifted from attempts to hold the river in place to a focus on building resilience and supporting ecosystem functioning, reflecting movements within the field of river management (Fryirs et al. 2013, Brierley and Fryirs 2008). The morphology and broader ecosystem structure of Crisp's Creek reflects this history of evolving management practice, the river recognisable as an emergence of interaction between social and physical processes.

4.4 Contemporary river management setting

The contemporary river management structure surrounding Crisp's Creek is a 'middle-ground' structure, summarised in Figure 4.3, where LLS exist as a catchment-scale nexus for funding and knowledge transfer (Gregory et al. 2011, Hillman and Brierley 2005). Funding and policy are delivered from the Sydney Catchment Authority (SCA) and the State Government to LLS. LLS then engage with landowners to prioritise and fund appropriate river management projects and also provide training to educate landowners on improving their land management practices. LLS are responsible for land management in a broad sense, which means that they are able to address river management issues in a way that recognises linkages between land uses in different landscape units throughout the catchment. LLS engage other groups as needed, including volunteer conservationists in Landcare groups and the Pejar LALC. LLS also connects to Macquarie University for knowledge exchange through an Australian Research Council (ARC) Linkage grant on chains of ponds and upland swamps and through participation in *River Styles* fluvial geomorphology professional training courses organised by academics from Macquarie University. This relationship creates a link between research and practice with LLS able to implement new knowledge through the middle-ground structure. However, this kind of cooperation is not ubiquitous in Australia and the majority of river rehabilitation occurs either entirely within the State Agency sphere or entirely in the scientific sphere (Fryirs et al. 2008). Although this structure is well designed to achieve funding of rehabilitation and knowledge transfer, participatory aspects of the structure are only partly developed and act as barriers to ensuring that sustainable river management is taking place (c.f. Ashby et al. 2015b, a). One of these barriers is a lack of community participation in river management, particularly from Indigenous voices. For example, the reduction of Indigenous input to responding to artefact finds devalues the broader approach of caring for Country that encapsulates Indigenous cultural values alongside particular heritage values.

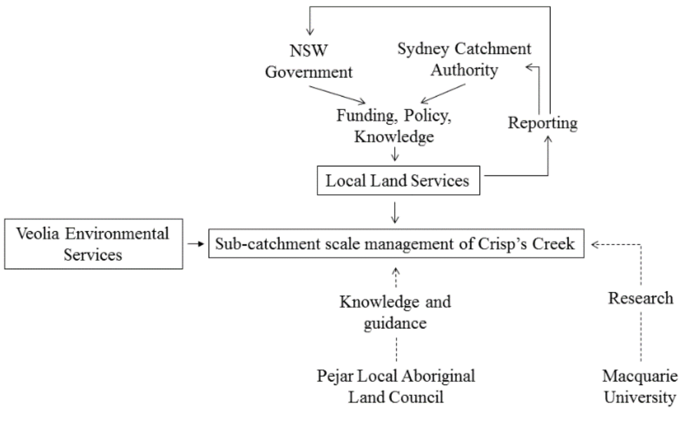

Figure 4.3: The management structure surrounding Crisp's Creek is a 'middle-ground' model, where LLS are a nexus for funding and knowledge exchange for implementation at the catchment scale.

4.4.1 Participation from Indigenous voices

Responses from LLS and LALC participants indicated that interaction is limited between these two institutions because LLS are not required to engage with the LALC unless physical archaeological material is found on or near a rehabilitation site. However, the LALC participant expressed that they feel a responsibility to, "[care] for the whole of Country, not just for our artefacts" (LALC Participant 2015). This scenario is a common feature in Australian river management, where 'Indigenous issues' and values are considered within a narrow cultural heritage paradigm that isolates Indigenous voices as 'cultural' only, preventing involvement of Indigenous people in matters that are considered 'social' or 'environmental' (Carter 2010, Jackson 2006, McIntyre-Tamwoy 2004). This segregation conflicts with Indigenous concepts of *Country* as a holistic term that includes what Western knowledges distinguish as people, animals, plants and the physical landscape and the relationships between these (e.g. Kingsley et al. 2009). This denial of Indigenous voices in caring for Country beyond cultural artefacts is ingrained in many institutional environmental management structures. Suchet (2002) describes the marginalisation of Indigenous voices in this manner as an example of *deep colonisation* (Rose 1999), whereby colonial politics are entrenched and reinforced (usually unintentionally) through governance structures, often including those designed to counteract colonisation (Rose 1999).

At Crisp's Creek, management policies sideline Indigenous voices as being only relevant to cultural matters and ensure that environmental matters are chiefly the concern of technical experts. Because the institutionally dominant technical and intellectual traditions that created this distinction are the same traditions that judge these distinctions to be appropriate, there is a closed loop of self-referential justification that obscures from view other ways of seeing and understanding landscapes. Rose (1999) called this the *hall of mirrors* and according to Suchet (2002), these mirrors must be reassembled into 'doors' if environmental management practice is to move beyond its Eurocentric view of what environmental management should entail and which knowledges should be included in its practice. Crisp's Creek's management setting reveals a disconnect between what LLS and LALC see as the purposes and processes of environmental management. Although institutional constraints on the LLS side and in some cases landowners' needs (not in the case of Crisp's Creek) may resist engagement of the LALC in all projects, it appears that more could be done to increase the level of dialogue between members of these two institutions and increase participation more generally.

