The Hydro-Geomorphic Structure, Function and Evolution of Chains-of-Ponds: Implications for Recognition of These Discontinuous Watercourses in River Management

Rory T. Williams
BSc (Hons)

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Department of Environmental Sciences
Macquarie University
New South Wales, Australia

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For Chren and Jude

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Abstract

The hydro-geomorphic structure and function of river and wetland systems provide a physical template for ecosystem functions, allowing for their recognition, conservation and rehabilitation. This thesis examines the diverse geomorphic structure and hydrological processes of a spectrum of chain-of-ponds morphologies, identifying the intrinsic and extrinsic controls on their formation, evolution and impairment or loss. Chains-of-ponds consist of steep-sided ponds separated by densely vegetated alluvial valley-fill sediments that contain shallow ephemeral channels or preferential flow paths. They are part of the spectrum of discontinuous watercourses that are important landscape features due to their unique geomorphological, hydrological and ecological function.

Analysis of seven headwater chain-of-ponds reaches reveal morphological diversity, in both planform and stratigraphy, and in varying stages of evolution. Sensitivity assessments of these reaches, combined with two-dimensional hydraulic modelling, precipitated the quantification of measurable pond and planform characteristics associated with geomorphic condition. This examination developed three quantitative metrics that provide a measure of event sensitivity, morphological sensitivity and change sensitivity that can be used to guide the management of smaller-scale headwater systems.

Stratigraphic analysis and luminescence dating of larger-scale chains-of-ponds on higher-order streams show different formation processes that result from threshold changes in fluvial energy over the late Quaternary, with antecedent controls on the size and position of much deeper (up to 7 m) and more stable ponds. This adds important insight to the range of non-linear responses through both intrinsic controls and also more complex responses from the persistence of palaeo landforms.

This analyses improve the understanding of intrinsic controls on fluvial evolution and will help assess recovery potential through forecasting future trajectories, guiding approaches to maintaining or restoring ecosystem function of discontinuous headwater systems in southeast Australia and similar systems internationally.

Stable isotopes ($\delta^{18}O$ and $\delta^{2}H$), ^{222}Rn, and pond and floodplain water levels revealed that the hydrology and ecosystem function of large-scale chains-of-ponds, and discontinuous fluvial systems more generally, could be highly sensitive to local-scale water extraction, shallow groundwater aquifer interference and changes to groundwater recharge due to climatic changes. The surficial appearance of discontinuity masks the continuous longitudinal flow of the alluvial aquifer during both high-flow and no-flow stages, highlighting the importance of subsurface and hyporheic processes in defining the hydrological character of a river.

This thesis strengthens the understanding of the hydro-geomorphological processes of discontinuous systems to facilitate ecosystem managers to develop workable strategies for protecting and managing systems that, due to their discontinuous form, do not as yet receive the same legal status or protection as other rivers.

Statement of Originality

This work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

19 May 2018

Rory T. Williams

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Chapter 1

Introduction

1.1. Hydro-geomorphic structure and processes, and ecosystem function of chains-of-ponds

Fundamental to the protection and management of riverine ecosystems is the integration of ecological, hydrological and geomorphological processes (Mažeika et al., 2004; Newson and Newson, 2000; Thoms and Sheldon, 2002; Vaughan et al., 2009), which operate, and often evolve concurrently, within variable and dynamic riverine environments (Renschler et al., 2007). Ideally, river management should aim for self-sustaining recovery (Palmer et al., 2005; Rutherfurd et al., 2000a), requiring knowledge of natural and modified processes, morphology and variability of fluvial systems (Fryirs et al., 2012; Kondolf and Larson, 1995).

Hydro-geomorphic processes, or the interactions between streamflow and geomorphic features, govern the physical template for fluvial ecosystem function (Bellmore and Baxter, 2014; Montgomery, 1999). The magnitude and frequency of these processes set limits to the geomorphic forms, upon which, feedbacks between hydrology, geomorphology and biota (Corenblit et al., 2011; Gurnell et al., 2012) create a range of morphologies and habitats across spatial and temporal scales (Brierley et al., 2006; Datry et al., 2016; Montgomery, 1999; Thorp et al., 2006). These scales range spatially from an individual geomorphic unit, such as a riffle in a stream, to the whole channel network, and temporally from hours to thousands of years. Therefore, foundation science on the hydrological processes and geomorphic structure of riverine ecosystems is essential, as it provides a critical component in establishing ecosystem function (Brierley and Fryirs, 2005) and services (Thorp et al., 2010).

Rivers are dynamic in their adjustment of form across a range of temporal and spatial scales and applies to both the flow of water and their geomorphic character and behaviour (Brierley and Fryirs, 2005). This adjustment is especially evident in catchment headwaters where geomorphic form is often shaped by highly variable flows, which act upon an area in the landscape that is at the threshold of form adjustment (i.e. channel formation). Headwater streams with discontinuity of flow and/or channel are geo-ecologically important (Acuña et al., 2017; Finn et al., 2011; Wohl, 2017) encompassing 50–70% of the global channel network (Downing et al., 2012; Nadeau and Rains, 2007; Sheldon et al., 2010), and influence downstream water quality (Alexander et al., 2007), sediment yields (Jaeger et al., 2017), biota and ecological connectivity (Freeman et al., 2007; U.S. EPA., 2015). These ecosystems also provide a number of services including carbon storage (Cowley et al., 2017; Grand-Clement et al., 2013), nutrient cycling (McClain et al., 2003), flood retention and base flow (Butturini et al., 2002; Freidman and Fryirs, 2015; Grand-Clement et al., 2013) and recreation (Steward et al., 2012), among others (Boulton, 2014; Koundouri et al., 2017). However, they may be perceived as less important (Armstrong et al., 2012) and remain under-represented in research due to a bias toward higher-order streams (Koundouri et al., 2017; Vaughan and Ormerod, 2010). There is an international call to understand the hydrological, geomorphological and ecological function and connectivity of headwater streams, especially those displaying discontinuity of flow and channel form (Acuña et al., 2014; Acuña et al., 2017; Bauer et al., 2017; Creed et al., 2017; Davies et al., 2011; Meyer et al., 2007; Wohl, 2017). This has stemmed from the uncertainty of their protection under policy and legislation (Doyle and Bernhardt, 2011; Kalen, 2007; Lamaro et al., 2007; Murphy, 2007; Taylor et al., 2011) and their unrepresentative or inadequate management (Gomi et al., 2002).

1.2. Channel and flow discontinuity in rivers

There have been numerous studies of discontinuous watercourses in upland settings that have both channel and flow discontinuity, and there is now a body of literature on their geomorphic structure and hydro-geomorphic processes. Figure 1, which broadly characterises examples of discontinuous watercourses relative to channel and flow continuity, shows that it is not a linear relationship between permanence or period of flow and channel continuity, but must be driven other factors. In temperate settings, discharge in these systems is often ephemeral but their alluvial valley floors maintain significantly higher moisture levels than the surround area and include; cut and fill landscapes (Erskine and Melville, 2008; Fryirs and Brierley, 1998; Johnston and Brierley, 2006; Prosser, 1991), swampy meadows (Mactaggart, 2008; Prosser et al., 1994), chains-of-ponds (Cartwright and Morgenstern, 2016; Eyles, 1977a; Hazell et al., 2003; Mould and Fryirs, 2017) and dambos (Mäckel, 1973; von der Heyden, 2004). Headwater discontinuous systems in more arid environments include arroyos (Bull, 1997; Cooke and Reeves, 1976; Schumm and Hadley, 1957) and vleis (Grenfell et al., 2009) among other ephemeral systems (Hooke, 2016; Sutfin et al., 2014), with larger scale floodouts and wetlands in lowland settings (Ellery et al., 1993; Ralph and Hesse, 2010; Tooth et al., 2014). In humid and higher rainfall environments, similar hydro-geomorphic processes of intermittent to ephemeral discharge over alluvial valley fills, create systems that (when undisturbed) are generally unchannelised, maintain higher water tables and may be peat forming, including but not limited to; upland swamps (Cowley et al., 2016; Freidman and Fryirs, 2015; Fryirs et al., 2014a; Fryirs et al., 2014b; Nanson, 2009), dells (Young, 1986a; Young, 1986b) and mires (Bragg, 2002; Bragg and Tallis, 2001;

Evans and Warburton, 2007; Gore, 1983; Nanson and Cohen, 2014; Pemberton, 2005). These range of forms show that there are diverse discontinuous geomorphic responses in valley-fill headwater systems, depending on the climate and variability of precipitation, lithology, surface water and groundwater flow, and vegetation (Evans and Warburton, 2007; Knighton, 1998).

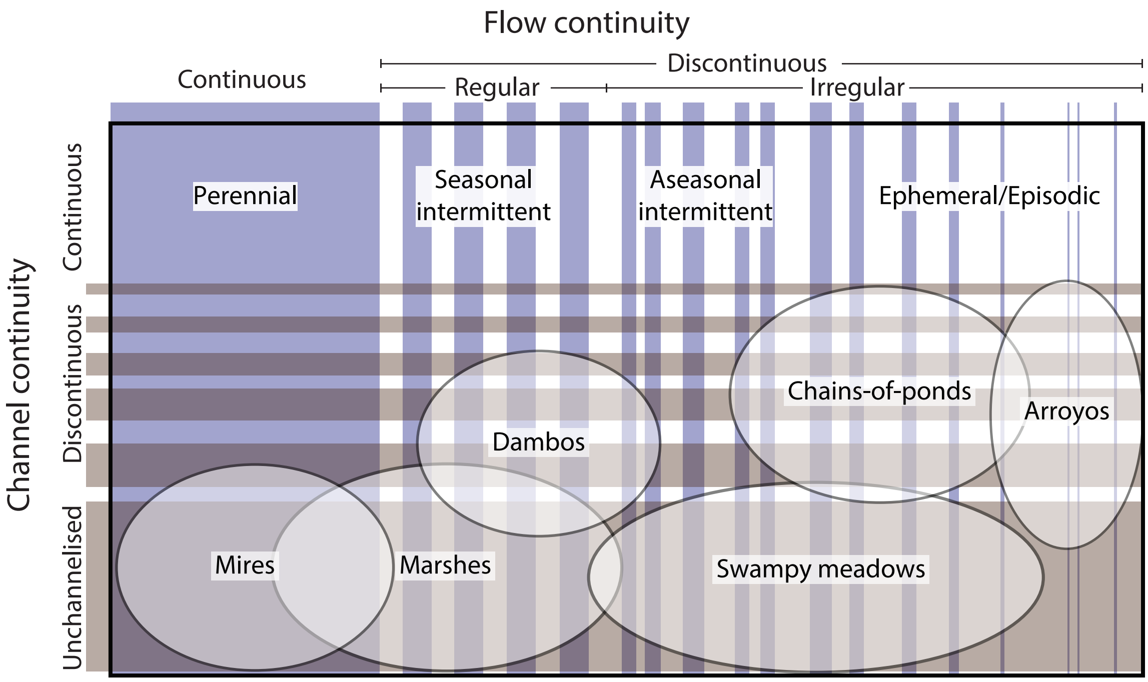

Figure 1. Broad characterisation of examples of rivers with channel and flow discontinuity using some of the terminology from Uys and O'Keeffe (1997), Mactaggart et al. (2008) and Gore (1983)

1.3. Alluvial valley-fill evolution

Valley-fill fluvial systems form in lower slope valley bottoms where a balance of stream power and vegetation allows the accretion of alluvial sediment, both fine-grained muds and sand sheets (Bull, 1997; Evans and Warburton, 2007; Fryirs and Brierley, 1998; Nanson and Croke, 1992; Prosser et al., 1994). The rates of valley-fill accretion vary depending on the lithology, slope and variability of flows. Valley-fills become incised, typically through gully development, when the system extends beyond a threshold. These thresholds can be either intrinsic, such as over steepening or in situ disturbance (both natural and anthropogenic), or extrinsic such as changes in climate or landuse (Bull, 1997; Erskine and Melville, 2008; Eyles, 1977a; Fryirs et al., 2016; Johnston and Brierley, 2006; Prosser et al., 1994). Similar to other headwater systems, many alluvial valley-fills have initiated since the Last Glacial Maximum (Eriksson et al., 2006; Fryirs et al., 2014a; Johnston and Brierley, 2006; Mould and Fryirs, 2017), but may have been through multiple phases of incision and aggradation over this time (Fryirs and Brierley, 1998; Prosser, 1991; Prosser and Winchester, 1996).

While these systems are generally a resilient landform, having stabilised over thousands of years, they are sensitive to disturbance, particularly rapid changes to landuse that alters the vegetation and hydrograph (Eyles, 1977b; Prosser et al., 1994).

1.4. Chains-of-ponds structure and function

The term chain-of-ponds has often been applied to systems based on their description of being irregularly spaced, steep-sided ponds separated by densely vegetated alluvial valley-fill sediments (Eyles, 1977a; Hazell et al., 2003; Mould and Fryirs, 2017) (see Figure 2). The basic morphological and planform descriptors of these discontinuous fluvial systems are not necessarily linked to the hydro-geomorphic processes that create or maintain them. The ponds that have been studied fall in two groups of different scale, in both ponds size and catchment location. In the headwater reaches (catchment area <10 km^2) studied by Eyles (1977a) and Mould and Fryirs (2017), ponds form through the scour of alluvial sediment of low-gradient drainage lines or floodplains, and are connected by shallow ephemeral channels or preferential flow paths across 'swampy meadows' (Mactaggart et al., 2008). The ponds are recorded as being up to 2.5 m deep, with surface areas of 1–255 m^2 (Eyles, 1977a), or widths up to 15 m (Mould and Fryirs, 2017). There is no research to date that describes the geomorphic structure and evolution of rarer large-scale chains-of-ponds, other than a mention by Eyles (1977b) that one of the ponds on the Mulwaree River was 11 m deep and may have formed as a 'fixed bar' pond. Other studies record large ponds with diameters up to 70 m (Zavadil and Ivezich, 2011) and are found in positions with catchment areas up to 300 km^2 (Cartwright and Gilfedder, 2015; Erskine and Melville, 2008; Zavadil and Ivezich, 2011). Headwater chains-of-ponds are noted as a previously ubiquitous landform in many upland drainage lines (Rutherfurd et al., 2000b), but land-use changes, such as agriculture or forestry, and direct modification have placed chains-of-ponds at risk or resulted in their loss (Eyles, 1977b; Prosser et al., 1994; Zavadil and Ivezich, 2011). The chains-of-ponds that remain, in headwaters or with larger catchment areas, are of (geo)ecological significance as they are habitat to species dependent on permanent (or longer term) lentic water (Hazell et al., 2003), provide refuge during periods of low- or no-flow (Cartwright and Gilfedder, 2015) and are representative of pre-European small– to medium–sized rivers (Brierley et al., 2002; Eyles, 1977b; Rutherfurd et al., 2000a). Despite the conservation priority for systems that are rare (Bennett et al., 2002; Dunn, 2000) or distinctive (Aquatic Ecosystems Task Group, 2012), knowledge of the geographical extent, and hydro-geomorphic and ecological diversity of chains-of-ponds is poor. This reduces the capacity of land managers to conserve and rehabilitate these rare and important systems, and for their protection through inclusion in policy and legislation.

Figure 2. Photos of chains-of-ponds showing intact and incised ponds, and the diversity in valley setting, planform characteristics and size. All photos are from the two field sites in this study: The Mulwaree River south of Goulburn, NSW, containing the large-scale chain-of-ponds, and; Mihi and Jacks Creeks, which are adjacent tributaries in the headwaters of the Macleay catchment in northern NSW.

To enable the protection of these ecosystems there needs to be an understanding of the hydro-geomorphic processes that form and maintain the variety of chains-of-ponds and the spectrum of discontinuous watercourse more generally. Specific knowledge gaps include: their long-term evolution, including the structure and timing of the valley fill sediments and the formation of the ponds, to guide efforts to restore or repair these systems; the sensitivity of chains-of-ponds to altered hydrological conditions, disturbance and landuse changes; surface and subsurface hydrological process, and how changes will impact the morphology and habitats of the system.

1.5. Thesis Aims and Structure

The overarching objective of this thesis is to understand the hydro-geomorphic structure, function and evolution of chains-of-ponds to provide a scientific foundation for the recognition, conservation and rehabilitation of these discontinuous watercourses. It is built on the understanding that hydro-geomorphic processes create a physical template upon which fluvial ecosystems function, and are therefore essential in the restoration and conservation of riverine ecosystems (Brierley and Fryirs, 2008; Larned et al., 2010; Thorp et al., 2006). This objective will be achieved by examining the geomorphological characteristics, hydrological process and evolutionary sequences of chains-of-ponds to explain the spectrum of channel continuity and diversity of reach morphologies. This will be incorporated with the geomorphic concepts of river sensitivity (Fryirs, 2017) and antecedence (Brierley, 2010) to identify the controls on their formation and impairment or loss. Finally, an analysis of legislative frameworks is required to understand how discontinuous watercourses are protected to facilitate management of these ecosystems.

This thesis has five aims:

Aim 1. Characterise the diverse hydro-geomorphic structure and function of chains-of-ponds (Chapters 2, 3 and 4);

Aim 2. Assess the nature and timing of the late Quaternary evolution of chains-of-ponds (Chapters 2 and 4);

Aim 3. Characterise the surface and subsurface hydrological processes and connectivity of chains-of-ponds (Chapters 3 and 4);

Aim 4. Develop quantitative metrics for assessing geomorphic sensitivity of chains-of-ponds (Chapter 4); and,

Aim 5. Evaluate the recognition and integration of discontinuous watercourses in policy and law (Chapter 5)

These aims are addressed via a series of in preparation papers in chapters two through five. The chapters are structured as papers and contain an introduction, regional setting, methods, results and discussion. Some repetition in the introduction and regional setting aspects of each is expected. The final chapter, the thesis discussion, synthesises the key findings of the four data chapters and highlights the significance of the contribution to the understanding of the hydro-geomorphic structure, function and evolution of chains-of-ponds and discontinuous watercourses more generally.

A summary of the relative contributions from authors on each of the in-preparation papers that comprise this thesis follows.

Chapter 2 – The morphology and evolution of a large chain-of-ponds river system: Mulwaree Ponds, NSW, Australia

Williams, R.T. and Fryirs, K.A., In Prep. The morphology and evolution of a large chain-of-ponds river system: Mulwaree Ponds, NSW, Australia

Fieldwork – Sediment core extraction carried out by RW with assistance from KF. Optically stimulated luminescence and dose rate sampling, and topographic and bathymetric surveys by RW.

Sample Analysis – All analyses carried out by RW except lithogenic radionuclides samples prepared and analysed by Australian Nuclear Science and Technology Organisation (ANSTO) staff.

Data compilation and analysis – All data compiled and analysed by RW.

Manuscript preparation – RW (85%), KF (15%). RW provided the majority of the manuscript organisation, produced and organised all the figures and wrote the majority of the manuscript. KF contributed to the writing of results and discussion and provided ideas on manuscript organisation.

Intellectual contribution – RW (90%), KF (10%). RW provided a majority of the intellectual contribution and oversaw the conceptual development of the paper, KF provided the initial idea for the paper and ideas for organisation of the results data and guidance on the discussion.

Chapter 3 – Surface water–subsurface water interactions in a large chain-of-ponds system: Hydrological function of a rare type of discontinuous watercourse

Williams, R.T., Fryirs, K.A. and Hose, G.C., In Prep. Surface water–subsurface water interactions in a large chain-of-ponds system: Hydrological function of a rare type of discontinuous watercourse

Fieldwork – All fieldwork carried out by RW

Sample Analysis – All samples prepared by RW and analysed by ANSTO staff.

Data compilation and analysis – Data compiled and analysed by RW (90%) and ANSTO staff (10%).

Manuscript preparation – RW (80%), KF (10%) and GH (10%). RW provided the majority of the manuscript organisation, produced and organised all the figures and wrote the majority of the manuscript. KF and GH contributed to the introduction, results, discussion and manuscript organisation.

Intellectual contribution – RW (80%), KF (10%) and GH (10%). RW provided a majority of the intellectual contribution and oversaw the conceptual development of the paper, KF and GH provided ideas for organisation of the results and guidance on the discussion.

Chapter 4 – Diversity of chains-of-ponds and reach-scale sensitivity analysis

Williams, R.T. and Fryirs, K.A., In Prep. Diversity of chains-of-ponds and reach-scale sensitivity analysis

Fieldwork – All fieldwork carried out by RW

Sample Analysis – All analyses by RW except lithogenic radionuclides samples prepared and analysed by ANSTO staff.

Data compilation, modelling and analysis – All by RW.

Manuscript preparation – RW (95%) and KF (5%). RW provided the majority of the manuscript organisation, produced and organised all the figures and wrote the majority of the manuscript. KF and provided feedback on the discussion and manuscript organisation.

Intellectual contribution – RW (95%) and KF (5%). RW provided a majority of the intellectual contribution and oversaw the conceptual development of the paper, KF provided ideas for organisation of the results data and guidance on the discussion.

Chapter 5 – Recognition of discontinuous watercourses in river science and policy

Williams, R.T. and Fryirs, K.A., In Prep. A commentary on the recognition of discontinuous watercourses in river science and policy in Australian law

Investigation and analysis – All by RW.

Manuscript preparation – RW (95%) and KF (5%). RW provided the majority of the manuscript organisation and wrote the majority of the manuscript. KF and provided feedback on the discussion and manuscript organisation.

Intellectual contribution – RW (95%) and KF (5%). RW provided a majority of the intellectual contribution and oversaw the conceptual development of the paper, KF provided ideas for organisation manuscript and guidance on the discussion.