'Opening doors' to river management presents a challenge to the institutional privileging of technical knowledge (Howitt and Suchet-Pearson 2003). As important players in river management (and rightly so), geomorphologists have an opportunity to recognise the political power of their work, both in substance and process, and to open up doors within their work to engage in dialogue with other ways of knowing and seeing the landscapes being studied. This is not proposed as an argument to reduce the power of sciences in management or to suggest that this transition is the responsibility of geomorphology alone. Rather, it is to promote the kinds of relationships that allow other voices to also have power in decision making, i.e. power with – not power over – others (Gaventa 2006). As in

Tadaki et al. (2015), this orientation to a conscious engagement with politics may take place within geomorphology rather than through adoption of a separate discipline; however, it is important to remember that although a reorientation can take place within the discipline of geomorphology and geomorphology may provide a basis for dialogue, dialogue must then extend outside of and beyond the discipline into a space where power relations are more equal (Howitt and Suchet-Pearson 2003, Suchet 2002, Rose 1999). The final section of this chapter will assemble an argument that sociogeomorphic and ethnogeomorphic principles together could inform more politically engaged geomorphological research practices (Tadaki et al. 2015, 2012) capable of supporting the kinds of cross-cultural dialogue required for sustainable management of rivers as simultaneously physical-and-social landscapes (Wilcock et al. 2013, Wilcock 2013).

4.5 A physical-and-social research basis for river rehabilitation

The overarching aims of this research at Crisp's Creek were: **(i)** to understand how the studied chain of ponds system has formed and changed over time as a physical-and-social landscape; **(ii)** to connect this understanding to characterisation of the contemporary management setting and identify opportunities for this to contribute to improved management practices; and, **(iii)** to apply principles from sociogeomorphology and ethnogeomorphology in a socially engaged research project to explore ways of opening geomorphology to diverse ways of understanding simultaneously physical-and-social landscapes. Through this research the first aim was met with a reconstruction of the river's evolution throughout the Holocene to the present day, documenting the transition to an era of river repair. However, meeting the second aim was not as straightforward as expected. Rather than establishing a direct connection between the geomorphic evidence and improvement of management techniques, the value of this research became apparent as a process of rehabilitation in a relational sense, in that this research contributed to a process of 're-making' the river through the making and re-making of relationships between people and between people and place. Although at a small scale, this research demonstrates potential for a way of 'doing' geomorphic research (Howitt 2001) that recognises social processes and embraces its political work by using geomorphic knowledge as a foundation for dialogue that can provide an additional mode of participation in river management.

4.5.1 Sociogeomorphology: Connecting people and place through geomorphology

Reconstruction of the evolution of Crisp's Creek in this thesis was informed by the constructivist approach outlined in Reading the Landscape (Fryirs and Brierley 2013), which enabled the river's morphology and behaviour to be explained in terms of contingent boundary conditions, processes and events. The result was an interpretation of the river's evolution grounded in a sense of place and history (Brierley et al. 2006). Through investigation of the river's more recent (mostly post-European) history, the significant role of human agency in shaping the river became apparent. By adopting a sociogeomorphic way of seeing river morphology (Ashmore 2015), analysis of this history of human agency in the landscape could be expanded from a list of impacts (Head 2008) recorded in sediments and archival sources (as in Prosser 1991, Eyles 1977b) into an articulation of some of the broader social processes that influenced these geomorphic changes, situating morphology within a co-produced and co-constituted physical-and-social landscape (Ashmore 2015). For example, through this sociogeomorphic frame, the incision and sedimentation that followed the arrival of European farming practices at Crisp's Creek became visible not simply as the result of overgrazing or other alluvial fill surface disturbance, but as a physical manifestation of human and non-human agencies operating at scales from the local to global and through relationships between these scales (Howitt 1998). That is, incision not only being a local problem caused by discrete human actions but also as part of a global context of economic and political flows that constructed local actions in the physical landscape as part of a wider agenda of empire- and colony-building (Hugo 2011).

A sociogeomorphic frame highlights how social and physical processes and conditions, influenced by history, limit sustainable human relationships with place in the present through underdevelopment of key linkages in sustainable river governance (Gregory et al. 2011, Hillman 2009). The marginalisation experienced by members of the LALC in environmental decision making is an example of this because the contemporary environmental management discourses, to some degree, continue to perpetuate historical colonisation (c.f. Gibbs 2009, Jackson 2006, Suchet 2002). River morphologies and behaviours that were co-produced by social and physical processes are defined as problematic according to Western, technical knowledges, ensuring that solutions to these problems will also be largely technical in nature. Although the intention is undoubtedly good, this is 'hall of mirrors' thinking (Suchet 2002, Rose 1999) and the result is that non-technical knowledges are marginalised in river management. In a colonised landscape, situated participation and collaboration must be seen not only as a way of improving the quality of management response by drawing on multiple knowledges ('two heads are better than one'), but also as a way of de-colonising environmental management by returning power to Indigenous people through recognition of their perspectives and agencies (Wilcock et al. 2013, Howitt and Suchet-Pearson 2003, Suchet 2002).

4.5.2 Doing river rehabilitation through relational research

At Crisp's Creek, there was willingness on the part of all research participants to improve the river's health but institutional barriers limited the potential for deep participation in these efforts. Hillman (2009), in reporting on the apparent lack of institutional change since the age of river repair and sustainable river management, in part attributed this common problem to the often-slow rate of change in governance systems. So, is it possible that more can be done through management-focused scientific research to promote Indigenous voices? At the small scale, the present research at Crisp's Creek made some surprising connections between people and between people and place that may have implications at coarser scales of river management. This was made possible by the adoption of ethnogeomorphic principles in a consciously political engagement with Indigenous people that used the geomorphic landscape as a foundation for dialogue across cultures (Wilcock et al. 2013).