1.6. Field sites

Two field sites have been chosen that characterise distinct chains-of-ponds. The more commonly described headwater, or small-scale, chains-of-ponds (Eyles, 1977a; Hazell et al., 2003; Mactaggart et al., 2008; Mould and Fryirs, 2017) are found along the upper reaches of Mihi Creek, NSW (Figure 3), and are examined in Chapter 4. The large-scale chains-of-ponds are located on the Mulwaree River, NSW (Figure 3), and their morphology, evolution and hydrology are discussed in Chapters 2 and 3.

1.6.1. Mihi Creek, Northern Tablelands, NSW

The Northern Tablelands field sites are in the headwaters of Mihi Creek Catchment (Figure 3, top inset) that flows into the coastal draining Macleay River. They are located on the property 'Eastlake' (near Uralla, NSW) on the adjacent Jacks and Mihi Creeks, each with catchment areas of ~19 km^2 at their confluence. All are on land that is grazed for cattle or sheep. These reaches incorporate a range of chain-of-ponds morphologies with varying stratigraphy, valley confinement, slope and lithology. Flow through these discontinuous systems is ephemeral or episodic and only flows for a short period after heavy or sustained rainfall. Most of the ponds contain water except during extended dry periods.

1.6.2. Mulwaree River, Southern Tablelands, NSW

The Mulwaree River is a tributary in the Hawkesbury–Nepean catchment (Figure 3, bottom inset). At a catchment area of 73 km^2 the river debouches onto broad alluvial valley-fills and continues for 58 km where it joins the Wollondilly River at Goulburn, NSW. This large scale chain-of-ponds is dotted with over 100 ponds of varied size (10–50 m wide) that are connected by shallow, ephemeral channels and preferential flow paths. Episodic overland flow along the river is associated with larger rainfall events with the majority of the decline in discharge occurring during the first week, but may continue to flow for several months with successive precipitation events. Periods of no surface flow may extend for more than a year (NSW Water, 2016). The main study site, located on the property of 'Kelburn' 15 km south of Goulburn at a catchment area of 462 km^2, is a 1.7 km reach containing five large ponds that maintain permanent water. Nearly all of the lower Mulwaree River that contains the ponds is used for livestock grazing and cropping.

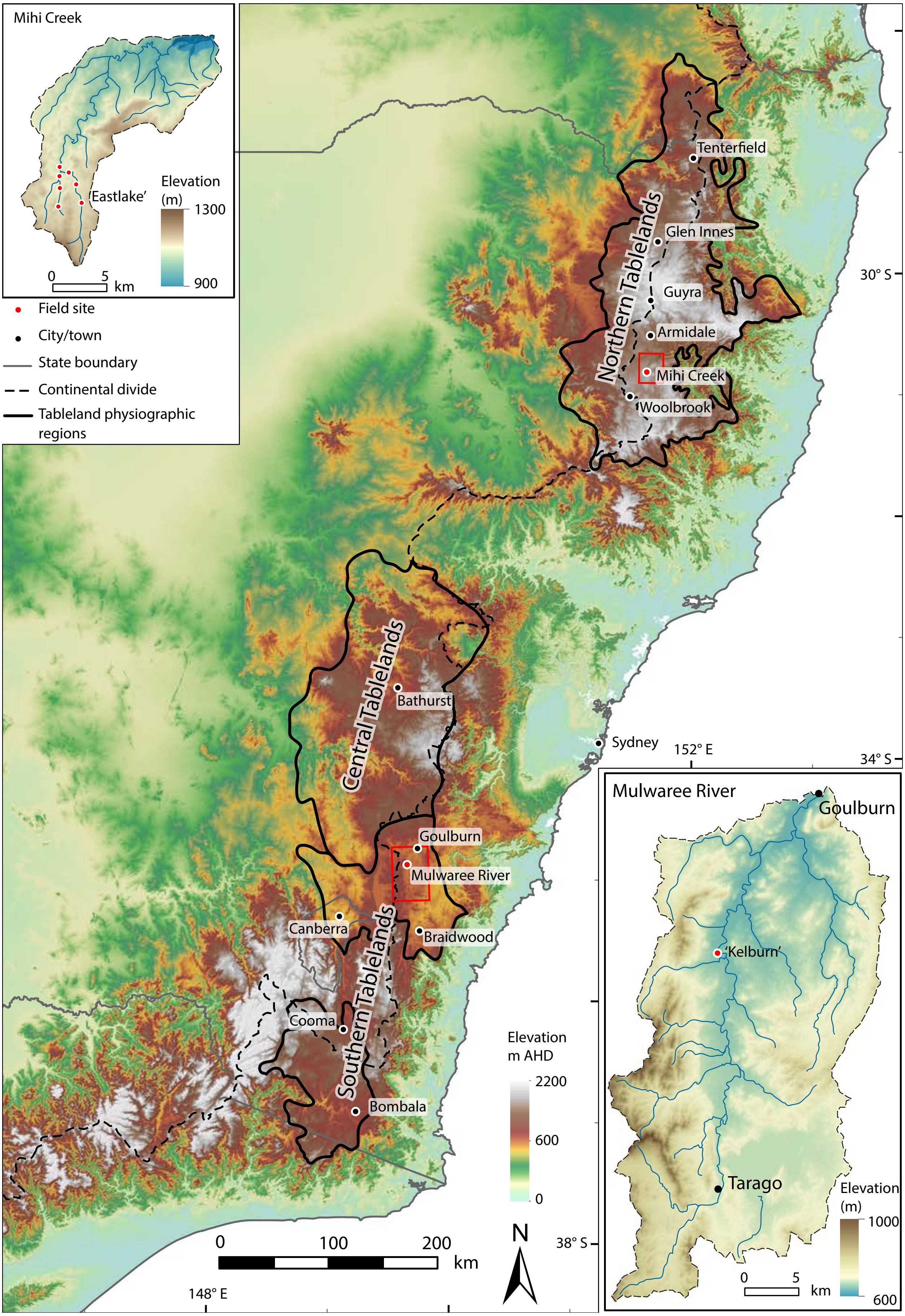

Figure 3. Tableland regions of southeast Australia. Physiographic boundaries from Pain et al. (2011) including the Tenterfield Plateau (Northern Tablelands), Bathurst Tableland (Central Tablelands) and the Werriwa and Monaro Tablelands (Southern Tablelands). Mihi Creek and Mulwaree River catchments, with field sites (red dots) shown in the top and bottom inset maps, respectively.

1.7. Regional Setting

1.7.1. Landscape and Geology

The tableland plateaus of New South Wales, Australia, extend along the Great Dividing Range, set between steep escarpments to the east and lower relief slopes and plains of the Murray Darling Basin to the west (Figure 3). Elevations are between 600 m and 1500 m, with median values higher in the North (~1000 m) compared with the Central and Southern Tablelands (700–900 m). The tablelands are dominated by Palaeozoic metamorphosed sedimentary and intrusive granite rocks of the southern Lachlan Fold Belt and northern New England Fold Belt, with Triassic granites through the northern most parts of NSW (Veevers, 2006) (Figure 4A). Extensive Tertiary basalt flows now sit atop the higher elevations and localised peaks, inverting the pre-basalt topography. The tablelands have been relatively tectonically stable for the past 20 million years and low rates of denudation (~10 m/Myr) (Bishop, 1985) have resulted in elevated, low relief plateaus with low gradient headwaters. These headwater reaches combine and flow over steep escarpments to the east, which are dissected with rapidly retreating (2 km/Myr) gorges (Nott et al., 1996; Seidl et al., 1996), and through dissected valleys and lowland plains to the west.

1.7.2. Climate and rainfall

The climate is temperate to cool temperate, with mean minimum and mean maximum temperatures ranging from approximately 12°C to 27°C in summer and approximately 0°C to 12°C in winter, varying ± 2°C across the 1000 km (or 8 degrees latitude) extent to the three tableland regions (Figure 4B) (Bureau of Meteorology, 2017). Annual precipitation is predominantly 600–1000 mm with higher values (>1400 mm) toward the eastern escarpment of the Northern Tablelands (Figure 4C). Over the majority of the Northern Tablelands rainfall is weakly summer dominant with 65–75% of the annual rainfall from November to April and is seasonally uniform over the Central and Southern Tablelands, all with moderate inter-annual variability (Bureau of Meteorology, 2017) (Figure 4C). Pan evaporation is 1200–1800 mm per year with an increasing gradient from the east on the Northern Tablelands and from the south in the Southern and Central Tablelands (Figure 4D). This creates a moisture deficit of 600–1000 mm except for the areas close to the eastern escarpment of the Northern Tablelands. This is reflected in the aridity index (mean annual precipitation divided by mean annual potential evapotranspiration) (Zomer et al., 2008) as the majority falls within the dry sub-humid to weakly humid range with values of 0.5–0.8 (Figure 4D).

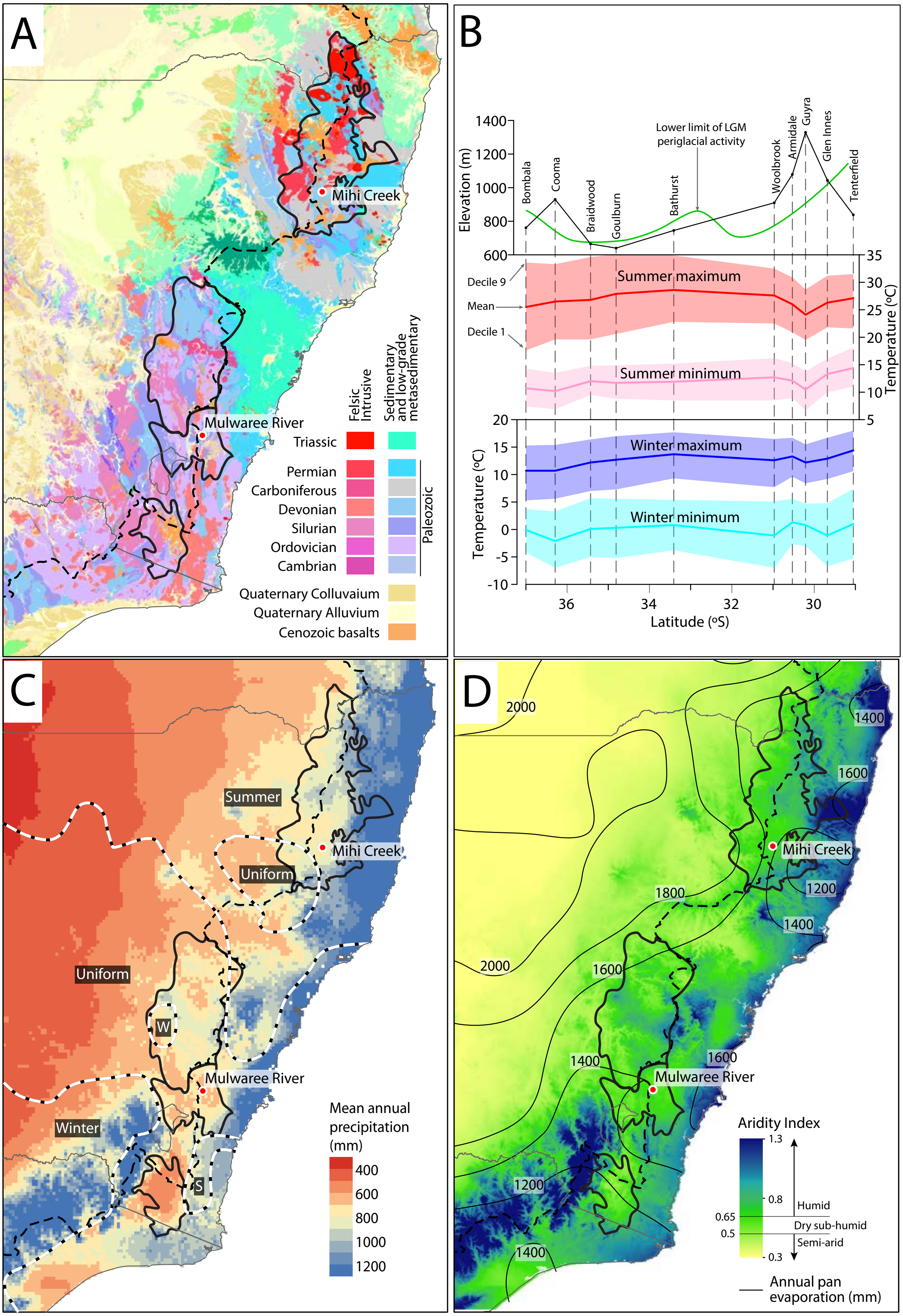

Figure 4. Extents of A, C and D are the same as Figure 3 and also shows the same physiographic regions (solid black line) and continental divided (dashed line). Details on the following page.

During the Last Glacial Maximum large parts of the Tablelands were affected by periglacial activity with temperatures up to 9°C colder in the south and 10.5°C colder in the north (Slee and Shulmeister, 2015) (Figure 4B). This led to changes in vegetation, with herbaceous plants replacing eucalypts between ~20–17 ka in higher regions, along with lower evaporation, leading to increases in runoff (Ellerton et al., 2017; Reinfelds et al., 2014; Woodward et al., 2014). There is also evidence of regionally humid conditions for the Northern Tablelands (Ellerton et al., 2017) and during this time further enhancing fluvial activity.

1.7.3. Landuse

Prior to European settlement, the Tablelands were inhabited by multiple aboriginal peoples since the mid Holocene (Hughes et al., 2014), often during the warmer months before moving to the coast or western plains for the cooler parts of the year (Godwin, 1983; Kerr et al., 1999; Rosen, 2009). Rapid land use changes occurred from the 1820s when the Tablelands were progressively settled by European squatters and pastoralists, with increased stocking rates of sheep and cattle, introduced grasses, and tree clearing through the 19th century (Butzer and Helgren, 2005; Starr, 1978).

Figure 4. (Page 14)

A) Geology of south eastern Australia (Geoscience Australia, 2012). The key only lists the main geological units of the Tableland region.

B) Mean and decile 1–9 minimum and maximum temperatures for the months of January (warmest) and July (coldest) relative to their latitude and elevation. Data for rainfall and temperature from the Bureau of Meteorology (2017). See Figure 3 for locations.

C) Rainfall of southeastern Australia showing total precipitation and seasonality of summer/winter dominance or uniform rainfall (white dashed lines).

D) CGIAR-CSI Global-Aridity Index (mean annual precipitation divided by mean annual potential evapotranspiration) (Zomer et al., 2008) and annual evaporation contours (thin black line with values).

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Chapter 2

The Morphology and Evolution of Large Chain-of-Ponds River System

Chapter in preparation as:

Williams, R.T. and Fryirs, K.A., In Prep. The morphology and evolution of a large chain-of-ponds river system: Mulwaree Ponds, NSW, Australia

2.1. Introduction

The form of a river is a product of its impelling and resisting forces (Fryirs and Brierley, 2013) and its geomorphic features are an expression of the most recent processes imprinted on an evolving landscape (Brierley, 2010; Brunsden, 1993). Current fluvial processes (or regimes) generally dictate the surficial expression of the river, creating an assemblage of geomorphic units consistent with the water and sediment supply that acts against any resisting forces. Among these geomorphic features, palaeo-landforms are generally distinguishable from the active processes, be it a terrace that imposes a narrower valley margin (Nott et al., 2002), or a palaeo-meander that influences the lateral migration of a meandering river (Phillips, 2009). Exceptions to this are fluvial systems that overlie other recent geomorphic environments (e.g. glacial) and are still adjusting to the geologic and climatic boundary conditions, or those with obscured antecedent controls (Brierley, 2010).

Rivers with discontinuous channels are no different, with the lack of channel continuity a result of resistance being greater than impelling forces. These river types, such as swamps (Fryirs et al., 2014; Young, 1986) and chains-of-ponds (Eyles, 1977; Fryirs and Brierley, 1998), are often found on upland plateaus, where a small catchment results in small and highly variable discharges that are dissipated across the valley floor. The energy is too low to form channels, but may have preferential flow paths or ponds, or are only able to maintain short channelised sections. Channel discontinuity is also found on floodplains that have downstream declining discharges, reduced slope and increases in valley width, all contributing to channel breakdown (Ralph and Hesse, 2010; Tooth et al., 2014). Common to both landscapes is the antecedent influence from alluvial deposition, creating a relatively wide valley and relatively low slope.

The preservation of ancient fluvial landforms is common across parts of southeast Australia, with 100 ka records such as terraces in confined or partly-confined valleys (e.g. Cohen and Nanson, 2008; Nanson et al., 2003) or arrays of palaeochannels strewn across laterally-unconfined plains (e.g. Page et al., 2009; Pietsch et al., 2013; Hesse et al., in press). These palaeo-landforms are relics, and while they may impose some control, the present fluvial system has adjusted and created its own geomorphic features within these larger boundaries in accordance with contemporary discharges, presenting an expected landscape form. The Mulwaree River is an exception to this expected landscape as the anomalously deep ponds are at odds with the other geomorphic features that sit predictably within the geologic (imposed) and climatic (flux) boundary conditions.

To ensure the preservation and, if necessary, the repair or restoration of the Mulwaree River, and other large-scale chain-of-ponds, there needs to be an understanding of the hydro-geomorphic processes that formed and now maintain these rare (geo)ecological environments. A key unknown is whether the deep ponds and other geomorphic features are a result of the current hydro-geomorphic processes, or are a preserved fluvial form shaped by different climatic and hydrological drivers. This will inform whether the current process have the capacity to recreate these landscape features, should they become degraded or destroyed. Therefore, the aims of this study are to; 1) establish the timing and hydro-geomorphic character of the late-Quaternary evolution of this large scale chain-of-ponds river; and, 2) describe and explain the geomorphology of the present system, in context of the of the current fluvial processes and antecedent controls.

2.2. Regional Setting

The Mulwaree River, a tributary in the Hawkesbury-Nepean catchment, sits atop the Great Dividing Range and drains an area of 790 km^2 (Figure 1A). The catchment is dominated by highly-weathered, folded felsic to mafic sedimentary units, with small areas of felsic volcanics and granite. Approximately 20% of the catchment is overlain with Quaternary alluvial or lake deposits (Thomas and Pogson, 2012). Ninety percent of the catchment has an elevation between 620 m and 800 m, consisting of rounded hills and floodplains, with the remaining higher elevations (up to 1010 m) being steeper dissected valleys on the western margin (Figure 1B).

Figure 1. (Page 29) Regional, catchment and field site maps.

A) Location of the Mulwaree River catchment on the Southern Tablelands of NSW and other sites (Δ) and rivers referred to in this paper.

B) Mulwaree River catchment showing the field site at 'Kelburn', and the weather observation sites of Springfield and Goulburn AWS and The Towers discharge gauging stations near Goulburn.

C) Digital elevation model of the field site, showing the elevation above the channel bed to illustrate the relative heights of the geomorphic features – note the scale is logarithmic. The 50 m crosshatch pattern that is evident on the steeper slopes is an artefact of the dataset from post-processing done by Geoscience Australia

D) Planform showing geomorphic units, transects and sampling locations. Cores and samples are named using the transect followed by the core number (e.g. core 7 on transect MK15_2 is MK15_2_7)

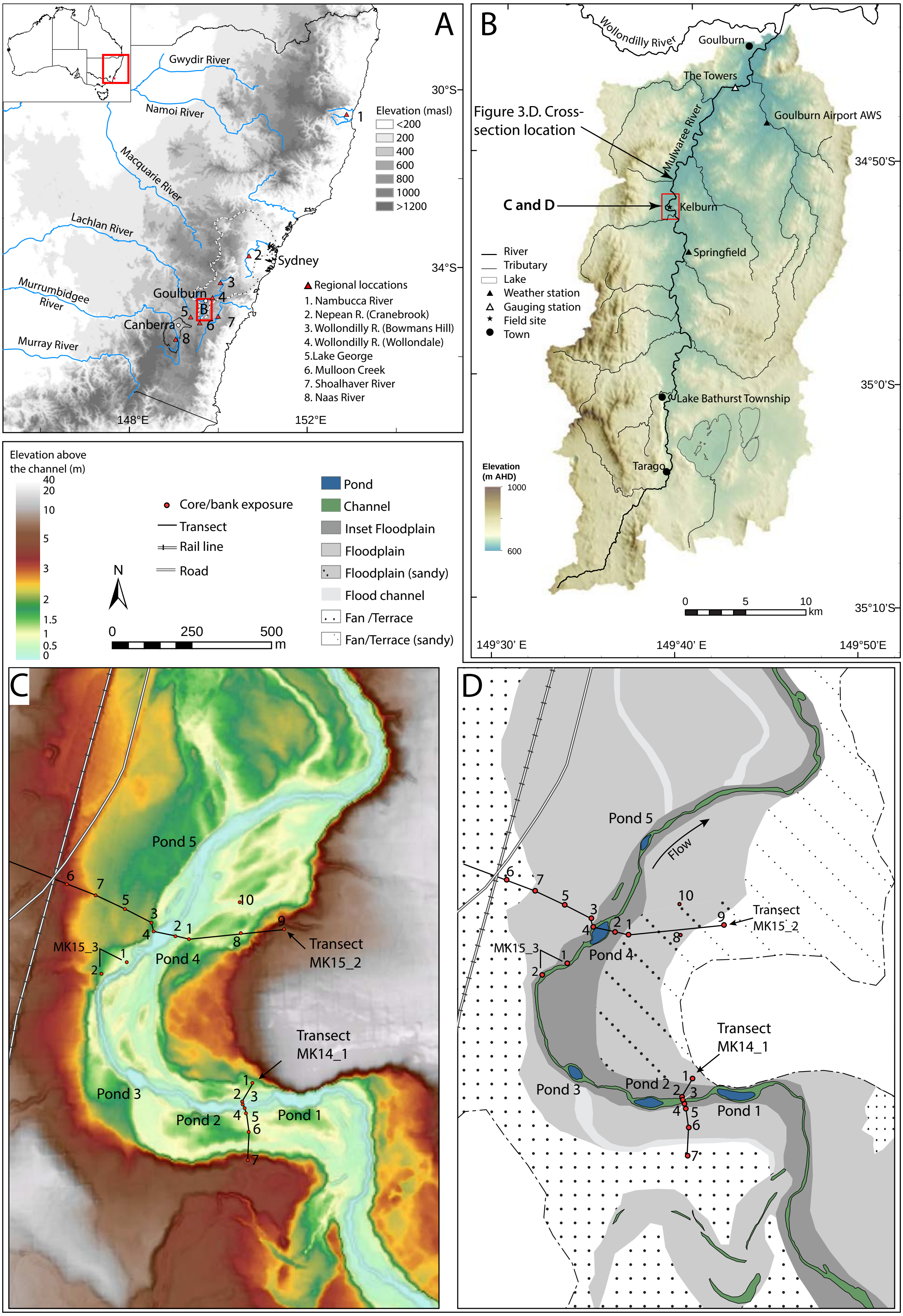

Figure 1. Regional, catchment and field site maps. Details previous page

The catchment consists of headwater tributaries in confined and partly-confined valleys, with slopes of 0.06–0.013 m/m and 0.007–0.003 m/m, respectively. The partly-confined reaches are predominately valley-fills or chains-of-ponds, similar to those described by Prosser et al. (1994) and Mould and Fryirs (2017). At a catchment area of 73 km^2, near Tarago (Figure 1B), the river debouches onto a broad floodplain that is up to 1 km wide. This low gradient partly-confined to laterally unconfined planform-controlled lower Mulwaree River reduces in gradient from 0.0016 m/m to 0.0008 m/m over the 58 km to where it joins the Wollondilly River at Goulburn, NSW. This lower reach, called the Mulwaree Ponds, is strung with over 100 ponds ranging in surface area from 80 m^2 to 13000 m^2, connected by a shallow, ephemeral channels and/or preferential flow paths. The catchment is set in a temperate climate with moderate inter-annual rainfall variability, with a seasonally uniform mean annual rainfall of 700 mm and annual pan evaporation of 1450 mm (Bureau of Meteorology, 2017). The Towers gauging station, at a catchment area of 604 km^2, records a mean annual flood for the Mulwaree River of 25 m^3s^{-1} (14–46 m^3s^{-1}, 95% confidence interval) (Rustomji et al., 2006). The main study site, located on the property of 'Kelburn' 15 km south of Goulburn at a catchment area of 462 km^2, is a 1.7 km reach containing five large ponds (Figure 1 B, C and D).