Following the site visit undertaken with the LALC participants, one participant reflected on the impact that this visit had in changing the way they saw the landscape. At the beginning of the site visit, the participant remarked of the ponds,

> "So your little fascination is with those little circle things?" (LALC Participant 2015)

Following the visit, the participant's perspective on the chain of ponds had changed significantly,

> "Now they're sort of fascinating me … I'm looking for them now … I'm not meaning to, but it's like subconsciously I'm doing it." (LALC Participant 2015)

The pond hydrology was also a point of interest, the participant reporting that they now wanted to know why the ponds held water even in dry times, suggesting that the site visit had been a point of inspiration that ignited more than superficial interest. To the researcher, this moment of seeing the landscape differently as described by the participant was similar to the 'geomorphic lens' that developed and subsequently sharpened since a first undergraduate geomorphological field trip. Through the site visit undertaken with LALC participants, the relationship between participant and place was re-made as the participant took on a more geomorphic way of seeing the fluvial landscape. The participant reflected that this recognition of chains of ponds in the landscape would change the way that they performed their role in consulting for development and conservation projects. It could be envisaged that new awareness of the river type may yet produce in the participant a motivation to advocate for the chains of ponds in future projects that contain such a river type. As an actor in regional river management, this LALC participant could take their interest in chains of ponds to influence decisions at other sites.

In addition to re-making the relationship between participant and place, conversations held on the site visit, in place, provided a common point of reference for researcher and participant that formed a basis for making a stronger interpersonal relationship. In a telephone conversation following the site visit, the participant revealed that seeing and discussing bank exposures and sediment cores from Crisp's Creek had reignited a long-forgotten childhood interest in soils and sediments,

> "When I got home from when you showed us the dirt, I got home to my husband and I said, "Oh I didn't know whether to tell him that I used to be into dirt or just to leave it." And then I thought, "No, I'll just tell him when he rings up." … Like, the dirt in Young is really soft and powdery and the dirt in Tumut is sandy. It's got bits of – I can remember – it's got little bits of, like, it's sand and dirt. And then the dirt here [in Goulburn] is clayey." (LALC Participant 2015)

This revelation suggests that the time spent on the site visit was important for building a level of trust, the participant only feeling comfortable revealing more personal reflections after researcher and participant were able to spend time talking and understanding each other's perspective. Conversations about the landscape, in an ethnogeomorphic approach, provided a way to connect at a personal level indirectly through a common interest, the outcome being a common point of reference for future conversations (Wilcock et al. 2013). This interpersonal connection is significant because it provides an open line of communication by which knowledge can be shared in the future. Although the official environmental management institutions may be slow to adopt a deeper participatory framework, this participation in a smaller scale, more agile research project has allowed a way for communication to take place on environmental management issues between the LALC and a researcher whose work contributes directly to river management practice through cooperation with LLS. This communication pathway may provide a supplementary, less formal mechanism for participation in sustainable river management.

Emerging from experiences at Crisp's Creek is the potential for a physical-and-social research approach to form a parallel mode of participation in river management. Beginning with the development of a sociogeomorphic understanding of the landscape that recognised human agency as co-productive of river morphology, this way of seeing the landscape provided a platform from which the research could develop into a more politically conscious process of making and re-making relationships between people and between people and place. This re-making of relationships through an ethnogeomorphic-style engagement with Indigenous people can be seen as a form of relational river rehabilitation in its own right; as people ↔ people and people ↔ place relationships are re-made, so is the fluvial landscape re-made or reassembled in the eyes of those involved. Conversations with the LALC participants as well as with participants from LLS and Veolia changed the researcher's perception of the landscape in two significant ways: **(i)** in seeing the landscape for its material reflection of political and social processes; and, **(ii)** in expanding the researcher's definition of what river rehabilitation can and should entail. This expanded view of rehabilitation as including the building of dialogue across cultures, through conversations on a physical-and-social landscape, constitutes a repositioning of the politically powerful role that geomorphological research could play in realising sustainable river management.

5 Conclusion

This thesis applied sociogeomorphological and ethnogeomorphological principles to a study of the geomorphic evolution and contemporary management setting of Crisp's Creek, an upland chain of ponds system in southeast Australia. A sociogeomorphic frame allowed the river to be seen as an emergent landscape that was – and continues to be – co-produced by physical and social processes operating at a range of spatial and temporal scales (Ashmore 2015). This sociogeomorphic evolution provided historical context for analysis of the contemporary management setting and current efforts to rehabilitate Crisp's Creek in terms of both the physical legacies of past land use and the social impacts of lingering colonisation in river governance, and linkages between these. Conversations with research participants from the State Agency responsible for river management and members of a local Indigenous organisation involved in environmental management revealed divergence between Indigenous participants' understanding of their responsibility to 'care for Country' in a holistic sense and the narrower opportunities these voices were afforded in the formal management structure. This structure compartmentalised Indigenous voices as being relevant mostly only to matters of physical cultural heritage (artefacts) and not broader environmental issues (c.f. Jackson 2006). Recognising these organisational limitations, this thesis adopted an ethnogeomorphic research approach that used conversations on landscape and emergence as a basis for dialogue across geomorphological and Indigenous ways of seeing and understanding the landscape (Wilcock et al. 2013). These conversations demonstrated the beginnings of shared understandings of the river and dialogue that may, in the future, support a parallel mode of participation in river management through research, supplementing the currently limited formal participation pathway. A sociogeomorphic and ethnogeomorphic perspective brings focus to the simultaneously physical-and-social landscape and the relationships that constitute it, making space for a broadening of definitions of 'river' and 'rehabilitation' to include social and physical processes and actors and relationships between them. From this perspective, the work this thesis achieved in making and re-making relationships between people and between people and place can be seen as river rehabilitation in its own right. Longer term engagement and investment in this relationship may yield stronger collaborative links between Indigenous organisations, State Agency and researchers at the catchment as well as reach scale. This should be a focus for further research that recognises and works with the political power of scientific research (Tadaki et al. 2015, 2012) and the role that science can play alongside other ways of knowing in sustainable river management.

6 References

Allan, J. L. (2015). "Designing forward with an eye to the past: Morphogenesis of the Lower Yuba River." Geomorphology, DOI 10.1016/j.geomorph.2015.07.009.

Anderson, J. (2004). "Talking whilst walking: a geographical archaeology of knowledge." Area **36**(3): 254-261.

Arbalis, J. (2006). A local history of Tarago and Lake Bathurst, Self-published.

Ashby, N., K. Fryirs and R. Howitt (2015a). "Exploring scale in environmental management: The case of Temperate Highland Peat Swamps on Sandstone (THPSS), Blue Mountains, NSW." Geoforum **Submitted**.

Ashby, N., K. Fryirs and R. Howitt (2015b). "Prospects for, and Challenges of, Research Design and Training in Cross-Disciplinary Environmental Management Research." Geographical Research **53**(1): 81-94.

Ashmore, P. (2015). "Towards a sociogeomorphology of rivers." Geomorphology, DOI 10.1016/j.geomorph.2015.02.020.

Banner, S. (2005). "Why Terra Nullius? Anthropology and property law in early Australia." Law and History Review **23**(1): 95-131.

Benda, L. E., N. L. Poff, C. Tague, M. A. Palmer, J. Pizzuto, S. Cooper, E. Stanley and G. Moglen (2002). "How to avoid train wrecks when using science in environmental problem solving." BioScience **52**(12): 1127-1136.

Blong, R. J. and R. Gillespie (1978). "Fluvially transported charcoal gives erroneous 14C ages for recent deposits." Nature **271**: 739-741.

Bohn, B. A. and J. L. Kershner (2002). "Establishing aquatic restoration priorities using a watershed approach." Journal of Environmental Management **64**(4): 355-363.

Bowdler, S. (1981). "Hunters in the Highlands: Aboriginal adaptations in the Eastern Australian Uplands." Archaeology in Oceania **16**(2): 99-111.

Bracken, L. J. and E. A. Oughton (2006). "What do you mean? The importance of language in developing interdisciplinary research." Transactions of the Institute of British Geographers **31**(3): 1-12.

Brierley, G. (2010). "Landscape memory: the imprint of the past on contemporary landscape forms and processes." Area **42**(1): 76-85.

Brierley, G. and K. Fryirs (2005). Geomorphology and River Management: Applications of the River Styles Framework. Oxford, UK, Blackwell Publishing.

Brierley, G. and K. Fryirs (2008). Moves toward an era of river repair. River Futures: An integrative scientific approach to river repair. G. Brierley and K. Fryirs. Washington DC, USA, Island Press: 3-12.

Brierley, G. and K. Fryirs (2009). "Don't fight the site: three geomorphic considerations in catchment-scale river rehabilitation planning." Environmental Management **43**(6): 1201-1218.

Brierley, G. and K. Fryirs (2015). "The use of evolutionary trajectories to guide 'moving targets' in the management of river futures." River Research and Applications, 10.1002/rra.2930.

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

Brierley, G., M. Hillman and K. Fryirs (2006). "Knowing Your Place: an Australasian perspective on catchment-framed approaches to river repair." Australian Geographer **37**(2): 131-145.

Bureau of Meteorology. (2015a). "Daily Rainfall: Goulburn (Springfield)." Retrieved 15.09.2015, from http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=136&p_display_type=dailyDataFile&p_startYear=&p_c=&p_stn_num=070077.

Bureau of Meteorology. (2015b). "Monthly mean maximum temperature: Goulburn Airport AWS." Retrieved 19.06.2015, from http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=36&p_display_type=dataFile&p_startYear=&p_c=-981055956&p_stn_num=070330.

Bureau of Meteorology. (2015c). "Monthly mean minimum temperature: Goulburn Airport AWS." Retrieved 19.06.2015, from http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=38&p_display_type=dataFile&p_startYear=&p_c=&p_stn_num=070330.

Bureau of Meteorology. (2015d). "Monthly rainfall: Lake Bathurst (Somerton)." Retrieved 19.06.2015, from http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=139&p_display_type=dataFile&p_startYear=&p_c=-981055956&p_stn_num=070036.

Butzer, K. W. and D. M. Helgren (2005). "Livestock, land cover, and environmental history: The tablelands of New South Wales, Australia, 1820-1920." Annals of The Association of American Geographers **95**(1): 80-111.

Carter, J. (2010). "Displacing Indigenous cultural landscapes: The naturalistic gaze at Fraser Island World Heritage Area." Geographical Research **48**(4): 398-410.

Castree, N. (2002). "False antitheses? Marxism, nature and actor-networks." Antipode **31**: 111-146.

Castree, N. (2014). "The Anthropocene and geography I: The back story." Geography Compass **8**(7): 436-449.

Castree, N., W. M. Adams, J. Barry, D. Brockington, B. Buscher, E. Corbera, D. Demeritt, R. Duffy, U. Felt, K. Neves, P. Newell, L. Pellizzoni, K. Rigby, P. Robbins, L. Robin, D. B. Rose, A. Ross, D. Schlosberg, S. Sorlin, P. West, M. Whitehead and B. Wynne (2014). "Changing the intellectual climate." Nature Climate Change **4**(9): 763-768.

Church, M. (2010). "The trajectory of geomorphology." Progress in Physical Geography **34**(3): 265-286.

Clark, M. J. (2002). "Dealing with uncertainty: Adaptive approaches to sustainable river management." Aquatic Conservation: Marine and Freshwater Ecosystems **12**(4): 347-363.

Collis, P. and J. Webb (2014). "The visible and the invisible: legacies of violence in contemporary Australian Aboriginal contexts." Journal of Australian Studies **38**(4): 490-503.

Coventry, R. J. and P. H. Walker (1977). "Geomorphological significance of late quaternary deposits of the Lake George Area, N.S.W." Australian Geographer **13**(6): 369-376.

Dodson, J. R. (1986). "Holocene vegetation and environments near Goulburn, New South Wales." Australian Journal of Botany **34**: 231-249.

Dodson, J. R. (1987). "Mire development and environmental change, Barrington Tops, New South Wales, Australia." Quaternary Research **27**(1): 73-81.