2.3. Methods

Interpretation of the surface topography, bathymetry and stratigraphy, combined with single-grain optical-dating of sediments, was used to explain the current fluvial processes and establish the palaeo-morphology. Two cross-sections and two bank exposures were analysed; MK14_1 crosses a connecting channel, MK15_2 crosses a pond, and the bank exposures (MK15_3) are upstream of Pond 4 (Figure 1, C and D). The stratigraphy was revealed through examination of surface pits, bank exposures and 17 sediment cores (2.5–9 m deep) across the two valley-wide transects. These cross section locations were chosen as they crossed a range of sedimentary units that were visible from satellite imagery and in the field, while the bank exposures showed the upper section of stratigraphy on an eroded concave bank. Core samples were collected using a direct push corer (Geoprobe 54LT) and underwent laser-diffraction particle size analysis and loss on ignition to calculate organic content. Calculations of water and organic content were made by drying samples at 105°C for 24 hours and then heating at 550°C for 4 hours (Rayment and Lyons, 2010).

A digital elevation model (DEM) was created by combining surface topography and a bathymetric survey. The surface topography was acquired using a Leica C10 Scan Station (accuracy <0.01 m) and the bathymetric survey was undertaken using a CeeScope 200 dual-channel echo sounder with vertical accuracy of <0.02 m and horizontal accuracy from GNSS satellite receiver of <1 m. The data was filtered using Cyclone (Leica) and LASTools (Isenburg, 2015) to remove irregularities and terrestrial and aquatic vegetation. The DEM was combined with the 5 m Goulburn Town LiDAR-derived DEM (Geoscience Australia, 2015) to extend the range, and adjust the elevation to Australian Height Datum (AHD). The DEM was then used in conjunction with orthorectified ADS40 aerial imagery, with 0.5 m ground sample distance (Spatial Services, 2013), and the stratigraphy to identify geomorphic assemblages.

Samples for optically stimulated luminescence (OSL) dating were collected using Geoprobe 54LT in opaque black tubing, or using steel tubes hammered into bank and pit exposures. Burial doses were determined using a modified single-aliquot regenerative-dose (SAR) protocol (Murray and Wintle, 2000; Wintle and Murray, 2006). Samples were processed at the Macquarie University luminescence dating facility and analysed on an automated Risø TL/OSL-DA-20 reader (Bøtter-Jensen et al., 2000) fitted with an EMI 9235QA PMT and Hoya U-340 detection filters. Optical stimulations were performed using blue LEDs (470 nm) or green laser (532 nm) for single-aliquot and single-grain analysis, respectively. Laboratory irradiations were performed by a calibrated $^{90}Sr/^{90}Y$ source with beta dose uncertainties of ± 2% incorporated in the equivalent dose.

Lithogenic radionuclide activity concentrations were determined using Compton suppression gamma spectrometry at the Australian Nuclear Science and Technology Organisation. Dose rates were calculated using dose-correction factors from Adamiec and Aitken (1998), with beta-dose attenuation factors from Mejdahl (1979), cosmic dose rates calculated following the procedures of Prescott and Hutton (1994) and adjustments for moisture content after Aitken (1985) and Readhead (1987). Dose rates are reported at 1σ uncertainty, calculated as the quadratic sum of the random and systematic uncertainties. OSL equivalent doses were calculated using a Minimum Age Model (Galbraith et al., 1999; Vermeesch, 2009). This model was used due to the fluvial environment and over-dispersion suggesting likely partial bleaching (Rhodes, 2011). Burial age uncertainty is reported at a 68% (1σ) confidence interval.

2.4. Results

2.4.1. Planform and cross-section morphology

The Mulwaree Ponds consist of five geomorphic units; deep ponds, shallow connecting channels, floodplains, inset floodplains and elevated terrace/fans (Figures 1 C and D, Figure 2). Flow data from NSW Water (2016) shows that the Mulwaree River receives episodic flow, with no discharge and the ponds disconnected from overland flow for 60% of the time. The depth of the ponds and limited surface water–subsurface water interactions mean they maintain a permanent water source, even during drought (Chapter 3). During surface discharges the connecting channels provide flow between ponds and as the flow reaches bankfull, chutes on the inset floodplain are activated. When the flow breaches the banks of the connecting channels and ponds, energy is dissipated across the 60–200 m wide inset floodplain, and in extreme floods the upper floodplain (~200–500 m wide). The terrace/fan, elevated ~3 m above the floodplain, is disconnected from flow from the contemporary Mulwaree River. The narrow connecting channels are densely vegetated and generally stable, but many contain shallow knickpoints and slumped banks in areas where stock have access to the river or where anthropogenic structures have been emplaced (e.g. culverts). This is producing a more entrenched, well-defined connecting channel between some ponds.

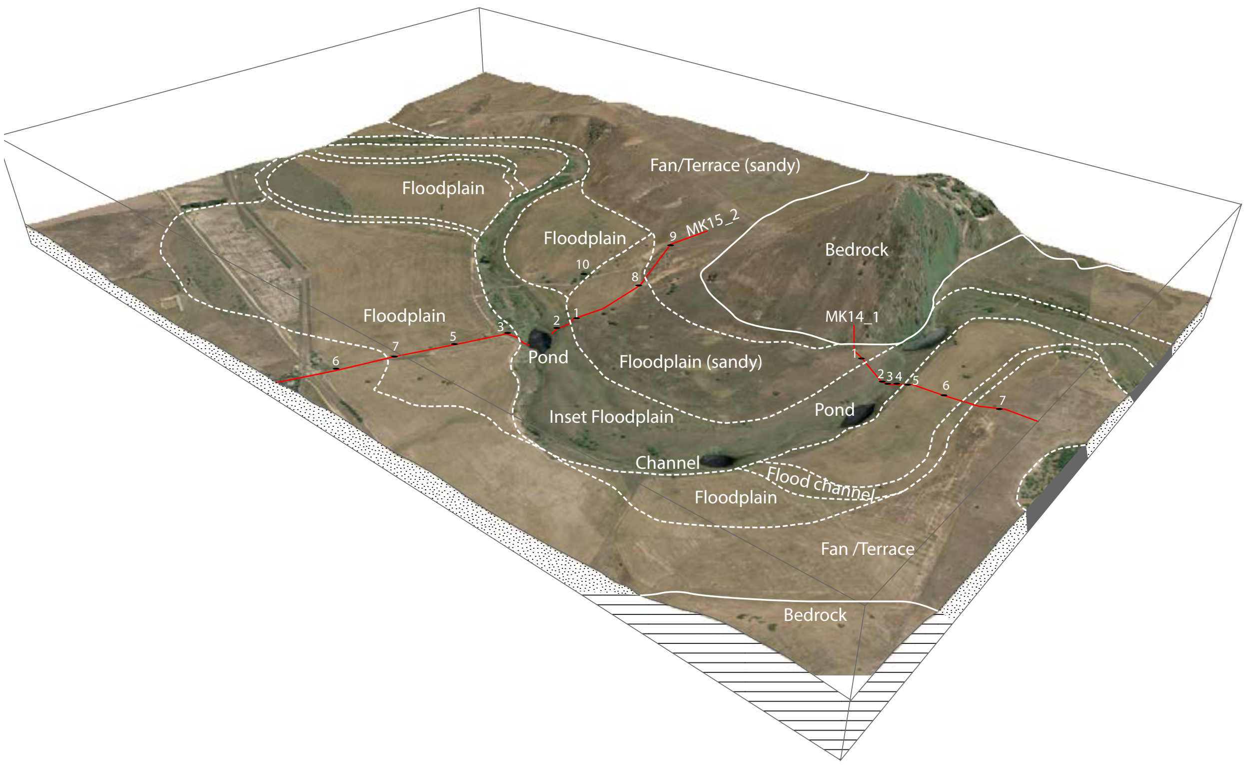

Figure 2. Oblique satellite image of the Mulwaree River at 'Kelburn' overlain on surface elevation at 5x vertical exaggeration. Flow direction from right to left. Surface elevation a combination of terrestrial laser scanner, total station and bathymetry surveys, combined with 5 m LiDAR-derived DEM (Geoscience Australia, 2015).

In the main study reach the five ponds are 'eye-shaped' (elliptical with pointed ends), roughly symmetrical and have a length to width ratio of 1.8–3.5:1. The scale of these ponds varies in surface area (~1700–4000 m^2), depth (3.4–7.0 m) and volume (2000–10600 m^3) (Table 1). Their longitudinal profiles are arcuate and near symmetrical, with a slope of 15–20 degrees entering and exiting the ponds, and 0–5 degrees on the pond bed (Figure 3). In cross-section, the ponds are narrow and symmetrical with bank slopes of up 45 degrees (Figure 3).

Table 1. Morphometrics of the five ponds along the study reach. See Figure 1D for locations and Figure 3 for comparative cross-sectional and longitudinal profiles

Pond	Length (m)	Width (m)	Area (m^2)	Perimeter (m)	Volume (m^3)	Mean Depth (m)	Max Depth from water outflow level (m)
1	135.5	42.4	3962	305	10655	2.7	5.1
2	103.7	35.7	2474	228	7909	3.2	6.6
3	66.0	36.5	1818	167	4943	2.8	4.9
4	97.2	46.6	3001	237	10616	3.5	7.0
5	108.4	30.7	1738	244	1964	1.2	3.4

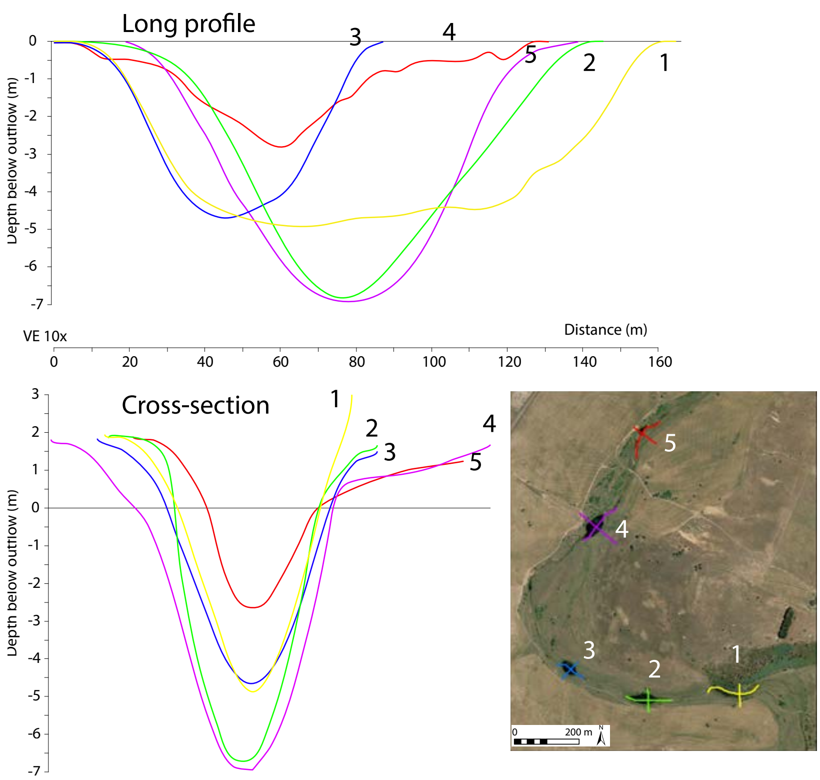

Figure 3. Longitudinal profile and cross-section of the five ponds. Numbers related to ponds on Figure 1D moving downstream in order.

2.4.2. Stratigraphy and chronology

There are seven broad sedimentary packages in the Mulwaree Ponds valley fill, summarised in Table 2, with planform locations shown in Figure 2 and stratigraphic architecture illustrated in Figure 4 (detailed sediment cores are in Appendix 1). These sediment packages are associated with the different geomorphic units that make up the valley floor (e.g. fan/terraces, floodplain and inset floodplain) and correspond with periods of its late Quaternary evolution.

Table 2. Summary of the seven sedimentary packages on the Mulwaree River, interpreted using the stratigraphy and burial ages from the extracted sediment cores. The age range of each unit was determined from the age (±1σ uncertainty) of the OSL samples in each unit (see Table 3).

Package	Sediment	Depth (below surface)	Age
Basal terrace sequence	Moderate–well sorted clayey sand (fine–medium) and fine sandy clay loam separated by poorly sorted reddish, coarse sand and gravel	2–7 m (Terrace)	80–100 ka
Lower gravel unit	Gravelly sand, and sand with occasional clay layers	5.5–7.5+ m (Floodplain)	80–110 ka
Upper gravel unit	Poorly sorted, red to dark red, sand and gravel separated by clayey/silty sand	3–7 m (Floodplain)	50–60 ka
Younger gravel unit	Poorly sorted medium–sand and gravel	2–6 m (Floodplain)	20–30 ka
Upper sandy package	Alternating sequences of sandy clay-loams and clayey sands topped with 0.5 m of well-sorted fine–medium sand	0–2 m (Terrace)	<17 ka (possibly <50 ka)
Floodplain package	Silty-sand and sandier toward the surface, with sandy sections on the eastern floodplain	0–3 m (Floodplain)	<30 ka
Inset floodplain package	Clay loams at the base to sandy loams at the surface	0–2 m (Inset Floodplain)	<3 ka

Figure 4. (Page 35) Stratigraphic architecture and OSL ages of the Mulwaree Ponds. Surface elevation of all transects are a combination of terrestrial laser scanner, total station and bathymetry surveys, combined with a 5 m LiDAR-derived DEM (Geoscience Australia, 2015). See Methods for details and Figure 1 for cross-sections locations. Additional stratigraphic columns, particle size analysis, sediment core images and loss on ignition plots in Appendix 1.

A) Cross-sections MK15_2 and stratigraphy of the Mulwaree River at 'Kelburn', incorporating the stratigraphy from groundwater bore (WB) GW028651 (Office of Water, 2016). Surface morphology labelled in grey and sedimentary packages (Table 2) labelled in black. OSL sample locations with age ± error (Table 3)

B) Cross-sections MK14_1 and stratigraphy of the Mulwaree River at 'Kelburn'.

C) Longitudinal profile of the Mulwaree River at 'Kelburn' showing floodplain, inset floodplain, channel and pond bed elevations. Fine–coarse boundary extrapolated from cores MK14_1_3 and MK15_2_2.

D) Cross-section of the Mulwaree River ~3 km downstream from 'Kelburn' using the Goulburn Town 5 m LiDAR-derived DEM (Geoscience Australia, 2015) — see Figure 1B for location. Stratigraphy interpreted from groundwater bores GW036420, GW036421 and GW036423 (Office of Water, 2016).

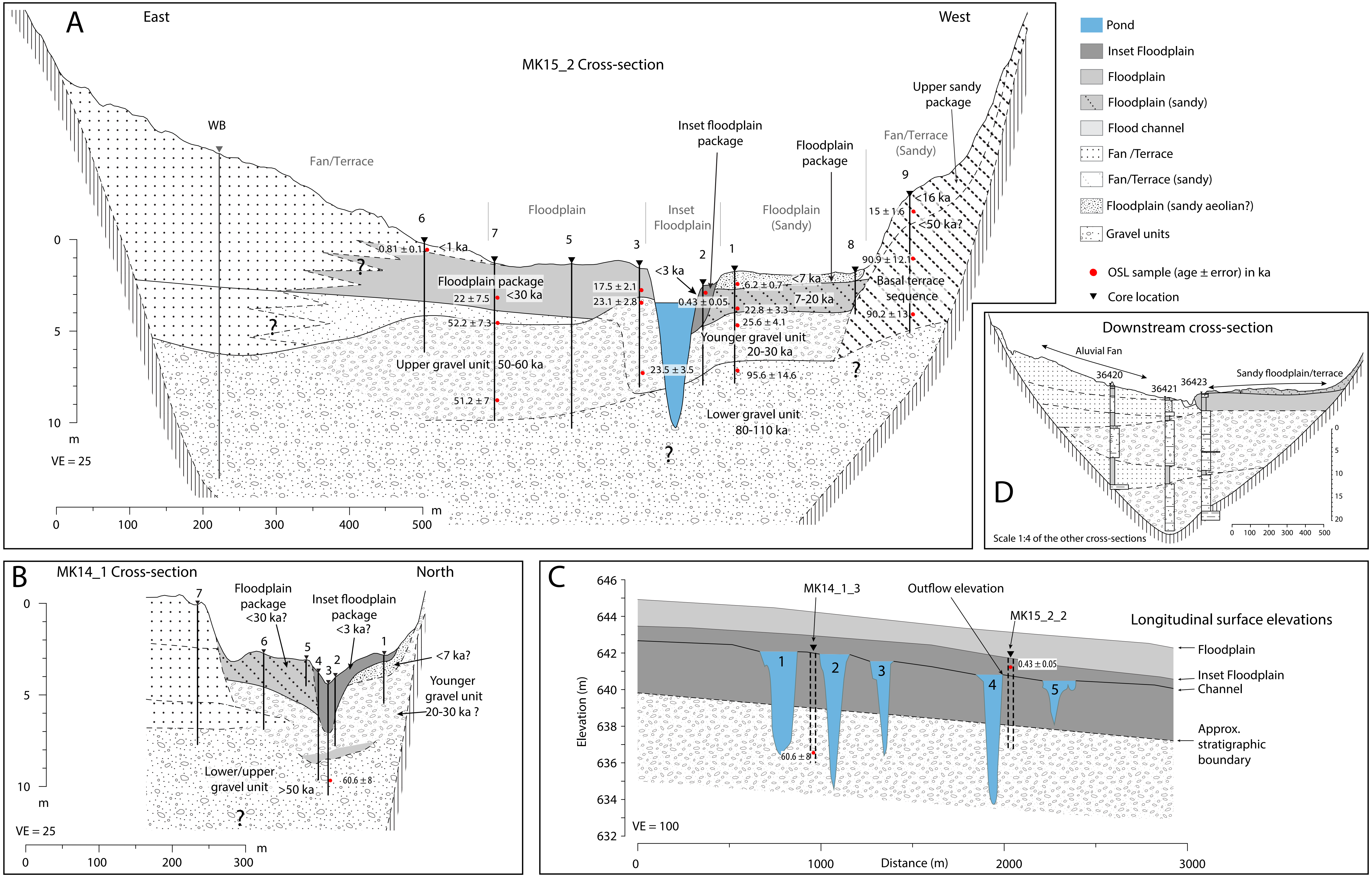

Figure 4. Stratigraphic architecture and OSL ages of the Mulwaree Ponds. Details on previous page.