Dudgeon, D., A. H. Arthington, M. O. Gessner, Z. Kawabata, D. J. Knowler, C. Leveque, R. J. Naiman, A. H. Prieur-Richard, D. Soto, M. L. Stiassny and C. A. Sullivan (2006). "Freshwater biodiversity: importance, threats, status and conservation challenges." Biological Reviews: Cambridge Philosophical Society **81**(2): 163-182.

Elliott, S. J. (2001). "The transdisciplinary knowledge journey: A suggested framework for research at the water-health nexus." Current Opinion on Environmental Sustainability **3**(6): 527-530.

Eyles, R. J. (1977a). "Bircham's Creek: the transition from a chain of ponds to a gully." Australian Geographical Studies **15**(2): 146-157.

Eyles, R. J. (1977b). "Changes in drainage networks since 1820, Southern Tablelands, N.S.W." Australian Geographer **13**(6): 377-386.

Felton, E. A. and M. B. Huleatt (1975). Braidwood 1:100 000 Geological Sheet 8827, Geological Survey of New South Wales.

Fitzsimmons, K. E. and T. T. Barrows (2010). "Holocene hydrologic variability in temperate southeastern Australia: An example from Lake George, New South Wales." The Holocene **20**(4): 585-597.

Frissell, C. A., W. J. Liss, C. E. Warren and M. D. Hurley (1986). "A hierarchical framework for stream habitat classification: Viewing streams in a watershed context." Environmental Management **10**(2): 199-214.

Fryirs, K. and G. Brierley (1998). "The characher and age structure of valley fills in Upper Wolumla Creek Catchment." Earth Surface Processes and Landforms **23**(3): 271-287.

Fryirs, K. and G. Brierley (2013). Geomorphic analysis of river systems: An approach to reading the landscape. Hoboken, NJ, USA, Wiley.

Fryirs, K. and G. J. Brierley (2009). "Naturalness and place in river rehabilitation." Ecology & Society **14**(1): 1-10.

Fryirs, K., B. Chessman, M. Hillman, D. Outhet and A. Spink (2008). The Australian river management experience. River Futures: An integrative scientific approach to river repair. G. Brierley and K. Fryirs. Washington DC, USA, Island Press.

Fryirs, K., B. Chessman and I. Rutherford (2013). "Progress, problems and prospects in Australian river repair." Marine and Freshwater Research **64**(7): 642.

Fryirs, K., B. Freidman, R. Williams and G. Jacobsen (2014a). "Peatlands in eastern Australia? Sedimentology and age structure of Temperate Highland Peat Swamps on Sandstone (THPSS) in the Southern Highlands and Blue Mountains of NSW, Australia." The Holocene **24**(11): 1527-1538.

Fryirs, K., J. Gough and G. C. Hose (2014b). "The geomorphic character and hydrological function of an upland swamp, Budderoo plateau, southern highlands, NSW, Australia." Physical Geography **35**(4): 313-334.

Gale, S. and P. Hoare (2012). "The stratigraphic status of the Anthropocene." The Holocene **22**(12): 1491-1494.

Galloway, R. W. (1965). "Late Quaternary climates in Australia." The Journal of Geology **73**(4): 603-618.

Gaventa, J. (2006). "Finding the spaces for change: A power analysis." IDS Bulletin **37**(6): 23-33.

Gibbs, L. (2009). "Just add water: colonisation, water governance and the Australian inland." Environment and Planning A **41**: 2964-2983.

Grabowski, R. C., N. Surian and A. M. Gurnell (2014). "Characterizing geomorphological change to support sustainable river restoration and management." Wiley Interdisciplinary Reviews: Water **1**(5): 483-512.

Gregory, C., G. Brierley and R. Le Heron (2011). "Governance spaces for sustainable river management." Geography Compass **5**(4): 182-199.

Harrison, S. (2001). "On reductionism and emergence in geomorphology." Transactions of the Institute of British Geographers **26**(3): 327-339.

Hazell, D., W. Osborne and D. Lindenmayer (2003). "Impact of post-European stream change on frog habitat: southeastern Australia." Biodiversity & Conservation **12**(2): 301-320.

Head, L. (2008). "Is the concept of human impacts past its use-by date?" The Holocene **18**(3): 373-377.

Head, L. (2011) "More than human, more than nature." Griffith Review **31**.

Head, L. (2014). "Contingencies of the Anthropocene: Lessons from the 'Neolithic'." The Anthropocene Review **1**(2): 113-125.

Head, L. (2015). "The Anthropoceneans." Geographical Research **53**(3): 313-320.

Hillman, M. (2005). "Justice in river management: community perceptions from the Hunter Valley, New South Wales." Geographical Research **43**(2): 153-161.

Hillman, M. (2006). "Situated justice in environmental decision-making: Lessons from river management in Southeastern Australia." Geoforum **37**(5): 695-707.

Hillman, M. (2009). "Integrating knowledge: The key challenge for a new paradigm in river management." Geography Compass **3**(6): 1988-2010.

Hillman, M. and G. Brierley (2005). "A critical review of catchment-scale stream rehabilitation programmes." Progress in Physical Geography **29**(1): 55-70.

Hillman, M., G. Brierley and K. Fryirs (2008). Social and biophysical connectivity of river systems. River futures: An integrative scientific approach to river repair. G. Brierley and K. Fryirs. Washington DC, USA, Island Press.

Hobbs, R. J., E. Higgs and J. A. Harris (2009). "Novel ecosystems: implications for conservation and restoration." Trends in Ecology and Evolution **24**(11): 599-605.

Hogg, A. G., Q. Hua, P. G. Blackwell, M. Niu, C. E. Buck, T. P. Guilderson, T. J. Heaton, J. G. Palmer, P. J. Reimer, R. W. Reimer, C. S. M. Turney and S. R. H. Zimmerman (2013). "SHCal13 Southern Hemisphere calibration, 0-50,000 years cal BP." Radiocarbon **55**(4): 1889-1903.

Holling, C. S. and G. K. Meffe (1996). "Command and control and the pathology of natural resource management." Conservation Biology **10**(2): 328-327.

Hope, G. (2002). The mountain mires of southern New South Wales and the Australian Capital Territory: Their history and future. International Year of Mountains Conference, Jindabyne, Australia.

Howitt, R. (1993). "Social impact assessment as applied peoples geography." Australian Geographical Studies **31**: 127-140.

Howitt, R. (1998). "Scale as relation: musical metaphors of geographical scale." Area **30**: 49-58.

Howitt, R. (2001). Rethinking Resource Management: justice, sustainability and Indigenous peoples. London, UK, Routledge.

Howitt, R. and S. Suchet-Pearson (2003). Ontological pluralism in contested cultural landscapes. Handbook of Cultural Geography. K. Anderson, M. Domosh, S. Pile and N. Thrift. London, UK, SAGE Publications.

Howitt, R. and S. Suchet-Pearson (2006). "Rethinking the building blocks: Ontological pluralism and the idea of 'management'." Geografiska Annaler: Series B, Human Geography **88**(3): 323-335.

Hughes, P., W. Shawcross, M. Sullivan and N. Spooner (2014). "The geoarchaeology of a Holocene site on the Woolshed Embankment, Lake George, New South Wales." Australian Archaeology **78**: 24-32.

Hugo, G. (2011). "Geography and population in Australia: A historical perspective." Geographical Research **49**(3): 242-260.

Humphries, P. (2007). "Historical Indigenous use of aquatic resources in Australia's Murray-Darling Basin, and its implications for river management." Ecological Management & Restoration **8**(2): 106-113.

Jackson, R. B., S. R. Carpenter, C. N. Dahm, D. M. McKnight, R. J. Naiman, S. L. Postel and S. W. Running (2001). "Water in a changing world." Ecological Applications **11**(4): 1027-1045.

Jackson, S. (2006). "Compartmentalising culture: The articulation and consideration of Indigenous values in water resource management." Australian Geographer **37**(1): 19-31.

Jackson, S., M. Storrs and J. Morrison (2005). "Recognition of Aboriginal rights, interests and values in river research and management: Perspectives from northern Australia." Ecological Management & Restoration **6**(2): 105-110.

Jacobsen, G., J. Jankowski and R. S. Abell (1991). "Groundwater and surface water interaction at Lake George, New South Wales." BMR Journal of Australian Geology and Geophysics **12**: 161-190.

Jacobsen, G. and A. W. Schuett (1979). "Water levels, balance, and chemistry of Lake George, New South Wales." BMR Journal of Australian Geology and Geophysics **4**(1): 25-32.

Johnston, P. and G. Brierley (2006). "Late Quaternary river evolution of floodplain pockets along Mulloon Creek, New South Wales, Australia." The Holocene **16**(5): 661-674.

Kershaw, A. P., D. M. D'Costa, J. R. C. McEwen and B. E. Wagstaff (1991). "Palynological evidence for Quaternary vegetation and environments of mainland southeastern Australia." Quaternary Science Reviews **10**: 391-404.

Kingsley, J. Y., M. Townsend, R. Phillips and D. Aldous (2009). ""If the land is healthy ... it makes the people healthy": the relationship between caring for Country and health for the Yorta Yorta Nation, Boonwurrung and Bangerang Tribes." Health and Place **15**(1): 291-299.

Knighton, A. D. and G. C. Nanson (2000). "Waterhole form and process in the anastomosing channel system of Cooper Creek, Australia." Geomorphology **35**(1-2): 101-117.

Kondolf, G. M. (1995). "Geomorphological stream channel classification in aquatic habitat restoration: Uses and limitations." Aquatic Conservation: Marine and Freshwater Ecosystems **5**(2): 127-141.

Lane, S. N. (2014). "Acting, predicting and intervening in a socio-hydrological world." Hydrology and Earth System Sciences **18**(3): 927-952.

Lave, R., M. W. Wilson, E. S. Barron, C. Bierman, M. A. Carey, C. S. Duvall, L. Johnson, M. Lane, J. Lorimer, N. McClintock, D. Munroe, R. Pain, J. Proctor, B. L. Rhoads, M. M. Robertson, J. Rossi, N. F. Sayre, G. Simon, M. Tadaki and C. Van Dyke (2014). "Intervention: Cultural physical geography." The Canadian Geographer / Le Géographe canadien **58**(1): 1-10.

Lewin, J. and M. G. Macklin (2014). "Marking time in Geomorphology: should we try to formalise an Anthropocene definition?" Earth Surface Processes and Landforms **39**(1): 133-137.

Linton, J. and J. Budds (2014). "The hydrosocial cycle: Defining and mobilizing a relational-dialectical approach to water." Geoforum **57**: 170-180.

Liu, J., T. Dietz, S. R. Carpenter, M. Alberti, C. Folke, E. Moran, A. N. Pell, P. Deadman, T. Kratz, J. Lubchenco, E. Ostrom, Z. Ouyang, W. Provencher, C. L. Redman, S. H. Schneider and W. W. Taylor (2007). "Complexity of coupled human and natural systems." Science **317**(5844): 1513-1516.

Local Land Services. (2015). "About LLS." Retrieved 26.08.2015, from http://www.lls.nsw.gov.au/about.

Mactaggart, B., J. Bauer and D. Goldney (2007). "When history may lead us astray: Using historical documents to reconstruct swampy meadows/chains of ponds in the New South Wales Central Tablelands, Australia." Australian Geographer **38**(2): 233-252.

Mactaggart, B., J. Bauer, D. Goldney and A. Rawson (2008). "Problems in naming and defining the swampy meadow – an Australian perspective." Journal of Environmental Management **87**(3): 461-473.

McIntyre-Tamwoy, S. (2004). "Social Value, the Cultural Component in Natural Resource Management." Australasian Journal of Environmental Management **11**(4): 289-299.