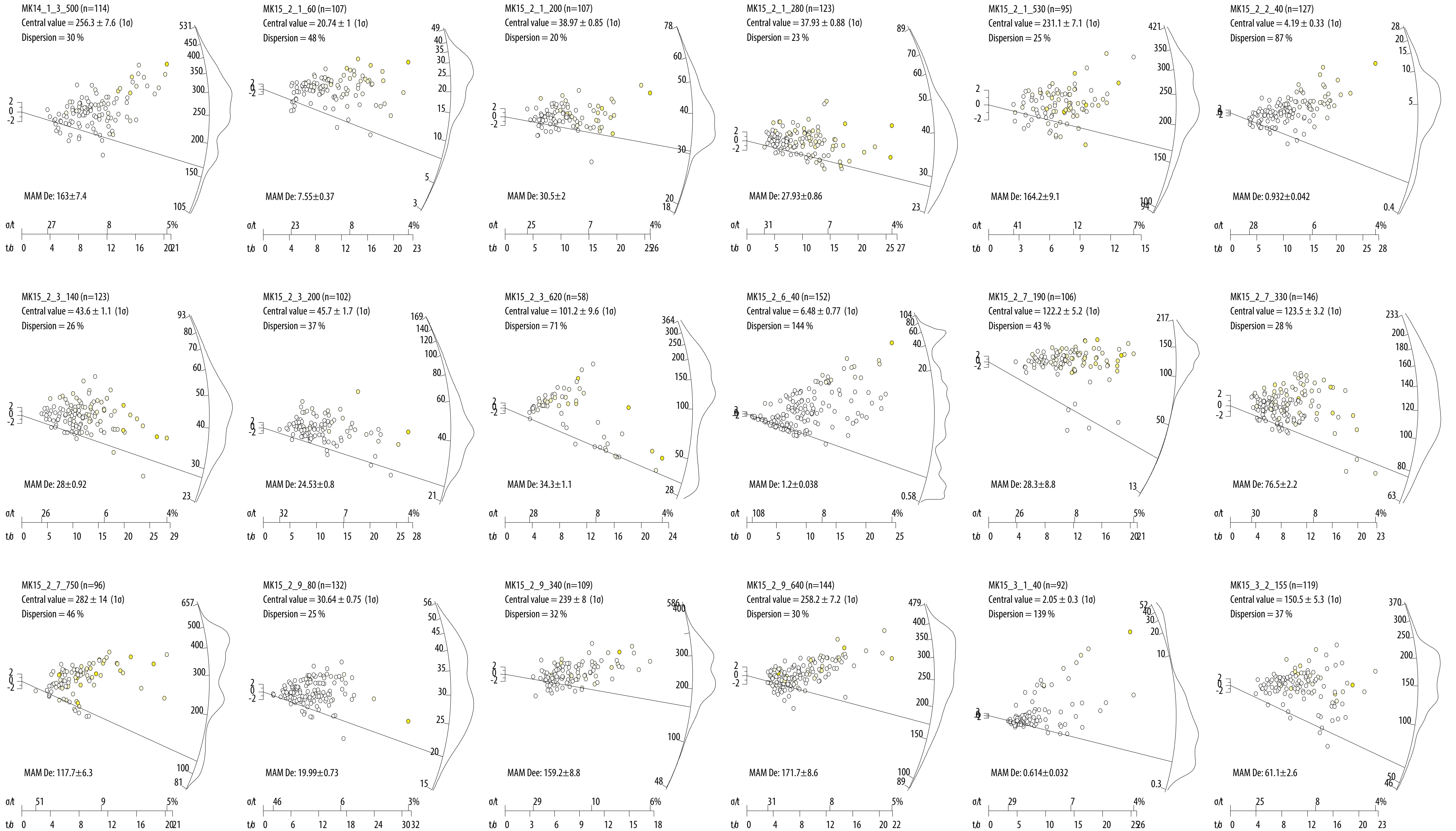

Figure 5. Radial plots (x-axis error, radial (y) axis equivalent dose, left y-axis is 2σ error) with kernel density estimate (right of radial axis) of single-grain OSL equivalent dose distributions and statistical model results. The line from the left y-axis to the radial axis is the Minimum-Age-Model equivalent dose (MAM De) and the fill colour (white to yellow) of the circles is proportional natural signals from each grain for the sample. Radial plots created using Radial Plotter 8.1 (Vermeesch, 2009). See Table 3 for the OSL ages and associated sedimentary package.

Table 3. Single-grain optically stimulated luminescence results for the Mulwaree at 'Kelburn'. Depth, water content, Dose rate from lithogenic radionuclide concentrations, dispersion (σD), palaeodose and calculated burial ages.

Sample	Unit	Depth (m)	Water content [a] (%)	Dose Rate: Lithogenic radionuclides [b] (Bq/kg) 40K	210Pb	226Ra	228Ra	228Th	238U	Beta (Gy/ka)	Gamma (Gy/ka)	Cosmic [c] (Gy/ka)	Total Dose Rate [d] (Gy/ka)	Palaeodose: Grains accepted (Count/%)	σD [e] (%)	Equivalent Dose [f] (Gy)	Age [g] (ka)
MK15_2_9_340	Basal Terrace	3.4	12.5 ± 5	236 ± 14	27 ± 8	26 ± 2	36 ± 3	33 ± 5	28 ± 6	0.861 ± 0.078	0.712 ± 0.124	0.146 ± 0.019	1.75 ± 0.19	109 / 18%	32%	159.2 ± 8.8	90.9 ± 12.1
MK15_2_9_640	Basal Terrace	6.4	18 ± 10	278 ± 15	36 ± 7	26 ± 2	42 ± 3	38 ± 5	26 ± 7	0.951 ± 0.107	0.817 ± 0.124	0.104 ± 0.015	1.90 ± 0.24	144 / 13%	32%	171.7 ± 8.6	90.2 ± 13.0
MK15_2_1_530	Lower Gravel	5.3	22 ± 12	242 ± 14	43 ± 6	31 ± 2	33 ± 2	28 ± 4	30 ± 5	0.853 ± 0.120	0.722 ± 0.099	0.111 ± 0.017	1.72 ± 0.23	95 / 19%	25%	164.2 ± 9.1	95.6 ± 14.6
MK15_2_7_330	Upper Gravel	3.3	20 ± 10	279 ± 15	26 ± 5	29 ± 2	42 ± 2	38 ± 4	17 ± 5	0.767 ± 0.091	0.529 ± 0.085	0.137 ± 0.02	1.46 ± 0.19	146 / 21%	28%	76.5 ± 2.2	52.2 ± 7.3
MK15_2_7_750	Upper Gravel	7.5	20 ± 10	236 ± 13	87 ± 7	73 ± 5	34 ± 2	33 ± 4	24 ± 5	1.074 ± 0.119	1.100 ± 0.140	0.093 ± 0.013	2.3 ± 0.27	131 / 11%	46%	117.7 ± 6.3	51.2 ± 7.0
MK14_1_3_500	Upper Gravel	5.0	12.5 ± 5	382 ± 22	42 ± 12	37 ± 3	61 ± 4	59 ± 8	25 ± 12	1.339 ± 0.128	1.194 ± 0.202	0.125 ± 0.016	2.69 ± 0.31	114 / 14%	30%	163.0 ± 7.4	60.6 ± 8.0
MK15_2_1_280	Younger Gravel	2.8	25 ± 10	208 ± 13	15 ± 7	14 ± 2	18 ± 2	17 ± 4	11 ± 4	0.537 ± 0.083	0.385 ± 0.071	0.137 ± 0.019	1.09 ± 0.16	123 / 18%	23%	27.9 ± 0.9	25.6 ± 4.1
MK15_2_3_200	Younger Gravel	2.0	5 ± 3	149 ± 8	18 ± 3	12 ± 1	17 ± 1	14 ± 2	14 ± 3	0.491 ± 0.042	0.377 ± 0.058	0.164 ± 0.023	1.06 ± 0.11	102 / 20%	37%	24.5 ± 0.8	23.1 ± 2.8
MK15_2_3_620	Younger Gravel	6.2	20 ± 10	214 ± 12	28 ± 7	20 ± 2	32 ± 2	28 ± 5	20 ± 7	0.713 ± 0.094	0.608 ± 0.099	0.104 ± 0.015	1.46 ± 0.20	58 / 7%	71%	34.3 ± 1.1	23.5 ± 3.5
MK15_3_2_155	Younger Gravel	1.6	20 ± 10	400 ± 22	54 ± 7	37 ± 3	60 ± 4	62 ± 6	33 ± 7	1.368 ± 0.151	1.239 ± 0.160	0.163 ± 0.024	2.80 ± 0.33	119 / 17%	37%	61.1 ± 2.6	21.8 ± 2.9
MK15_2_9_80	Upper Sandy	0.8	8 ± 3	185 ± 12	<21	16 ± 2	23 ± 2	20 ± 4	15 ± 5	0.627 ± 0.054	0.478 ± 0.085	0.199 ± 0.025	1.34 ± 0.11	132 / 22%	25%	20.0 ± 0.7	15.0 ± 1.6
MK15_2_3_140	Floodplain	1.4	15 ± 5	229 ± 13	31 ± 6	23 ± 2	31 ± 2	24 ± 4	17 ± 6	0.767 ± 0.067	0.630 ± 0.097	0.174 ± 0.022	1.60 ± 0.16	123 / 18%	26%	28.0 ± 0.9	17.5 ± 2.1
MK15_2_1_60	Floodplain	0.6	7 ± 3	159 ± 10	<17	13 ± 1	19 ± 1	15 ± 3	18 ± 4	0.564 ± 0.047	0.419 ± 0.078	0.206 ± 0.026	1.22 ± 0.10	107 / 21%	48%	7.6 ± 0.4	6.2 ± 0.7
MK15_2_1_200	Floodplain	2.0	20 ± 10	208 ± 12	24 ± 4	17 ± 1	23 ± 1	22 ± 3	12 ± 3	0.631 ± 0.072	0.516 ± 0.072	0.156 ± 0.023	1.34 ± 0.16	107 / 18%	20%	30.5 ± 2.0	22.8 ± 3.3
MK15_2_7_190	Floodplain	1.9	20 ± 10	193 ± 11	25 ± 6	17 ± 2	20 ± 1	19 ± 3	16 ± 5	0.609 ± 0.078	0.486 ± 0.076	0.158 ± 0.023	1.28 ± 0.17	106 / 13%	43%	28.3 ± 8.8	22.0 ± 7.5
MK15_2_6_40	Floodplain/fan	0.4	12.5 ± 5	192 ± 11	18 ± 6	21 ± 2	34 ± 2	29 ± 5	22 ± 6	0.687 ± 0.066	0.570 ± 0.103	0.198 ± 0.026	1.49 ± 0.17	152 / 25%	144%	1.20 ± 0.04	0.81 ± 0.10
MK15_2_2_40	Inset Floodplain	0.4	15 ± 7	195 ± 12	83 ± 8	27 ± 2	21 ± 2	23 ± 4	17 ± 5	0.961 ± 0.080	0.994 ± 0.146	0.193 ± 0.026	2.18 ± 0.23	127 / 18%	87%	0.93 ± 0.04	0.43 ± 0.05
MK15_3_1_40	Inset Floodplain	0.4	12.5 ± 7	284 ± 16	46 ± 7	33 ± 2	35 ± 2	35 ± 4	21 ± 7	1.040 ± 0.083	0.913 ± 0.145	0.198 ± 0.027	2.18 ± 0.23	97 / 10%	139%	0.61 ± 0.03	0.28 ± 0.04

a. Water content, expressed as (mass of water/mass of dry sample) × 100, used to calculate the total dose rates and OSL ages.

b. Concentrations determined from high resolution gamma spectrometry measurements of dried and milled sediment sample.

c. Time-averaged cosmic-ray dose rates, each assigned an uncertainty of ±10%.

d. Mean ± total (1σ) uncertainty, calculated as the quadratic sum of the random and systematic uncertainties. An internal dose rate of 0.032 ± 0.011 Gy/ka was included in the total

e. Dispersion of single-grain equivalent doses.

f. Due to the fluvial environment and over-dispersion, the Minimum Age Model was used to determine the equivalent dose and standard error. See radial plots (Figure 5)

g. Uncertainties at 68% (1σ) confidence interval. Single-grain optically stimulated luminescence results for the Mulwaree River at 'Kelburn'. Depth, water content, dose rate from lithogenic radionuclide concentrations, dispersion (σD), equivalent dose and calculated burial ages.

On the eastern valley margin, the ***basal terrace sequence*** is dominated (~75 wt.%) by moderate- to well-sorted clayey sand (fine–medium) and fine sandy clay loam. These consist of occasional sandier, red mottled sections (<0.05 m thick) separating extensive (1–2.5 m) yellowy grey clayey sand. These finer-grained units are divided by poorly sorted reddish, coarse sand and gravel (mostly <4 mm, but up to 20 mm) with small amounts (<5 wt.%) of clay and silt. This unit is dated to around 80–100 ka (90.2 ± 13.0 ka at 6.4 m and 90.9 ± 12.1 ka at 3.4 m). The terrace/fan unit southwest of the current river has a similar composition with extensive fine-grained sections separated by coarse clayey sand and clayey gravel. However, the finer sections are less well sorted with more silt and clay (up to 50 wt.%) and more distinct and thinner sedimentary facies than the eastern terrace.

The ***lower gravel unit*** extends across the width of the floodplain terminating 5.5–8.5 m below ground level (Figure 4, A and B). This package consists of an alternating sequence of gravelly sand, and sand with occasional clay layers. One OSL age from a depth of 5.3 m constrains the upper portion of this unit to approximately 80–110 ka (95.6 ± 14.4 ka), and is synchronous with the stratigraphically distinct basal terrace sequence. The cores analysed only capture the youngest portion of this unit with a maximum depth of 9 m. Nearby water bore logs (Office of Water, 2016) suggest that this package, or similar older sequences, extends to a depth of 30 m (Figure 4D). These bores describe very similar sediments to those found at the field site, and all consistently contain sand/gravel and clay bands, above shale bedrock.

The 3–4 m thick ***upper gravel unit*** displays similar sedimentary sequences to the lower gravel unit but occurs at a shallower depth of 3–8.5 m below the surface (Figure 4A). It is dominated by poorly sorted, red to dark red, sand and gravel separated by clayey/silty sand. These coarse-grained layers are 0.1 m to >1.5 m thick and the finer deposits range from 0.02 m to 0.7 m thick. However, these fine-grained layers are rarely homogeneous with distinct layers usually thinner than 0.1 m. This unit extends under much of the western floodplain. Three OSL ages constrain this unit to ~45–70 ka (Figure 4A, Table 3). The oldest (60.6 ± 8.0 ka) is from a fine-grained layer (60 wt.% <63 μm) 5 m below the current connecting channel. The other ages are from the same core at the lower and upper boundaries of this unit and returned ages of 51.2 ± 7.0 ka and 52.2 ± 7.3 ka, respectively.

The ***younger gravel unit*** is more homogeneous and occurs at a depth of between 2 m and 6 m below the surface (Figure 4, A and B). The top of this unit is elevated above both the older, *upper gravel unit* by ~1 m. It ranges in thickness from 3 to 5 m and is comprised of consistently poorly sorted medium–coarse sand and gravel, including gravels >50 mm b-axis. This unit is dated at ~20–30 ka (Table 3). Two samples at the western extent (core MK15_2_3) constrain the lower (23.5 ± 5.0 ka) and upper (23.1 ± 2.8 ka) boundaries of this unit. The core 200 m downstream through a lower part of the eastern floodplain (MK15_2_10) has a similar sedimentary profile, with the top of the gravels at an equivalently pronounced elevation. Bank exposure site MK15_3_2 (location shown in Figure 1D) was also used to date this unit, where a sample from the upper portion of this unit has a similar age of 21.8 ± 2.9 ka. On the eastern side of the valley, one sample from a leached, well-sorted sand layer (~0.25m thick), between coarse sandy gravel layers, dates to 25.6 ± 4.1 ka (MK15_2_1_280). Above the overlaying sandy gravel, a series of alternating clayey fine–medium sand and coarse sand was dated to 22.8 ± 3.2 ka (MK15_2_1_200).

On the Eastern terrace, the ~2 m deep ***upper sandy package*** (Figure 4A) is composed of alternating sequences of sandy clay-loams and clayey sands topped with 0.5 m of well-sorted fine–medium sand. One sample near the middle of this unit produced an age of 15.0 ± 1.6 ka (MK15_2_9_80, Table 3). The southwest terrace/fan (transect MK14, core 7 in Figure 4B) has a similar finer-grained upper package, but like its lower units, it contains more fine sand, silt and clay, and is dominated by sandy clay with a thinner (0.2 m) sandy cap. East of the eastern terrace, the lower part of the hillslope is draped with ~1 m of similarly well-sorted sand. There are no OSL ages for these sediments.

The ***floodplain package*** is on average 2 m thick across the valley, and consists of relatively homogeneous silty sand that becomes generally sandier closer to the surface. This package contains finer sediments (mostly silt and fine- to medium-sand) extending to a depth of between 1 and 3 m, with a pronounced distal fining in its deeper parts. Sediments that contain mostly fine- to medium-sand (~70 wt.%) are evident in the upper parts of the floodplain on the eastern side of the channel. These are very similar in composition to the eastern *upper sandy package* and those on the hillslopes adjacent to the terrace and eastern margin of the floodplain. This is in contrast to the western side where there are deep (>2 m) silty (~60 wt.%) sediments that also contain clay (~5 wt.%). Many cores showed evidence of leaching through grey colouring and all contained strong mottling. On the western side, an age at the base of the package (17.5 ± 2.1 ka) dates its onset at ~19–15 ka, making this contemporaneous to the upper terrace unit. On the eastern side, the floodplain sediments become gradually finer (up to 40 wt.% silt) from a depth of ~1.8m. At 2 m depth this unit is dated at 22.8 ± 3.2 ka. A second OSL age from the same core, at a depth of 0.6 m where there is a higher sand content, continues this sequence to 6.2 ± 0.6 ka. Sediments 0.4 m below the surface on the far western edge of the floodplain are much younger with an age of 0.81 ± 0.10 ka. This site is slightly elevated and shows evidence of where a palaeo-tributary may have debouched onto the floodplain, making it a distinct geomorphic feature.

The surface of the ***inset floodplain package*** is approximately 0.5 m lower than the *floodplain package* surface and includes the current connecting channel and ponds. It is dominated by silt, and ranges from clay loams at the base (~2 m deep) to sandy loams at the surface. The colour is also much darker with higher organic content than any other package. At a depth of 0.4 m, the sediment is 0.43 ± 0.05 ka in age. At the same elevation, and depth below the surface, a bank exposure sample from a thin (0.1 m) dark organic rich layer is 0.28 ± 0.04 ka in age. There is no sample from the base of this unit to identify its onset.

2.5. Discussion

2.5.1. Palaeomorphology and evolution of the Mulwaree Ponds

The evolutionary sequence for the Mulwaree Ponds is shown in Figure 6 preserving a record spanning over 100 ka. The timing of transitions in the evolution of this system is similar to other rivers in southeast Australia, but the geomorphic result of those adjustments is different. Nanson et al. (2003) in an analysis of the Nepean River, of which the Mulwaree is a tributary, document changes in fluvial activity over an equivalent timeframe. Many of the transitions in sedimentary structure of that system coincide with transitions occurring in the Mulwaree.

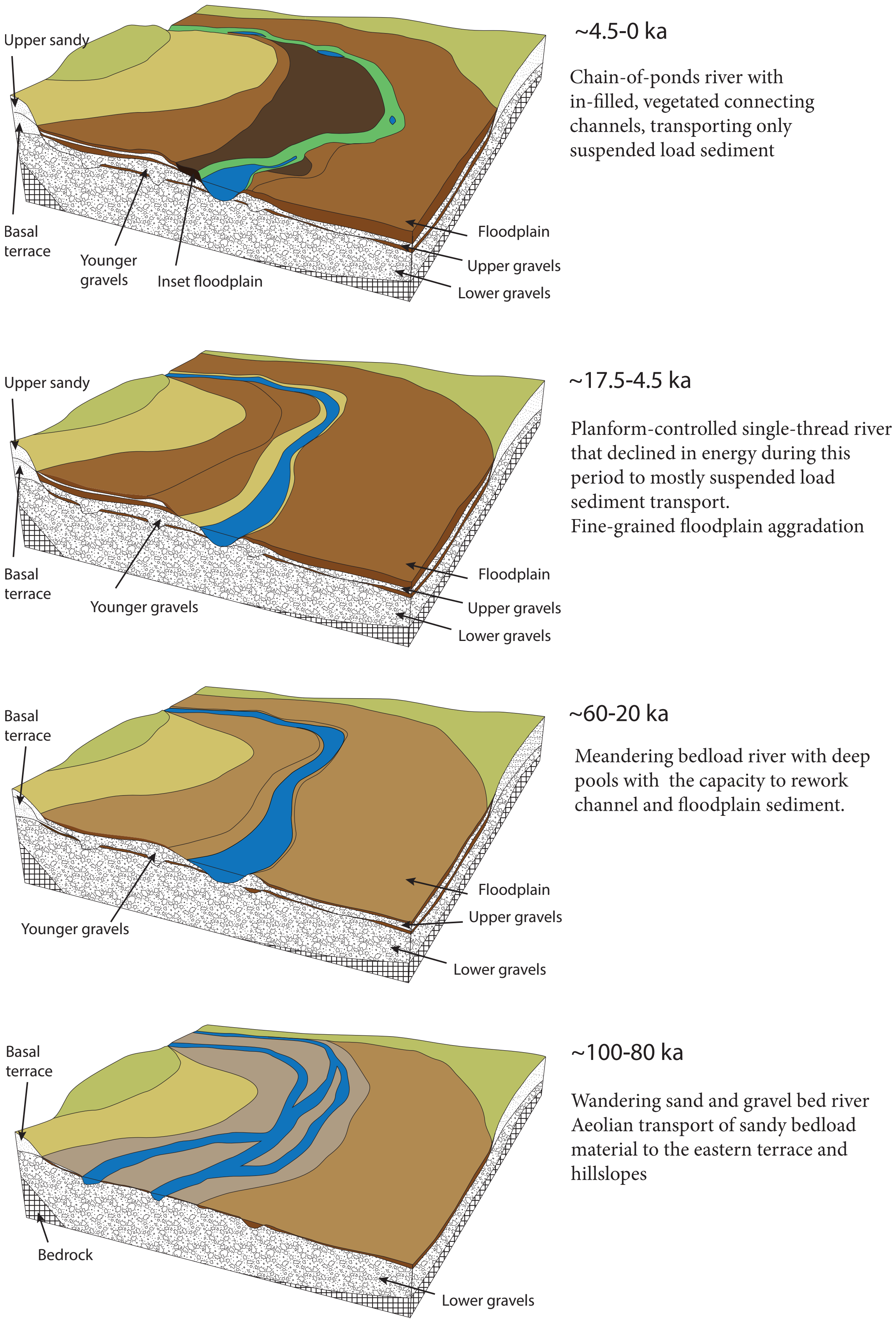

Figure 6. Evolutionary sequence of the Mulwaree River from a high energy bedload system to the discontinuous chain-of-ponds. Time sequences associated to the sedimentary units in Figure 4 and Table 2. Flow direction is from top to bottom.