Miall, A. D. (1999). "In defense of facies classifications and models." Journal of Sedimentary Research, Section A: Sedimentary Petrology and Processes **69**(1): 2-5.

Mortlock, A. J. (1982). "Lake Bathurst: Investigating its history and environs." Canberra Historical Journal **10**: 13-15.

Murray, A. B., G. Coco and E. B. Goldstein (2014). "Cause and effect in geomorphic systems: Complex systems perspectives." Geomorphology **214**: 1-9.

Naiman, R. J., D. G. Lonzarich, T. J. Beechie and S. C. Ralph (1992). General principles of classification and the assessment of conservation potential in rivers. River conservation and management. P. J. Boon, P. Calow and G. E. Petts. Chichester, UK, Wiley.

Nanson, R. A. (2009). "The evolution of peat-swamp channels and organic floodplains, Barrington Tops, New South Wales, Australia." Geographical Research **47**(4): 434-448.

Nanson, R. A. and T. J. Cohen (2014). "Headwater peatland channels in south-eastern Australia; the attainment of equilibrium." Geomorphology **212**: 72-83.

Navin Officer Heritage Consultants (1998). A study at Crisp's Creek and Woodlawn, Unpublished report.

NSW Aboriginal Land Council. (2009). "About ALC: Aims and objectives." Retrieved 26.08.2015, from http://www.alc.org.au/about-nswalc/our-organisation.aspx.

O'Faircheallaigh, C. (1999). "Making social impact assessment count: A negotiation-based approach for Indigenous peoples." Society & Natural Resources **12**: 63-80.

Oxley, J. (1820). Remarks on the country between Bathurst and Lake George, including the country southwest of the Cowpastures.

Phillips, J. D. (2006a). "Deterministic chaos and historical geomorphology: A review and look forward." Geomorphology **76**(1-2): 109-121.

Phillips, J. D. (2006b). "Evolutionary geomorphology: thresholds and nonlinearity in landform response to environmental change." Hydrology and Earth System Sciences **10**(5): 731-742.

Phillips, J. D. (2007). "The perfect landscape." Geomorphology **84**(3-4): 159-169.

Phillips, J. D. (2015). "Badass geomorphology." Earth Surface Processes and Landforms **40**(1): 22-33.

Plumwood, V. (2002). "Decolonisation relationships with nature." PAN: Philosophy Activism Nature **2**: 7-30.

Prosser, I. P. (1990). "Fire, humans and denudation at Wangrah Creek, Southern Tablelands, N.S.W." Australian Geographical Studies **28**(1): 77-95.

Prosser, I. P. (1991). "A comparison of past and present episodes of gully erosion at Wangrah Creek, Southern Tablelands, New South Wales." Australian Geographical Studies **29**(1): 139-154.

Prosser, I. P., J. Chappell and R. Gillespie (1994). "Holocene valley aggradation and gully erosion in headwater catchments, south-eastern highlands of Australia." Earth Surface Processes and Landforms **19**(5): 465-480.

Prosser, I. P. and C. J. Slade (1994). "Gully formation and the role of valley-floor vegetation, southeastern Australia." Geology **22**(12): 1127.

Prosser, I. P. and S. J. Winchester (1996). "History and processes of gully initiation and development in eastern Australia." Zeitschrift fur Geomorphologie Supplementband **105**: 91-109.

Ralph, T. J. and P. P. Hesse (2010). "Downstream hydrogeomorphic changes along the Macquarie River, southeastern Australia, leading to channel breakdown and floodplain wetlands." Geomorphology **118**(1-2): 48-64.

Rose, D. B. (1999). Indigenous ecologies and an ethic of connection. Global ethics and environment. N. Low. London, UK, Routledge**:** 175-187.

Rustomji, P. and T. Pietsch (2007). "Alluvial sedimentation rates from southeastern Australia indicate post-European settlement landscape recovery." Geomorphology **90**(1-2): 73-90.

Ryder, D. S., M. Tomlinson, B. Gawne and G. E. Likens (2010). "Defining and using 'best available sceience': A policy conundrum for the management of aquatic ecosystems." Marine and Freshwater Research **61**(7): 821-828.

Schumm, S. (1977). The fluvial system. Caldwell, NJ, USA, The Blackburn Press.

Snelder, T. H. and B. J. F. Biggs (2002). "Multiscale river environmental classification for water resources management." Journal of the American Water Resources Association **38**(5): 1225-1240.

Steffen, W., J. Grinevald, P. Crutzen and J. McNeill (2011). "The Anthropocene: conceptual and historical perspectives." Philosophical transactions. Series A, Mathematical, physical and engineering sciences **369**(1938): 842-867.

Suchet, S. (2002). "'Totally Wild'? Colonising discourses, indigenous knowledges and managing wildlife." Australian Geographer **33**(2): 141-157.

Surian, N., L. Ziliani, F. Comiti, M. A. Lenzi and L. Mao (2009). "Channel adjustments and alteration of sediment fluxes in gravel-bed rivers of North-Eastern Italy: Potentials and limitations for channel recovery." River Research and Applications **25**(5): 551-567.

Tadaki, M., G. Brierley and C. Cullum (2014). "River classification: theory, practice, politics." Wiley Interdisciplinary Reviews: Water **1**(4): 349-367.

Tadaki, M., G. Brierley, M. Dickson, R. Le Heron and J. Salmond (2015). "Cultivating critical practices in physical geography." The Geographical Journal **181**(2): 160-171.

Tadaki, M., J. Salmond, R. Le Heron and G. Brierley (2012). "Nature, culture, and the work of physical geography." Transactions of the Institute of British Geographers **37**(4): 547-562.

Talma, A. S. and J. C. Vogel (1993). "A simplified approach to calibrating C14 dates." Radiocarbon **35**(2): 317-322.