The first time period is presented for around 100 ka. We hypothesise that the river at this time was a high energy, gravel bed river system, possibly with a wandering-type morphology. In other places this period is also represented by a much higher energy river, with much higher sediment load, than present. For example, underlying the terraces of the Nepean River is evidence of a braided system that was active 110–75 ka and significantly more energetic than the current single-thread channel (Nanson et al., 2003). On the Wollondilly River, at Wollondale, some 45 km downstream of the Mulwaree sites, a sand lens amongst large cobbles (up to 200 mm) is dated to 88 ± 15 ka (Rustomji and Pietsch, 2007). In the adjacent Shoalhaven catchment, the lower part of the Mayfield terrace was aggrading from 75.5 ± 13.9 ka until ~57 ka (Nott et al., 2002). There are also several terraces that are much older than 80 ka on the Shoalhaven River, including the Larbet terraces (>79 ± 20.2 ka, 244 ± 88 ka and 461 ± 271 ka) (Nott et al., 2002). Nott et al., (2002) interprets these terraces to have formed under aggradational conditions along a braided or meandering river type, and may be coeval with the much deeper sediments of to the Mulwaree River not dated in this study. Similarly, on the west of the Great Dividing Range, rivers that were much larger than present were also active during this period including the Coleambally (Murrumbidgee) at 105–80 ka (Page et al., 1996), and Green Gully and Tallygaroopna (Murray) at 110–80 ka (Page et al., 1991). Further north, the Bullurah alluvial sand and gravel deposits of the Gwydir in Central-North NSW are dated to ~85 ka (Pietsch et al., 2013), and the Worrel Terrace, in the Nambucca Catchment north east NSW, is 78.1 ± 6.1 ka old.

Given the variability in the stratigraphy of the basal terrace sequence and the lower gravel unit of the Mulwaree system, we suggest that it too experienced a highly variable flow regime with seasonal drying, similar to the Murrumbidgee palaeochannels (Page et al., 2001). At this time, it is likely that variability in discharge may have been over long periods with large floods interspersed between dry periods (Bowler, 1978; Singh et al., 1981). These floods likely deposited the coarse-grained, poorly sorted materials on the floodplain. During dry periods it is hypothesised that some wind-blown material may have been deposited on the Mulwaree terraces and the adjacent hillslope. Two dates, 90.9 ± 12.1 ka and 90.2 ± 13.0 ka, from the thick, fine–medium sandy clay parts of the eastern terrace unit are coeval with the gravel bed river. This unit is also synchronous with the Yarragundary source bordering dunes (86.6 ± 25 ka and 111 ± 22 ka) of the Murrumbidgee River at Wagga Wagga (Page et al., 2001).

The second time period is presented for ~60–20 ka. At this time, the river is still a high-energy, gravel-bed river but may have shifted towards a more sinuous, single thread planform akin to that documented elsewhere (Hesse et al., in press; Kemp and Rhodes, 2010; Page and Nanson, 1996). These changes were driven by lower evaporation and different vegetation during this colder glacial period (Slee and Shulmeister, 2015) and led to relatively higher runoff and increased discharge (Reinfelds et al., 2014). This increase in runoff efficiency corresponds well with the adjacent Lake George high stand at ~50 ka (previously dated by Coventry and Walker (1977) at ~27 ka) (Pietsch, 2006). At this time it is suggested that both discharge into the lake and water levels within the lake were high, as noted by the presence of beach sands and adjacent (assumed) aeolian deposits (Pietsch, 2006). Singh and Geissler (1985) also record higher lake levels (from pollen records) and possibly increased rainfall ~50–40 ka, followed by fluctuating lake levels and lower rainfall (~35–28 ka), with a return to higher lake levels, but moderate to lower rainfall through the Last Glacial Maximum (LGM) until ~17 ka.

During this period there is evidence of increased fluvial activity. Along the Nepean River, the palaeochannels of a large gravel-bed rivers were operating during early MIS 3 (Nanson et al., 2003). Like the Mulwaree there are no ages (or none preserved) in the latter part of MIS 3, possibly due to reworking during MIS 2. Downstream of the Mulwaree River, Rustomji and Pietsch (2007) dated cobbles under a terrace of the Wollondilly River at Bowmans Hill to 30 ± 5 ka and probably part-aeolian sandy sediments overlying cobbles on the Eastern side at Wollondale from 39.9 ± 5.7 ka to <16.5 ± 1.6 ka. Upstream on the Mulwaree River at Tarago (catchment of 99 km^2), the upper portion of a gravel unit is dated to 21.3 ± 2.1 ka, followed by a switch to finer-grained channel deposits (Rustomji and Pietsch, 2007). Approximately 30 km east of the field site, higher (bedload-dominated) fluvial activity in Limekiln Creek near Bungonia is recorded at ~60–30 ka (Wray et al., 1993). Again, the timing is also similar to that of the Kerarbury (~55–35 ka) and Gum Creek palaeochannels (35–25 ka) on the Murrumbidgee west of the Great Dividing Range (Page et al., 1996). Single-thread channels that are much larger than present are also recorded on the Lachlan (Kemp et al., 2017; Kemp and Rhodes, 2010), Namoi (Young et al., 2002), Macquarie (Hesse et al., in press) and Gwydir (Pietsch et al., 2013) floodplains.

The third time period straddles the late Pleistocene to late Holocene between around 17.5–4.5 ka. This occurs at the transition from the LGM (Barrows et al., 2002; Martinson et al., 1987) and records a slow decline in fluvial activity and a significant shift in river morphology. At this time floodplain sediments shifted towards fine-grained, sandy material. A significant decrease in fluvial activity likely accompanied this transition with the channel no longer migrating, becoming planform-controlled by the coarse older deposits. Upstream at Tarago, the Mulwaree River preserves a transition in channel deposition from sands and gravels to silts and clays prior to the oldest date in the fine-grained unit of 13 ± 1.25 ka (Rustomji and Pietsch, 2007). Assuming their estimated rate of deposition of 0.06 m/ka post 13 ka, the base of this unit would be ~17.5 ka, which is congruent with the age at our sites.

One date (15.0 ± 1.6 ka) from the clayey fine sand upper terrace unit may be aeolian and is synchronous with a larger planform-controlled river with highly variable discharge. This corresponds with the Murrumbidgee Yanco phase and elevated discharges until 13 ka (Page et al., 1996). The timing also corresponds with dune activity on the Murrumbidgee River (Page et al., 2001) and nearby Shoalhaven River (Nott and Price, 1991). The period from 10 ka to 4.5 ka, termed the Nambucca Phase, is noted as having larger discharges than present with low sediment yields across many partly confined valleys in southeast Australia, leading to reworking of older deposits and thereby creating a gap in the alluvial record (Cohen and Nanson, 2007). These larger discharges are also recorded as higher water levels in Lake George (Singh et al., 1981) and the Breadalbane region (15 km northwest of the study site) (Dodson, 1986). This is coeval with the upper sandy portion of the eastern floodplain and may result from higher discharges during this period providing sandy bedload that is transported eastward by the prevailing westerlies.

Later in this period and into the Holocene there has been a noticeable downward shift in fluvial activity in this system, and others in the area. Rivers on, and draining, the Southern Tablelands of NSW record a period prior to fluvial decline and channel infilling at this time (Eriksson et al., 2006; Johnston and Brierley, 2006; Kemp and Rhodes, 2010). On the Wollondilly at Wollondale, a finer drape above an elevated cobble bar is ~14 ka and fine-grained alluvium of a contracting channel is dated from 13.4 ± 1.3 ka to present with a relatively constant deposition rate until European settlement (~0.2 ka) (Rustomji and Pietsch, 2007). Additional nearby palaeo proxies show a decline in lake levels and rainfall post LGM in Lake George (Coventry, 1976; Singh and Geissler, 1985; Singh et al., 1981), swamp formation on sandstone plateaus of the Blue Mountains and Southern Highlands of NSW (Fryirs et al., 2014), and the abandonment of the Riverdale Terrace on the Shoalhaven River at ~17 ka (Nott et al., 2002). Along the Mulwaree, this decline in fluvial activity has been expressed through the formation of a more discontinuous channel as infilling of connecting areas between ponds formed a discontinuous, swampy preferential flow path. The ponds we see in the system today may be located in palaeo-pools of the previous higher-energy single-thread river.

The fourth time period occurs from ~4.5 ka to present. During the early part of this phase, the Mulwaree became a fully formed chain-of-ponds system. The inset valley floor is characterised by finer-grained silty clay materials, reflecting deposition and sediment trapping in a near-still water, swampy environment. While the connecting channels became more discontinuous during this time, the ponds have been maintained and are currently >5 m deep. This form of channel breakdown is coincident with the decline in fluvial activity on the Southern Tablelands over the late-Holocene, including lower lake levels (Dodson, 1986; Singh et al., 1981), fine-grained valley-fill aggradation beginning ~4 ka in Mulloon Creek, a tributary of the Shoalhaven River (Johnston and Brierley, 2006), and ~3.3 ka in the Naas River (Eriksson et al., 2006). A similar evolution is also recorded in the Mulwaree River tributary of Crisps Creek (Mould and Fryirs, 2017). This decline has also been recorded further afield as a vertically accreting phase in the Nambucca catchment from 3 ka (Nanson et al., 2003), and formation of the modern river morphology on the Lachlan River (3 ka) (Kemp and Rhodes, 2010) and Gwydir River (~5 ka) (Pietsch et al., 2013).

2.5.2. Post LGM decline in fluvial activity

Shifts in river type have been recorded for a range of rivers in southeast Australia over the late Quaternary. While the morphological adjustments may be different (e.g. from wandering or braided gravel-bed systems to a single channel fine-grained systems, or discontinuous watercourses, marshes and swamps) there is a coeval downward shift in energy of these rivers over at least the last 100 ka. This has been particularly pronounced over at least the late Pleistocene and throughout the Holocene with a distinct shift post-LGM. In the Mulwaree system this shift in energy and channel capacity is demonstrated by the fine-grained deposition over the past ~17 ka.

There has be a further decline on the Mulwaree since the major change post-LGM as the capacity of the channel and sediment size reduced possibly around 4.5 ka. This final stage is expressed as deep ponds separated by an often discontinuous channel with no capacity for bedload transport. Other rivers in southeast Australia, such as the Murrumbidgee, have maintained a continuous channel, while others like the Macquarie have become discontinuous, terminating in marshes. The reason for this channel breakdown in some of the westward or inland draining rivers (e.g. the Macquarie River) is downstream declining discharge with positive feedbacks related to sedimentation, and an increase in floodplain width (Hesse et al., in press: Ralph and Hesse, 2010). Unlike many inland draining rivers with downstream channel discontinuity (Kemp, 2010; Pietsch and Nanson, 2011; Ralph and Hesse, 2010; Tooth, 2000) the Mulwaree River increases in discharge downstream with continued tributary inputs. In this system a rapid increase in valley/floodplain width and decrease in slope near Tarago (Figure 1) reduces stream power and, together with dense groundcover vegetation, produces conditions conducive to sediment trapping, channel contraction and valley-fill aggradation. Even minor floods are dispersed over the inset or broader floodplains, dissipating the channel-forming energy. This is not dissimilar to the mechanisms involved in producing downstream decreasing channel capacities along the Illawarra coastal streams (Nanson and Young, 1981). A similar expression of discontinuity has been recorded in the nearby Mulloon Creek, with a discontinuous swamp forming after the channel loses capacity due to combination of a reduction of slope, instream sedimentation and an increase in valley width (Johnston and Brierley, 2006).

2.5.3. Antecedence, preservation and maintenance of the Mulwaree Ponds

The preservation of relict fluvial landforms is seen in many rivers across southeast Australia. In westward draining systems of the Murray-Darling basin, meandering and aggrading palaeochannels are the dominant features on the expansive floodplains (Kemp and Rhodes, 2010; Page and Nanson, 1996; Pietsch et al., 2013). In eastern, or coastal rivers this is generally expressed as terraces and more recent floodplains and channel-contracting geomorphic units like benches (Cohen and Nanson, 2008; Nanson et al., 2003; Nott et al., 2002). In other instances, the absence of preservation also provides clues to past enhanced fluvial activity (Cohen and Nanson, 2007). Atop the tablelands and in lower energy settings, smaller rivers have created cut-and-fill sequences across their partly- to laterally-unconfined valleys, regularly eroding to bedrock before slowly accumulating sediment and adjusting the to the flow regime (Eriksson et al., 2006; Fryirs and Brierley, 1998; Johnston and Brierley, 2006; Mould and Fryirs, 2017; Prosser et al., 1994).

The Mulwaree River preserves not only the deep ponds, but the entire system that sits atop an archive of fluvial activity of at least 100 ka. It records an array of geomorphic features that have been created by (and imposed upon) past and present fluvial systems, through periods of aggradation and reworking, with the preservation of fan/terraces, floodplains and inset floodplains, and anomalously deep ponds. This landscape hints at processes that have adjusted the rivers form over time. Bedrock controls near the confluence with the Wollondilly River limit the slope, resulting in lower energy and a reduced capacity to transport sediment through the system. This is seen in the deep valley fill that has (generally) aggraded over more than 100 ka, and provides the river with broad floodplains and a near uniform downstream slope that combine to limit the concentration of flow and stream power. Broad floodplains also create a buffer to sediment transfer from upstream reaches and adjacent hillslopes to the channel and ponds (Fryirs et al., 2007). As discussed, there has been a rapid decline in discharge post-LGM, with the river only able to transport mostly suspended-load sediment. Reasons for, and controls on the positioning and formation of the ponds in the Mulwaree chain-of-ponds system, and other large scale systems like it (e.g. Cartwright and Morgenstern, 2016; Zavadil and Ivezich, 2011), remains unknown. However, their position and alignment is most likely related to the position of pools within a palaeo-river and are therefore a contemporary expression of a remnant geomorphic feature. Pools may have been locations of permanent or near permanent water, sunken into the water table, whereas the riffle or connecting geomorphic features may have become intermittently shallow or dry allowing vegetation to establish; thereby increasing sedimentation between the ponds and providing a positive feedback for their growth and disconnection from the water table (*sensu* Gurnell et al., 2012).

If this is true, then this demonstrates remarkable preservation potential and maintenance of these features over the longer term. They are, however, not solely a preserved landform, but an evolved geomorphic form imprinted or overwritten on the surface of a palaeo-landform, similar to 'a *palimpsest* (like a surface which has been written on many times after previous inscriptions have been partially erased)' (Brunsden, 1993 p.16, after Chorley et al., 1984). The preservation of these gravel bed pool forms are therefore directly tied to the processes that they imposed on the river as its energy lowered after the LGM.

2.6. Conclusions

The Mulwaree River is an example of Phillips' (2007) 'perfect landscape'. Its distinctive form is the result of a series of complex responses to climatic shifts (particularly over the past ~20 ka) within imposed boundary controls. While the current hydro-geomorphic processes have helped shape and maintain the form of the Mulwaree River, they do not have the capacity to recreate many of the features, including the deep ponds, that have resulted from antecedent preservation through a complex fluvial history. This study highlights the importance of considering the longer-term evolution of a system in the context of ongoing river management (Fryirs and Brierley, 2013) and that landscapes that have retained antecedent features need to be prioritised. More locally, it highlights the irreparable damage that may result from increased sediment yields or altered hydrological processes due to anthropogenic changes to the landscape and climate. Therefore, the protection of large-scale chains-of-ponds is necessary to ensure that these important environments are not lost.

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Chapter 3

Surface Water–Subsurface Water Interactions in a Large Chain-of-Ponds

Chapter in preparation as:

Williams, R.T., Fryirs, K.A. and Hose, G.C., In Prep. Surface water–subsurface water interactions in a large chain-of-ponds system: Hydrological function of a rare type of discontinuous watercourse

3.1. Introduction

Interactions between surface water and groundwater are not only a vital part of the hydrological processes of a riverine system (Sophocleous, 2002), but they are also critical to riverine groundwater dependent ecosystems (GDEs) (Kløve et al., 2011). The dependence of an ecosystem on groundwater generally is complex and, for most systems, poorly understood (Kløve et al., 2011; Murray et al., 2006; Winter, 1999), particularly if the system is characterised by irregular or intermittent discharge (Acuña et al., 2014; Datry et al., 2014; Leigh et al., 2016).

Temporary waterways, i.e. those having intermittent, seasonal, ephemeral or episodic flows, represent more than 50% of the global stream network, and up to 70% in more arid regions such as Australia (Datry et al., 2014; Sheldon et al., 2010). This does not include the spectrum of discontinuous watercourses that do not maintain a longitudinally defined channel, such as upland swamps (Fryirs et al., 2014; Young, 1986), swampy meadows (Mactaggart et al., 2008; Prosser, 1991), cut and fill (Fryirs and Brierley, 1998), dambos (Mäckel, 1973; von der Heyden, 2004), arroyos (Bull, 1997) and chains-of-ponds (Cartwright and Morgenstern, 2016; Eyles, 1977a; Mould and Fryirs, 2017). Most of these systems, located on alluvial valley fills in catchment headwaters, are ephemeral or episodic (Uys and O'Keeffe, 1997), flowing only after rainfall and generally appearing in dichotomous states of high-flow or no-flow. Within such discontinuous systems, the valley-fill alluvium may maintain higher soil moisture levels than the surrounding hillslopes and, depending on the climate and sediment characteristics, have permanent or periodically saturated soils that can absorb precipitation, altering storm hydrographs (Grayson et al., 2010), or may contribute to base flow in downstream reaches (McCartney, 2000).

Chains-of-ponds are one of the many forms of discontinuous watercourses. In headwaters with catchment areas generally less than 30 km^2, they are a series of irregularly spaced, steep sided ponds that are set into alluvial valley fills (Eyles, 1977a; Mould and Fryirs, 2017). The ponds are separated by densely vegetated alluvial sediments or swampy meadows, which may contain small, narrow ephemeral channels or preferential flow paths (Hazell et al., 2003; Mactaggart et al., 2008; Mould and Fryirs, 2017). After rainfall, flows are transmitted downstream over relatively broad alluvial valley-fills (Fryirs et al., 2014; Mactaggart, 2008; Prosser et al., 1994). The dissipated energy limits the capacity to form channels, with water transmitted through preferential flow paths, initiating localised scouring of shallow ponds (Eyles, 1977a; Mould and Fryirs, 2017) 0.3–2.5 m in depth with surface areas typically less than 50 m^2, but up to 250 m^2 (Eyles, 1977a; Mould and Fryirs, 2017). Large-scale chains-of-ponds on higher order streams with catchment areas generally >30 km^2 are less well documented in the scientific literature, with description of basic planform characteristics and geomorphic conditions of the lower reaches of Perry River (Zavadil and Ivezich, 2011), and surface water–subsurface water connectivity and residence times in Deep Creek only recently investigated (Cartwright and Gilfedder, 2015; Cartwright and Morgenstern, 2016). The large ponds on the Mulwaree River have only been mentioned briefly, noting their persistence since European settlement and depths up to 11 m (Eyles, 1977b).

There have been significant changes to landuse since the arrival of Europeans in Australia including: hillslope, riparian and floodplain vegetation clearing; the introduction and increased number of livestock; and the drainage of swamps and wet valley fills (Brierley et al., 1999; Butzer and Helgren, 2005; Prosser, 1991). This has led to changes in stream morphology and hydrology and resulted in many discontinuous watercourses, including chains-of-ponds, becoming degraded through incision and gully formation, or infilling through increased sedimentation (Erskine and Melville, 2008; Eyles, 1977b). The resultant changes to geomorphic structure have further altered the hydrology and impacted the ecological function of these riverine ecosystems (Hazell et al., 2003). Little is known about the hydrological function, including the groundwater–surface water interactions, of these 'wetland' riverine systems. Such understanding is vital for their management and conservation (Bunn and Arthington, 2002; Elosegi and Sabater, 2013). The aim of this paper is to characterise the hydrological function and surface–subsurface water interactions of an undocumented geomorphically, and possibly ecologically, significant chain-of-ponds system. We use surface and subsurface water levels, ^{2}H and ^{18}O stable isotopes and ^{222}Rn as a groundwater tracer to understand the hydrological function and processes in this system and develop a model for their hydrological function under no-flow and high-flow conditions.

3.1.1. Geochemical tracers in surface water–subsurface water interactions

Geochemical tracers have been used to estimate groundwater inflows in fluvial environments (Cook, 2013), with the radiogenic isotope ^{222}Rn and stable isotopes ^{18}O and ^{2}H used to map and quantify groundwater inflow in chains-of-ponds (Cartwright and Gilfedder, 2015). These isotopes are used as they typically have differing concentrations in groundwater compared to surface waters. The concentrations of ^{226}Ra, the parent isotope of ^{222}Rn, is several orders of magnitude higher in minerals than in dissolved in water, leading to much greater concentrations of the gas ^{222}Rn in groundwater than surface waters (Cecil and Green, 2000). ^{18}O and ^{2}H are found in varying abundance relative to the more common ^{16}O and H in the hydrologic cycle due to the process of fractionation (i.e. the preferential evaporation of the lighter isotopes and condensation of the heavier isotopes) (Gat and Gonfiantini, 1981). As such, surface waters generally become enriched in ^{18}O and ^{2}H and groundwater tends toward the average annual rainfall values (Gat and Gonfiantini, 1981). These difference can enable the distinction between sources and the estimation of groundwater inflows.

3.1.2. Setting

The Mulwaree River, a tributary in the Hawkesbury-Nepean catchment, is located near Goulburn some 200 km southwest of Sydney (Figure 1A). The catchment sits atop the Great Dividing Range and drains an area of 790 km^2 that is dominated by highly weathered, folded felsic to mafic sedimentary units, with small areas of felsic volcanics and granite (Thomas and Pogson, 2012). Approximately 20% of the catchment is overlain with Quaternary alluvial or lake deposits (Thomas and Pogson, 2012). Ninety percent of the catchment has an elevation between 620 m and 800 m consisting of round hills and floodplains, with the remainder being steeper, dissected valleys on the western margin up to an elevation of 1010 m (Figure 1B).

The catchment is set in a temperate climate with moderate inter-annual rainfall variability, with a seasonally uniform mean annual rainfall of 700 mm and annual pan evaporation of 1450 mm (Bureau of Meteorology, 2017). At the The Towers gauging station (catchment area 604 km^2), the mean annual flood for the Mulwaree River is 25 m^3s^{-1} (14–46 m^3s^{-1}, 95% confidence interval) (Rustomji et al., 2006).

At a catchment area of 73 km^2 the river debouches onto a broad floodplain that is up to 1 km wide with a downstream gradient of 0.0016 m/m that decreases to 0.0008 m/m by the confluence with the Wollondilly River 58 km downstream. This lower reach is dotted with over 100 ponds of various sizes that are surficially connected by shallow, ephemeral channels and/or preferential flow paths. The ponds are too large to be a feature created by the current flow regime (Chapter 2). Their position and alignment is most likely related to the position of pools within a higher-energy palaeo-river and are therefore a contemporary expression of a remnant geomorphic feature that is maintained by the present flow regime (Chapter 2). The main study site, located on the property of 'Kelburn' 15 km south of Goulburn at a catchment area of 462 km^2, is a 1.7 km reach containing five large ponds with surface areas of ~1750–4000 m^2 and depths of 3.5–7 m (Figure 1, C and D). These sit in alluvial sediments with basal materials comprised of poorly sorted clayey sand and gravel, including gravels >50 mm b-axis. This is overlain with ~2 m of fine-grained clay loam to sandy loam across the valley (Chapter 2) (see Figure 2). During no-flow condition the ponds contain water but there is no surface water between the ponds. During high-flow conditions, surface water flows continuously along connecting channels and into and through the ponds (Figure 3).

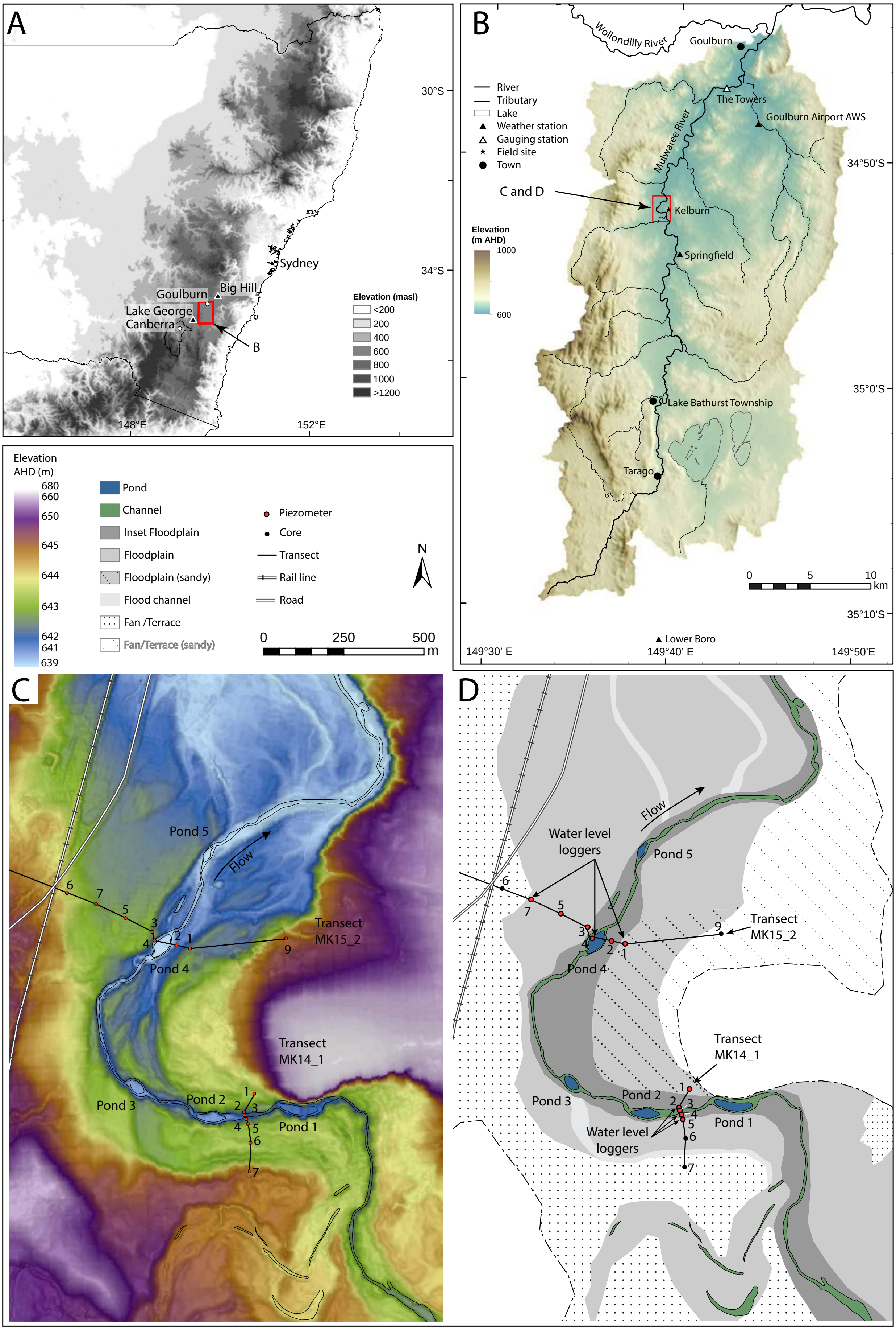


Figure 1. A) Location of the Mulwaree River catchment, and Lake George, Canberra and Big Hill rainfall isotope sampling locations from previous studies (Hughes and Crawford, 2013). **B)** Mulwaree River catchment showing the field site at 'Kelburn', and weather and discharge gauging stations. **C)** Digital elevation model of the field site showing the monitoring and sampling locations. **D)** Map of the field site showing geomorphic units and monitoring and sampling locations.

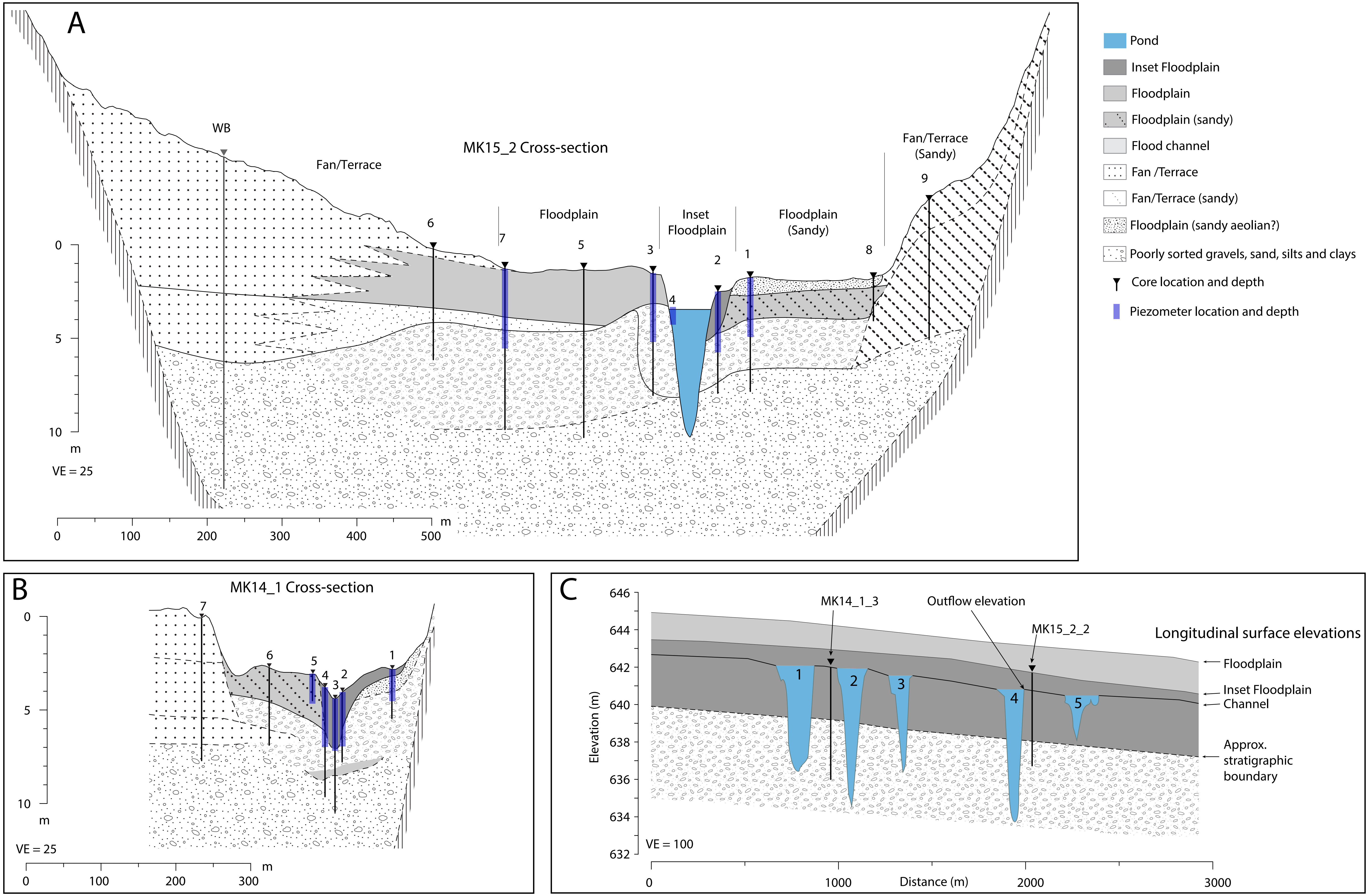


Figure 2. Cross-sectional and longitudinal stratigraphy of the Mulwaree River A) Cross-section (MK15_2 – see Figure 1D for location) and stratigraphy of the Mulwaree River at 'Kelburn'. Numbers are associated to MK15_2 cores and piezometers (e.g. 7 is MK15_2_7). Core WB is approximated from sediment descriptions from a driller's log of water bore GW028651 (Office of Water, 2016). The depth to bedrock is estimated from water bore driller's logs that cross the valley downstream (Office of Water, 2016). Figure 2B) Cross-section (MK14_1 – see Figure 1D for location) and stratigraphy of the Mulwaree River at 'Kelburn'. Numbers are associated to MK14_1 cores and piezometers (e.g. 3 is MK14_1_3). C) Longitudinal profile showing elevations of the floodplain, inset floodplain and the channel bed (including ponds). The approximate stratigraphic boundary between the surficial finer-grained sediment and the underlying coarse layer from two cores (see Figure 1D for location)

Figure 3. Images of the Mulwaree River showing the same locations during no-flow and high-flow. Photos taken from the hill to the east of the floodplain looking south to southwest.

Although there have been changes to landuse in the Mulwaree catchment that have increased sediment yields (Butzer and Helgren, 2005; Eyles, 1977a; Eyles, 1977b; Mould and Fryirs, 2017; Portenga et al., 2016), the Lower Mulwaree River (also called Mulwaree Ponds) has been disconnected from much of the sediment influx. This is due its broad floodplains buffering direct input from hillslopes and minor tributaries (Fryirs et al., 2007), and the reduction in slope at the point where the river becomes laterally-unconfined near Tarago has resulted in a sediment lobe (Chapter 2; Rustomji and Pietsch, 2007) capturing much of the longitudinal transfer. The study site around 'Kelburn', has largely escaped the geomorphic consequences of changes to catchment sediment flux and gullying, but is showing signs of deterioration via incision and channel formation connecting some of the ponds (Chapter 2). The Mulwaree Ponds is one of the few recorded large-scale chains-of-ponds systems in the country.

3.2. Methods

3.2.1. Piezometer installation

A network of piezometers was installed across the floodplain, inset floodplain and in connecting channels between the ponds using a direct push corer (GeoProbe LT54) and Dormer 50 mm hand auger (see Figures 1D and 2A). Piezometer depths ranged from 2 m to 4.5 m. Depth was limited by the saturated gravels collapsing into the hole. Piezometers were constructed from 50 mm diameter PVC pipe that was slotted over the entire depth.

3.2.2. Water levels

Water levels were recorded in three piezometers on transect MK14_1 from August 2014 to January 2015 (Figures 1D and 2B). Two were in the inset floodplain and one on the proximal edge of the main floodplain. Measurements were taken every 30 minutes using a Solinst Levelogger 3001 (accuracy ±0.01 m) and corrected for barometric pressure using a Solinst Barologger 3001 (accuracy ± 0.05 kPa). Subsurface water levels were initially measured at upstream locations (MK14_1_2, MK14_1_4 and MK14_1_5) but moved in April 2015 to more suitable downstream locations to obtain results from across the floodplain without hindering the landholders farming operations. One Levelogger was installed inside a slotted 50 mm PVC tube in the pond (MK15_2_4) to measure pond surface water levels and the other two Leveloggers were installed in piezometers on the main floodplain, one 60 m east (MK15_2_1) and the other 230 m west (MK15_2_7) of the pond (Figures 1D and 2A). There is no data for the ponds (MK15_2_4) and the eastern floodplain (MK15_2_1) from 1 December 2015 and 24 April 2016, respectively, until the 5 June 2016, as the water level fell below the sensors. For these data gaps, Pond 4 water level is predicted from a downstream gauge Mulwaree at The Towers. Relative levels were measured using a Leica TCR705 total station (accuracy ± 0.005 m) and adjusted to Australian Height Datum (AHD) using a LiDAR-derived digital elevation model (Geoscience Australia, 2015).

The relationship between mean daily water levels in the Mulwaree River at Kelburn and The Towers gauge (NSW Water, 2016) was described using observations of mean daily water levels for the periods April to December 2015 and May 2016 to January 2017 (Figure 4). Separate regressions were done for the high-flow and no-flow periods. During no-flow periods the water levels at the two sites varied linearly and a simple linear regression model was fitted. During high-flow periods a non-linear (logarithmic) regression was used to account for the logarithmic nature of the stage-discharge relationships and regression models were fitted using Minitab 17 (Minitab Inc., 2014). The coefficients of determination for the regressions were 0.7 (no-flow) and 0.95 (high-flow). These regressions were used to predict water levels at Kelburn for the period prior to the installation of water level loggers in Pond 4 and when the water level was below the sensor.

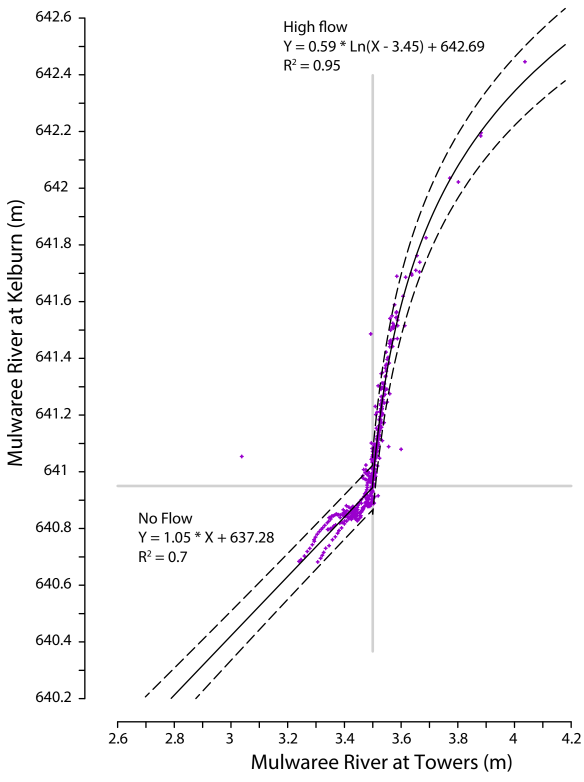


Figure 4. Correlation of mean daily water levels measured at The Towers gauging station (2122725) and the field site at Kelburn from April to December 2015 and May 2016 to January 2017. The lower values (The Towers <3.5 m) and linear line were when both sites exhibit no discharge, whereas the higher values and logarithmic function were during channel flow. The four largest outliers were all a 1 day lag at The Towers (left of the line) and Kelburn (right of the line). Predicted fits for Kelburn are shown (solid line) with 95% prediction intervals (dashed).

3.2.3. Atmospheric water flux and rainfall

A measure of the atmospheric water flux from the ponds was calculated by subtracting daily potential pan evaporation from daily rainfall. Pan evaporation data was from Goulburn Airport AWS (Station 070330, 10 km north) and daily rainfall data was from Goulburn Airport AWS and Springfield (Station 070077, 5 km south) (Bureau of Meteorology, 2017). Additional rainfall data was from Lower Boro (Station 070342, 35 km south) near the headwaters of the Mulwaree catchment to capture a better catchment wide average (Bureau of Meteorology, 2017) (Figure 1B). The cumulative atmospheric water flux was compared to the changes in water level recorded in the ponds and floodplain aquifer. This water flux measure is only relevant when the water level falls below the elevation at which surface water ceases to flow (see Figure 2C).

3.2.4. Stable Isotopes ($\delta^{18}O$ and $\delta^{2}H$)

Stable isotope samples were collected on 28 August 2014 to capture a high-flow, and 16 April 2015 and 27–28 October 2015 to record no-flow values after the different preceding seasonal (summer and winter) evaporation rates. Samples were collected from the ponds and from piezometers. During August 2014 only one pond was sampled due to the difficulty with flood conditions, and it was considered a likely representative sample as the ponds were connected by overland flow. In April and October 2015, there was no surface flow and at least four ponds were sampled during these times to record differences due to their varied morphology and sizes. Samples were taken from open-water ponds at 1 m intervals through the water column (and also from the benthic sediments in Ponds 4 and 5 in April 2015) using a Solinst 425 discrete interval sampler. Groundwater was sampled from piezometers every 0.5 m, starting at water level, using a peristaltic pump. The piezometers were purged prior to sampling, removing at least three well-volumes of water using a bailer or peristaltic pump. The peristaltic pump was run for at least 1 minute to ensure the tube was purged of previous samples.

Samples were collected directly into high-density polyethylene (HDPE) bottles, leaving no headspace, and sealed tightly. Temperature, pH and electrical conductivity were measured using a YSI Pro Plus multiparameter meter with measurements recorded after these parameters had stabilised. Prior to analysis, samples were extracted from the HDPE bottle and passed through Minisart 0.22 μm polyethersulfone filters, to remove any sediment, in to 2 ml glass vials. Water from the benthic sediments was also extracted using the same process.

Thirteen water samples were collected in August 2014 during a high-flow event and were analysed for $\delta^{18}O$ using an established continuous flow Isotope Ratio Mass Spectrometer (IRMS) method (Seth et al., 2006) using a Gasbench II connected to a Delta V Advantage IRMS. $\delta^{2}H$ values were obtained using an on-line combustion, dual-inlet IRMS method (Nelson and Dettman, 2001) using HDevice and Delta V Advantage IRMS. Results are accurate to ± 1.5 ‰ for $\delta^{2}H$ and ± 0.15 ‰ for $\delta^{18}O$. During no-flow periods in April and October 2015, 132 samples were collected and analysed using isotope ratio infrared spectroscopy (IRIS) (Kerstel and Gianfrani, 2008; Lis et al., 2008) on a Picarro L2130i cavity ring down spectrometer, accurate to ± 1 ‰ for $\delta^{2}H$ and ± 0.2 ‰ for $\delta^{18}O$. All 155 samples were analysed at Australian Nuclear Science and Technology Organisation (ANSTO), with a quality control reference standard included in each run and results normalised using ANSTO in-house standard reference material after which are standardised against VSMOW2-SLAP2. Results are expressed in parts per thousand (‰),, and reported relative to the international measurement standard for stable isotope analysis V-SMOW, where $\delta^{18}O$ and $\delta^{2}H$ values of SLAP are -55.5‰ and -427.5‰, respectively.