Taylor, K. (1990). "Historic cultural landscapes and emerging heritage values: and Australian perspective." Landscape Research **15**(2): 12-18.

Taylor, M. P. and R. Stokes (2005). "When is a river not a river? Consideration of the legal definition of a river for geomorphologists practising in New South Wales, Australia." Australian Geographer **36**(2): 183-200.

Thorne, C. R., R. D. Hey and M. D. Newson (1997). Applied fluvial geomorphology for river engineering and management, John Wiley & Sons Ltd.

Tooth, S. and T. S. McCarthy (2007). "Wetlands in drylands: geomorphological and sedimentological characteristics, with emphasis on examples from southern Africa." Progress in Physical Geography **31**(1): 3-41.

Vogel, R. M., U. Lall, X. Cai, B. Rajagopalan, P. K. Weiskel, R. P. Hooper and N. C. Matalas (2015). "Hydrology: The interdisciplinary science of water." Water Resources Research **51**(6): 4409-4430.

Walters, C. J. (1986). Adaptive management of renewable resources. New York, NY, USA, Macmillan.

Wasson, R. J., R. K. Mazari, B. Starr and G. Clifton (1998). "The recent history of erosion and sedimentation on the Southern Tablelands of southeastern Australia: Sediment flux dominated by channel incision." Geomorphology **24**(4): 291-308.

Weir, J. (2009). Murray River Country: An ecological dialogue with traditional owners. Aboriginal Studies Press, Canberra, ACT, Australia.

Whinam, J., G. S. Hope, B. R. Clarkson, R. P. Buxton, P. A. Alspach and P. Adam (2003). "Sphagnum in peatlands of Australia: Their distribution, utilisation and management." Wetlands Ecology and Management **11**(1): 37-49.

Wilcock, D. and G. Brierley (2012). "It's about time: Extending time-space discussion in geography through use of 'ethnogeomorphology' as an education and communication tool." Journal of Sustainability Education **3**(19).

Wilcock, D., G. Brierley and R. Howitt (2013). "Ethnogeomorphology." Progress in Physical Geography **37**(5): 573-600.

Wilcock, D. A. (2013). "From blank spaces to flows of life: transforming community engagement in environmental decision-making and its implications for localism." Policy Studies **34**(4): 455-473.

Wohl, E., A. K. Gerlak, N. L. Poff and A. Chin (2014). "Common core themes in geomorphic, ecological, and social systems." Environmental Management **53**(1): 14-27.

Woolley, J. (1990). Lake George with historical notes on Bungendore and Collector. Goulburn, NSW, Goulburn and District Historical Society.

Young, A. R. M. (1986). "Quaternary sedimentation on the Woronora Plateau and its implications for climatic change." Australian Geographer **17**(1): 1-5.

Zierholz, C., I. P. Prosser, P. J. Fogarty and P. Rustomji (2001). "In-stream wetlands and their significance for channel filling and the catchment sediment budget, Jugiong Creek, New South Wales." Geomorphology **38**(3-4): 221-235.

7 Appendix

Office of the Deputy Vice-Chancellor
(Research)

Research Office
Research Hub, Building C5C East
Macquarie University
NSW 2109 Australia
T: +61 (2) 9850 4459
http://www.research.mq.edu.au/
ABN 90 952 801 237

18 March 2015

Associate Professor Kirstie Fryirs
Department of Environmental Sciences
Faculty of Sciences and Engineering
Macquarie University
NSW 2109

Dear Associate Professor Fryirs

Reference No: 5201500083

Title: *Geomorphology and cross-cultural environmental history of a chain of ponds river, Crisp's Creek, southeast Australia*

Thank you for submitting the above application for ethical and scientific review. Your application was considered by the Macquarie University Human Research Ethics Committee (HREC (Human Sciences & Humanities)) at its meeting on 27 February 2015

I am pleased to advise that ethical and scientific approval has been granted for this project to be conducted at:

- Macquarie University

This research meets the requirements set out in the *National Statement on Ethical Conduct in Human Research* (2007 – Updated March 2014) (the *National Statement*).

This letter constitutes ethical and scientific approval only.

Standard Conditions of Approval:

1. Continuing compliance with the requirements of the *National Statement,* which is available at the following website:

http://www.nhmrc.gov.au/book/national-statement-ethical-conduct-human-research

2. This approval is valid for five (5) years, subject to the submission of annual reports. Please submit your reports on the anniversary of the approval for this protocol.

3. All adverse events, including events which might affect the continued ethical and scientific acceptability of the project, must be reported to the HREC within 72 hours.

4. Proposed changes to the protocol must be submitted to the Committee for approval before implementation.

It is the responsibility of the Chief investigator to retain a copy of all documentation related to this project and to forward a copy of this approval letter to all personnel listed on the project.

Should you have any queries regarding your project, please contact the Ethics Secretariat on 9850 4194 or by email ethics.secretariat@mq.edu.au

The HREC (Human Sciences and Humanities) Terms of Reference and Standard Operating Procedures are available from the Research Office website at:

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics

The HREC (Human Sciences and Humanities) wishes you every success in your research.

Yours sincerely

Dr Karolyn White
Director, Research Ethics & Integrity,
Chair, Human Research Ethics Committee (Human Sciences and Humanities)

This HREC is constituted and operates in accordance with the National Health and Medical Research Council's (NHMRC) *National Statement on Ethical Conduct in Human Research* (2007) and the *CPMP/ICH Note for Guidance on Good Clinical Practice.*

Details of this approval are as follows:

Approval Date: 27 February 2015

The following documentation has been reviewed and approved by the HREC (Human Sciences & Humanities):

Documents reviewed	Version no.	Date
Macquarie University Ethics Application Form	2.3	July 2013
Appendix A: Research Involving Aboriginal and Torres Strait Islanders		
MQ Participant Information and Consent Form (PICF) entitled *Crisp's Creek Geomorphic Environmental History Project*	1	12/02/2015
Interview questions		