3.2.5. Radon water chemistry

Water samples for ^{222}Rn analysis were collected during a no-flow period in October 2015 from the upper (0.2 m), middle (3.5 m) and lower depths (7 m) of Pond 4. One groundwater sample was also taken from each of three floodplain piezometers at distances of 20 m east, 30 m west and 230 m west of the pond at depths below water level of 1.1 m, 0.7 m and 0.8 m, respectively. Samples were collected using a peristaltic pump (Geotech Geopump Series II) with three well-volumes purged from each piezometer prior to sampling to ensure they were recharged with unexposed groundwater. Temperature and electrical conductivity were measured using a YSI Pro Plus multiparameter meter and water sampling for ^{222}Rn analysis was undertaken after these parameters had stabilised. Once at the correct depth, at least 1 L of water was pumped through the peristaltic pump tubing to ensure no contamination. Samples were collected in 1.25 L PET bottles, filled beyond overflowing to ensure removal of any headspace, sealed tightly and stored in an insulated container heated to 25°C prior to extraction. Within 4 hours of sampling, 50 ml of water was removed from the bottles using a syringe, before injecting in 25 ml of mineral oil scintillant. The bottle was then shaken for 4 minutes migrating the radon to the mineral oil. The oil was then extracted into 20 ml PTFE scintillation vials (Leaney and Herczeg, 2006). Samples were transported within 2 hours of extraction to the radon Analytical Laboratory at ANSTO and analysed using a Tri-Carb 3100TR liquid scintillation counter with results reported to 1σ and a quantification limit of 0.05 Bq/L.

In addition to field measurements of electrical conductivity, a longer term data set from The Towers (2122725) was obtained from NSW Water (2016).

3.3. Results

3.3.1. Water level

Flow in the Mulwaree River is episodic, with distinct periods with and without surface flow. There is no flow 60% of the time and these periods are typically of a longer duration than times of flow, with most years having continuous periods of 3–6 months without flow. Extended droughts have also led to periods up to 2 years without flow (Figure 5B). High-flow periods are correlated to regional rainfall events, and last from a week to several months depending on the antecedent conditions. However, these sustained periods of discharge are highly variable (e.g. June to December 2016, Figure 5A) and only 20% of the time do they exceed 10 Ml/d at The Towers gauging station (NSW Water, 2016).

At the 'Kelburn' field site, surface water does not flow when the level falls below an elevation of 640.95 m AHD in Pond 4, indicating a surficial disconnect between the ponds. Below this elevation the rate of change in water level (either rising or falling levels) was less than 0.01 m per day for 90% of the time. However, when the ponds were connected from overland flow (water level >640.95 m), the rates of change were much greater. This is illustrated in Figure 6 and seen in measurements at both the Kelburn field site and The Towers gauging station.

The relationships between pond/channel water level and the surrounding alluvial aquifer also varied depending on the water level relative to cease to flow elevation. During periods where there was no flow through the channel, water level in the ponds relative to the floodplain aquifer level were always within ± 0.4 m, and generally within ± 0.1 m (Figure 5A). This was in contrast to high-flow periods where differences in the water level of the ponds and floodplain aquifer were up to +1.7 m.

Figure 5. (Page 69)

A) Water level of the Mulwaree River and adjacent floodplain at the 'Kelburn' field site, and atmospheric water flux of the ponds.

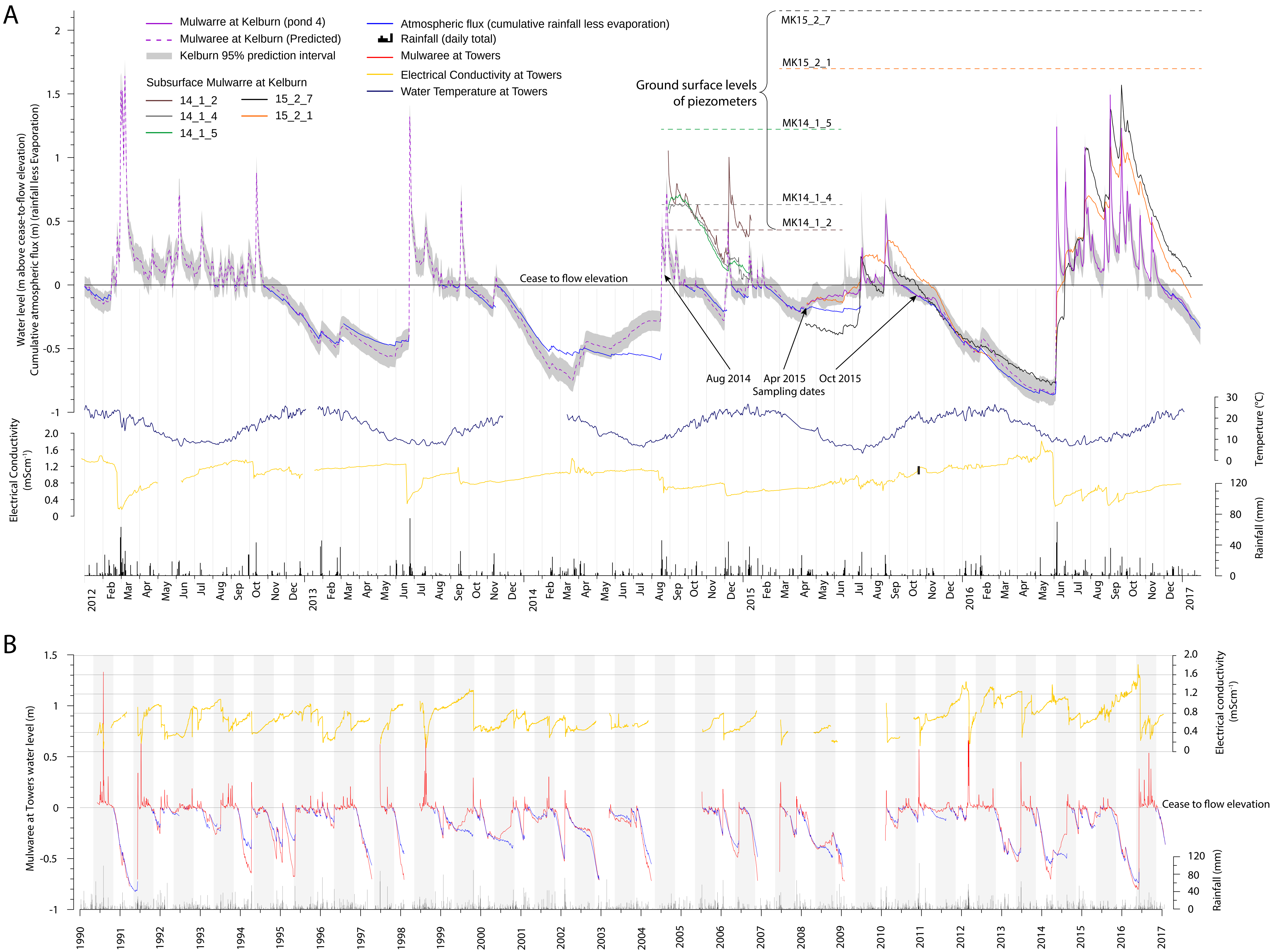
Water levels were initially measured at upstream locations (1_2, 1_4 and 1_5) but were moved in April 2015 to more suitable downstream locations 2_1, 2_4 (pond) and 2_7 (see Figure 2 for locations). Below installed sensor levels, Pond 4 water level is predicted from a downstream gauge Mulwaree at The Towers (dashed line with 95% prediction interval in grey) (NSW Water, 2016). Horizontal gridlines indicate surface elevations of sampling locations as labelled.

Precipitation less evaporation (blue line) was adjusted to zero when the pond level fell below outflow elevation (see methods for explanation).

The regional average rainfall (black column) was calculated from Bureau of Meteorology weather stations, Springfield (5 km south), Goulburn AWS (10 km north), and headwater station Lower Boro (35 km south) (Bureau of Meteorology, 2017) (locations shown in Figure 2).

Electrical conductivity (yellow) and water temperature (dark blue) were from Mulwaree at The Towers gauging station (2122725) (NSW Water, 2016).

B) Extended record from the Mulwaree River at The Towers gauging station (2122725 - see Figure 1B for location) (NSW Water, 2016). Water level (red), electrical conductivity (yellow) and precipitation less evaporation (blue line). Rainfall shown at bottom of plot.


A
Mulwarre at Kelburn (pond 4)
Mulwaree at Kelburn (Predicted)
Kelburn 95% prediction interval
Subsurface Mulwarre at Kelburn
14_1_2
14_1_4
14_1_5
15_2_7
15_2_1
Atmospheric flux (cumulative rainfall less evaporation)
Rainfall (daily total)
Mulwaree at Towers
Electrical Conductivity at Towers
Water Temperature at Towers
Ground surface levels
of piezometers
MK15_2_7
MK15_2_1
MK14_1_5
MK14_1_4
MK14_1_2
Cease to flow elevation
Aug 2014
Apr 2015
Oct 2015
Sampling dates
Water level (m above cease-to-flow elevation)
Cumulative atmospheric flux (m) (rainfall less Evaporation)
Electrical Conductivity (mScm⁻¹)
Temperture (°C)
Rainfall (mm)
2012 Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec 2013 Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec 2014 Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec 2015 Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec 2016 Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec 2017
B
Mulwaree at Towers water level (m)
Electrical conductivity (mScm⁻¹)
Cease to flow elevation
Rainfall (mm)
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017

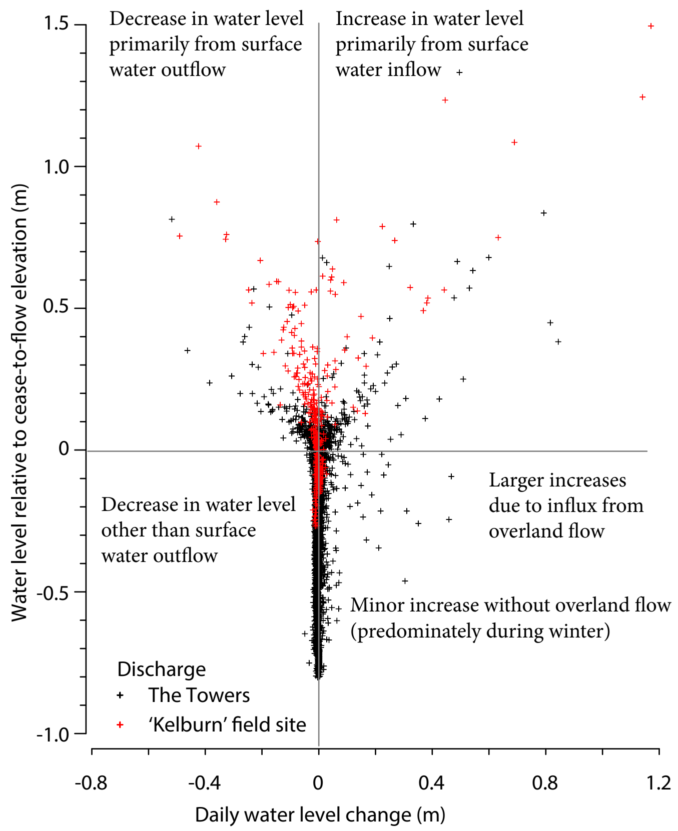


Figure 6. Water level and water level change for the Mulwaree River at The Towers gauging station and 'Kelburn' field site. Grey line is the water level where surface flow discharge is zero. The higher positive water level changes (y axis) that are associated with below zero flow (left of the grey line) are during heavy rainfall and flood events where the water filled the reservoir and continued above the zero discharge level.

During high-flow events the ponds and connecting channels recorded steep rises in water level (up to 1.2 m/day) followed by a relatively sharp declines (up to 0.5 m/day) for 3–7 days then gradually slowing back to the cease to flow elevation over the next 7–14 days. From this point, connecting channel flow ceased and the rate of water level decline in the ponds slowed markedly. During the high-flow events of July and August 2015, the water level of the floodplain aquifer rose by ~0.5 m, reaching a peak approximately 1–3 days after the peak water level of the ponds. Water level recession in the floodplain aquifer was much slower than in the ponds (0.01–0.05 m/day). This pattern is repeated elsewhere in the record. During the second series of high-flow events from June to November 2016, the channel and ponds rose rapidly, peaking and declining faster than the floodplain aquifer after each successive rainfall event. Cumulative impacts of successive rainfall events on water levels are noted by an upward stepped hydrograph, for example June–July 2016 (Figure 5A). Prior to the high-flow events beginning in June 2016, there had been an extended dry period from October 2015, with water level in the ponds below cease-to-flow elevation. The gradual decline in water level during this dry period corresponded broadly to atmospheric water flux (rainfall less evaporation) (Figure 5A). During the same dry period, the water level in the floodplain aquifer displayed a similar rate of decline to the surface water level and atmospheric water flux.

The extended record of water levels at The Towers gauging station (Figure 5B) showed a similar hydrographic pattern as the Kelburn site. Water levels rose rapidly during high-flow, followed by a steep decline until stabilisation at the overflow elevation of the weir. Below this point, the water level decreased at a slower rate, similar to the ponds at the study site. During extended dry periods, and when there was no discharge, the water levels showed a decline approximately 1.3 times faster than changes from rainfall and evaporation alone. These long declines typically occurred over summer and through lower rainfall autumns. Figure 7 shows that water levels below 0.4 m are uncommon from June to October (winter–spring). These no-flow periods were broken by either flooding from rainfall, which rapidly filled and overflowed the ponds, or gradual increases in water level over winter.

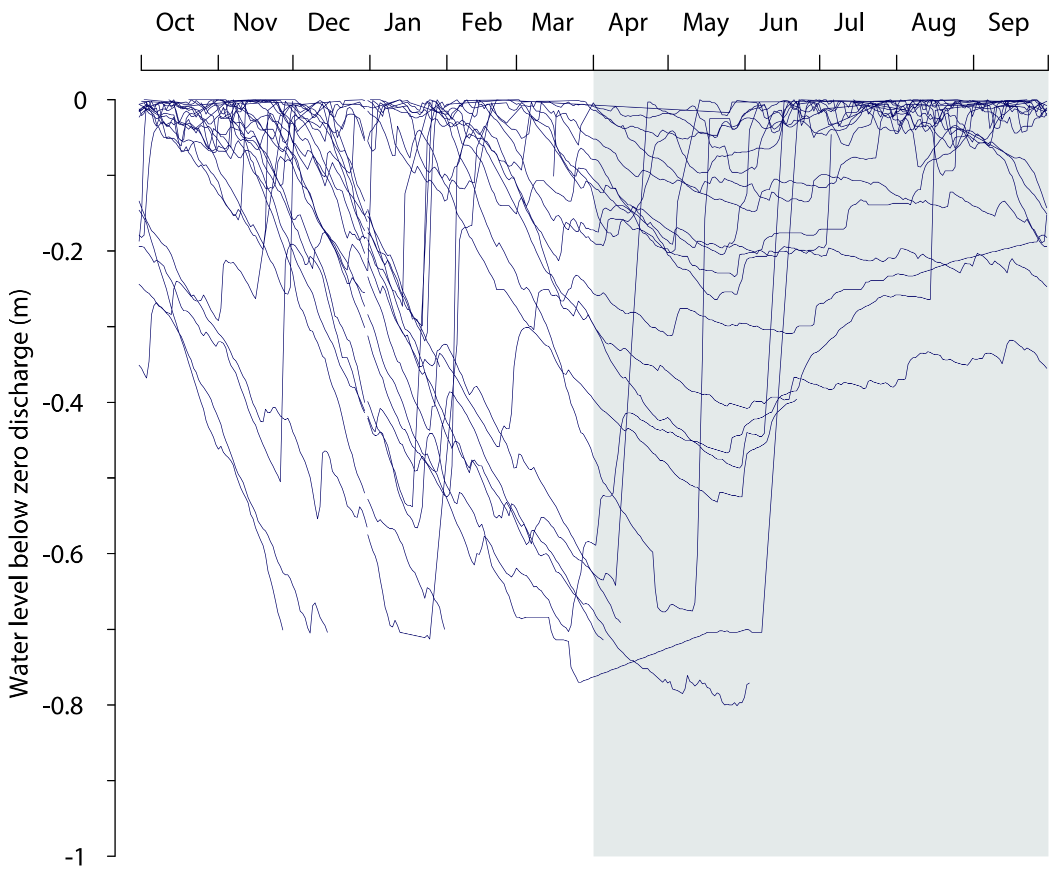


Figure 7. Water level when below cease to flow level at The Towers weir gauging station for 27-year record, relative to Julian day. Excludes mid-2004 to mid-2005 and 2009 when the level was below the monitoring equipment. Shaded area is the cooler months from April to September.

Relative water levels during the two 2015 no-flow sampling times are shown in Figure 8. During April 2015 the lateral hydraulic gradient from the ponds towards the floodplain aquifer from both the east (-0.005) and west (-0.009), was greater than the downstream gradient (~0.001). In October 2015 there was a lower hydraulic gradient from the eastern floodplain aquifer samples toward the pond (0.0025), and zero gradient from the west.

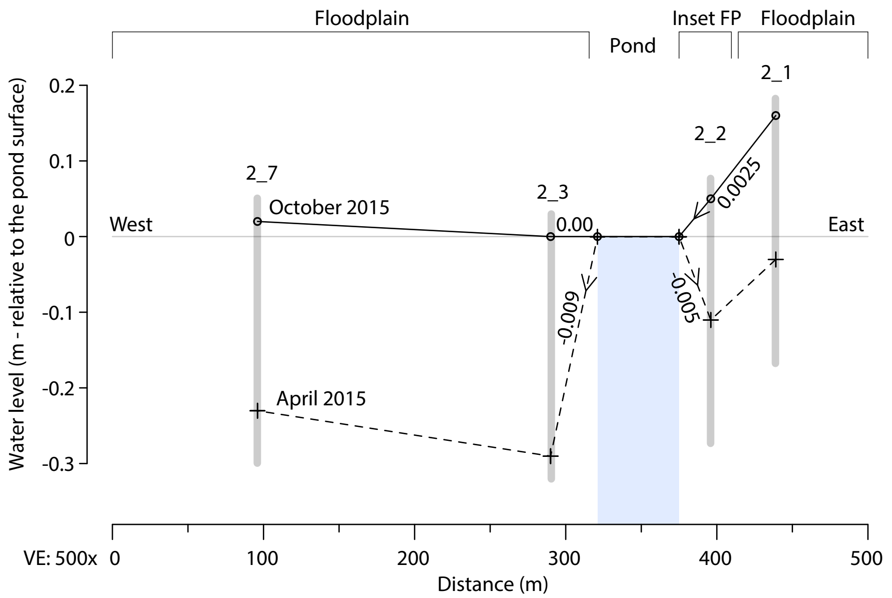


Figure 8. Water levels across the floodplain at no-flow isotope sampling times across transect MK15_2 (see Figure 1D for piezometer locations). Water levels are relative to the pond surface elevation with flow direction and gradients (m/m) shown.

3.3.2. Stable Isotopes

During a high-flow event in August 2014, the $\delta^{18}O$ and $\delta^{2}H$ isotope concentrations of the pond water were depleted and distinct from ground and surface water samples collected later in the study (Figure 9). Sampling was undertaken when the water level was ~1 m above the bed of the connecting channel (see Figure 5A). Stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) from throughout the depth profile of the pond and from water flowing through the connecting channel, had similar values ($\delta^{18}O$ = -8.1 ‰ to -8.2 ‰ and $\delta^{2}H$ = -52.8 ‰ to -51.6 ‰, Figures 9, 10A and 10C), suggesting thorough mixing of the water column during such flow events. These waters were depleted in ^{18}O and ^{2}H compared to groundwater samples collected at that time and the local rainfall average ($\delta^{18}O$ = -7.7 ‰ and $\delta^{2}H$ = -45.3 ‰ in winter and $\delta^{18}O$ = -6.2 ‰ and $\delta^{2}H$ = -35.4 ‰ in summer) calculated from unpublished data from nearby Lake George (unpublished data, M. Short ANU). August 2014 samples fall close to the local meteoric water lines for nearby sites (Hughes and Crawford, 2013; Jacobson et al., 1991) and we expect that this isotopic signature is influenced by ^{18}O and ^{2}H depleted rain water in the region at this time ($\delta^{18}O$ = -10.2 ‰ to -14.8 ‰ and $\delta^{2}H$ = -69 ‰ to -107 ‰ (unpublished data, M. Short ANU)). Samples from a piezometer in the connecting channel between Ponds 1 and 2 had ^{18}O and ^{2}H that were more enriched with depth and were close to the local mean rainfall values (Figure 9). These groundwater samples were partially mixed with the surface water due to leakage as the floodwater flowed around the slotted PVC piezometer during the sampling period. This resulted in mixing near the surface, diluting the groundwater in the upper sample, thereby making the deeper samples a more likely true groundwater value.

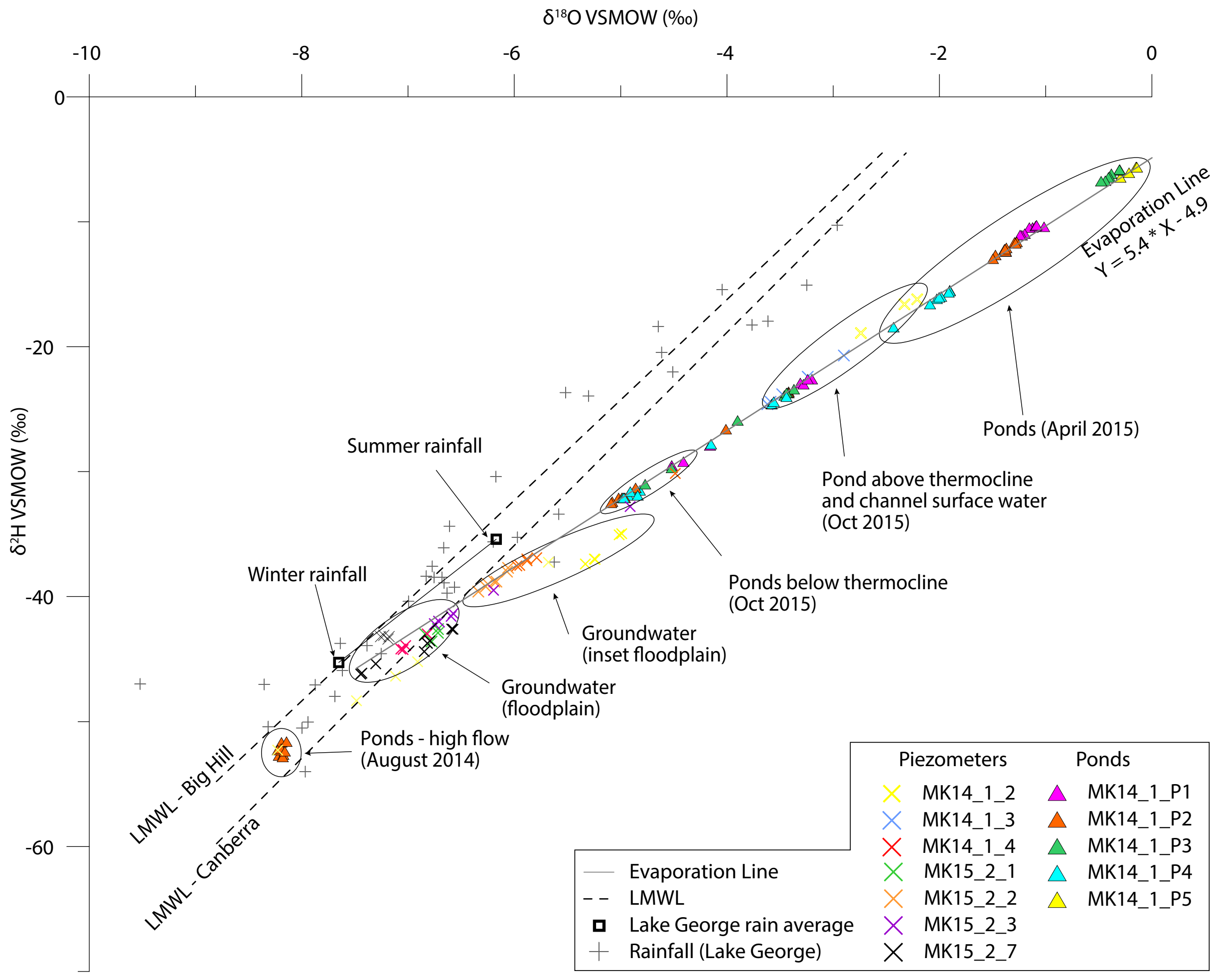


Figure 9. Stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) results relative to VSMOW for pond (Δ) and piezometer (×) samples. Local meteoric water line from Big Hill (Hughes and Crawford, 2013) and Canberra (Jacobson et al., 1991) (see Figure 1 for location). Evaporation line calculated from April and October 2015 pond no-flow samples. Groundwater samples are grouped (black ellipses) into two sets, floodplain and inset floodplain. Pond and connecting channel waters are grouped into four sets; August 2014 high-flow, April 2015 no-flow (where there was no thermocline), and October 2015 below and above the thermocline. Table of values in Appendix 2

In April 2015, following a prolonged dry period, there was considerable isotope enrichment of the pond water due to evaporation (c.f., Gonfiantini, 1986), which explains the deviation of those samples from the LMWL along a local evaporation line ($\delta^2H = 5.4 \times \delta^{18}O - 4.9$, Figure 9). Interestingly, the water column of most ponds is relatively homogeneous (Figure 10 A and C). However, water extracted from fine benthic surface sediments in Ponds 4 and 5 had $\delta^{18}O$ values similar to that of the groundwater and lower $\delta^{18}O$ than the pond water above (Figure 10 A and C). This indicates that pond water was not moving through these sediments into the aquifer at that time, which might be expected based on the hydraulic gradients (Figure 8). Conversely, it does not exclude the potential for groundwater contributions to the ponds because any groundwater would be quickly diluted due to the well mixed pond water.

During a second no-flow sampling round (October 2015), a weak thermocline had formed between 2 and 4 m depth in all ponds (Figure 11). The surface water $\delta^{18}O$ and δ^2H values were higher compared to those below the thermocline (Figures 9, 10B and 10D). Groundwater from the various piezometers had $\delta^{18}O$ and δ^2H values that were similar to the results obtained during the previous no-flow sampling rounds, but were more uniform through the water column. The groundwater samples from the floodplain were more enriched in ^{18}O and ^2H closer to the ponds than on the distal floodplain.

Groundwater from the floodplain, inset floodplain and connecting channel consistently had $\delta^{18}O$ and δ^2H values close to the mean rainfall values on the local meteoric water line (Figure 9). Samples taken from the inset floodplain (closer to the ponds) were more enriched in ^{18}O and ^2H than those from the distal floodplain but still more depleted than water from the ponds. The greater enrichment of ^{18}O and ^2H in April 2015, compared to October 2015, is likely due to the greater length of time since high-flow (~74 days and 43 days, respectively) and higher amount of evaporation (~280 mm and ~140 mm, respectively) in the period prior to sampling.

3.3.3. Radon and electrical conductivity

Radon samples collected in October 2015 (43 days after cessation of flow) showed that ^{222}Rn in the ponds were all less than 0.12 Bq/L compared to the groundwater from three piezometers across the floodplain with values from 30.7 ± 1.5 to 44.3 ± 2.2 (Table 1). This low concentration of radon in the ponds suggests that the inputs of groundwater to the ponds were small relative to the large pond volume, despite the hydraulic gradient toward the pond prior to sampling (Figures 6A and 8).

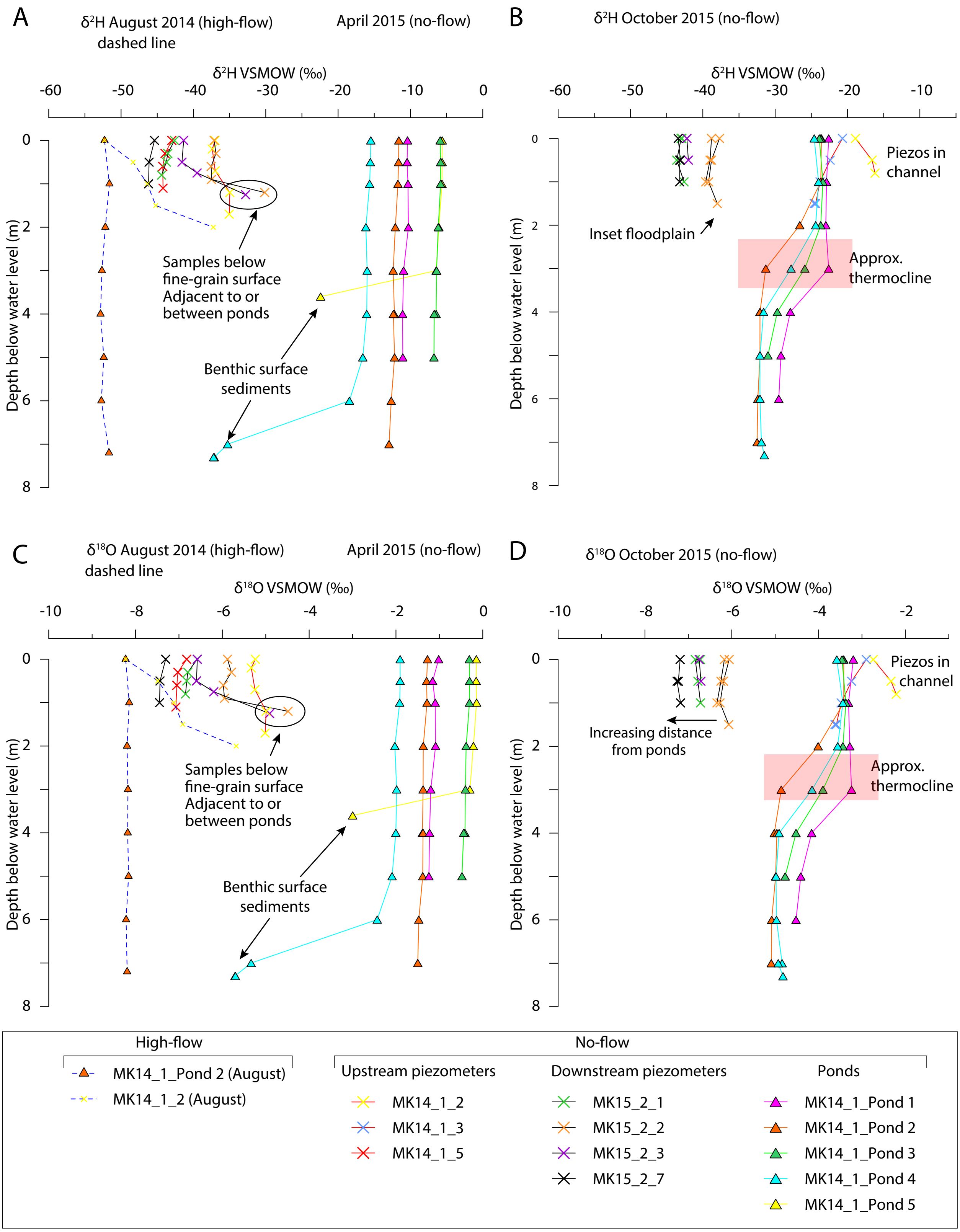


Figure 10. Stable isotope values ($\delta^{18}O$ and $\delta^{2}H$) for each pond and piezometer plotted relative to water level.
A) ^{2}H from August 2014 (dashed line), April 2015 (solid line) and **B**) ^{2}H from October 2015.
C) $\delta^{18}O$ from August 2014 (dashed line), April 2015 (solid line) and **D**) $\delta^{18}O$ from October 2015.
The depth of the thermocline is shown in B and D, with Ponds 2 and 4 having a greater temperature change (see Figure 11). Table of values in Appendix 2

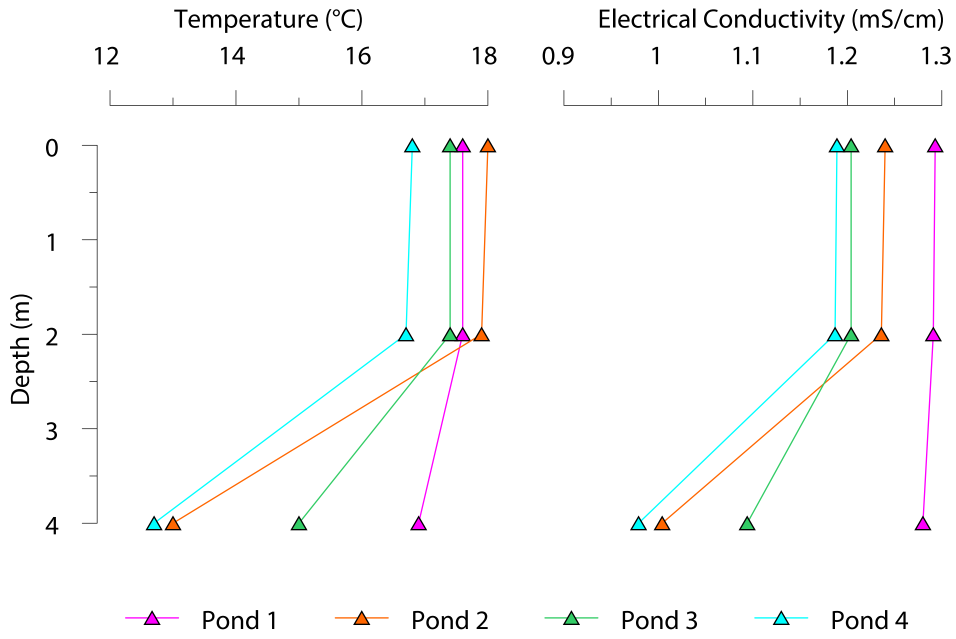


Figure 11. Temperature and electrical conductivity of four ponds during the October 2015 stable isotope and radon sampling round.

Table 1. Radon (^{222}Rn) activity from Pond 4 and piezometers along the intersecting transect (MK15_2)

Sample ID	Location	Date	Depth below water level (m)	^{222}Rn activity (Bq/L)	Uncertainty 1σ (Bq/L)
MK14_P4-T	Pond 4	28/10/2015	0.2	0.07	0.01
MK14_P4-M	Pond 4	28/10/2015	3.5	0.02^	0.01
MK14_P4-B	Pond 4	28/10/2015	7.0	0.12	0.01
MK15_2-2	Piezometer 2 (Inset floodplain, east)	28/10/2015	1.1	30.7	1.5
MK15_2-3	Piezometer 3 (Floodplain, west)	28/10/2015	0.7	44.3	2.2
MK15_2-7	Piezometer 7 (Floodplain, west distal)	28/10/2015	0.8	33.7	1.7

^Quantification limit for ^{222}Rn at 95% confidence interval is 0.05 Bq/L.

Electrical conductivity measured in October 2015 was 1.19–1.29 $mS.cm^{-1}$ in the surface water of the ponds compared to 0.98–1.09 $mS.cm^{-1}$ in the water 4 m below the pond surface and 0.41–1.01 $mS.cm^{-1}$ in the groundwater below the floodplain. The pond surface water values were close to those from The Towers gauging station downstream at the same time, where, in general, electrical conductivity gradually increased as the water level declined below no-flow level, and declined sharply with the influx from overland flow due to rainfall (Figure 5B). There were also increases in electrical conductivity as the water level rose slowly during some winter periods (e.g. 1999, 2000 and 2008, Figure 5B), suggesting that the inputs were slow moving surface water (that had higher electrical conductivity due to greater evaporation) and/or shallow groundwater influx.

3.4. Discussion

3.4.1. Hydrological function of a chain-of-pond system

The Mulwaree River can be separated into two hydrological states characterised by the continuity of surface flow. Here we present a conceptual model of the hydrological function for this chain-of-ponds system during a high-flow state and a no-flow state (Figure 12).

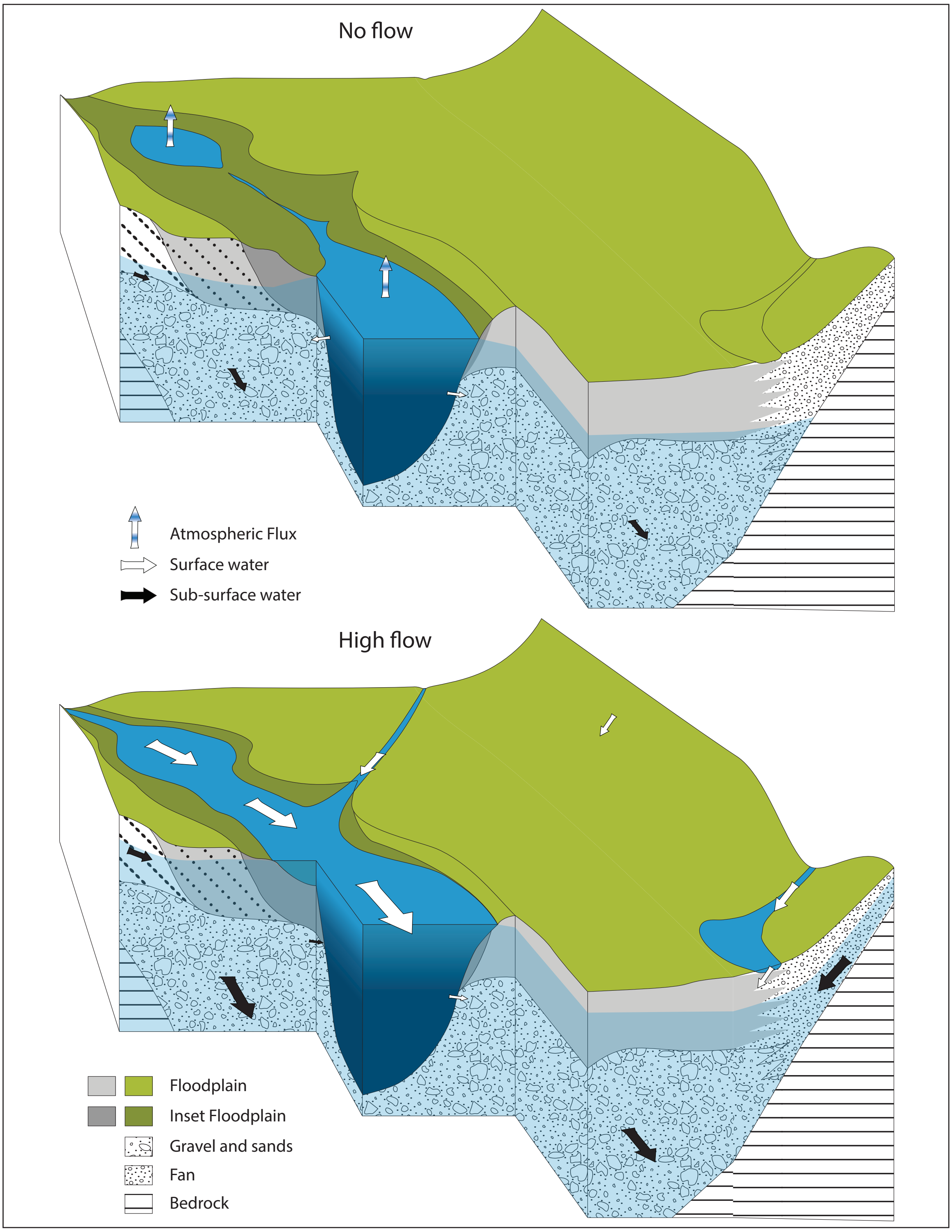


Figure 12. No-flow and high-flow conceptual models for surface flows (white arrows) and sub-surface flows (black arrows) of the Mulwaree River. Semi-transparent blue layer over the cross-section is the sub-surface water level. Size of the arrow represents the relative magnitude of flow.

High-flow Hydrological Function

During high-flow or flood events, the Mulwaree River is dominated by flow along the connecting channels and preferential flow paths between ponds. At this stage, flow is continuous through the system. The stable isotope ($\delta^{18}O$ and $\delta^{2}H$) values of the pond water during high-flow periods were close to the local meteoric water line and were more depleted than any floodplain groundwater samples suggesting that the pond water was dominated by inflow from overland flow sources at this flow stage. The isotope values did not vary through the depth profile of the ponds, indicating that the water column was well mixed. The system was surface water dominated similar to Cartwright and Gilfedder (2015) and little or no groundwater contributed to the hydrological function of the ponds at this time.

During and shortly after these flow events, the water level in the ponds is often greater than the water level in the surrounding floodplain aquifer. This produces a hydraulic gradient away from the ponds into the floodplain groundwater. Water is transferred laterally into the surrounding floodplain sediments, reflecting a losing wetland system (Jolly et al., 2008) as the floodplain groundwater aquifer is being recharged. However, this recharge is likely to be relatively small compared to the recharge occurring through infiltration of runoff across the floodplain and from adjacent hillslopes. For the high-flow events, this process occurred over only a relatively short period of 2–6 days after heavy rainfall and may have occurred 10 times during the monitoring period.

The lag time between water-level rise in the ponds and a response in the floodplain aquifer is controlled by antecedent water levels at the time of the high-flow event. This will dictate the extent to which sufficient hydraulic gradient is produced to trigger throughflow between the ponds and the floodplain aquifer (Ferone and Devito, 2004; Sophocleous, 2002; Wood et al., 1990). The drier the period preceding a high-flow event and the lower the water level in the floodplain aquifer relative to the pond water level, the stronger the hydraulic gradient after the rapid surface water level response to overland flow. After rain, surface flow declines and eventually ceases as pond water levels recede to the elevation of the outflow points.

No-Flow Hydrological Function

During no-flow periods the connecting channels and preferential flow paths are dry with surface water only present in the ponds. Surface flow between ponds is disconnected and water level in the ponds sits below the outlet point. Water levels within the ponds and the surrounding floodplain aquifer are roughly the same elevation. If during a particularly dry period the pond water level is lower than the floodplain aquifer water level, a hydraulic gradient towards the ponds is produced. Although not directly observed, this is likely to result in floodplain groundwater entering the ponds (Fetter, 2000). A gaining wetland system is produced (Jolly et al., 2008), which maintains the water level in the ponds. However, this groundwater input is relatively small, as noted by ^{222}Rn of <0.2 Bq/L in the pond water compared with the floodplain groundwater (>30 Bq/L), and the narrow overlap between the stable isotope signal for basal pond water and floodplain groundwater (Figure 10, A and C). Further work is required to assess whether groundwater input to these pond systems is enhanced during particularly dry periods and extended droughts.

The change in water levels in the ponds during no-flow (or extended dry periods) are coincident with the atmospheric flux, similar to other systems (e.g. Ferone and Devito, 2004). During no-flow periods, water in the ponds becomes enriched due to evaporation with stable isotope values occurring along a well-defined evaporation line. As a thermocline forms, this process becomes enhanced and the upper 3 m of pond water is significantly more enriched than that at depth. The level of enrichment is controlled by the period of time since the last high-flow and evaporation rate. For example, the higher enrichment values in April 2015, compared to October 2015, can be explained by a greater length of time (+31 days) and a higher amount of evaporation since high-flow (+140 mm). From the two no-flow periods monitored, it appears that it takes around 6 weeks or more after high-flow for the homogeneous profile of the ponds to change.

During extended dry periods, the water level in the floodplain aquifer can reach 1 m to 1.5 m below the surface. Given that the extinction depth for evapotranspiration is likely to be less than 1.5 m for the sandy or sandy loam sediments found in the floodplain (Shah et al., 2007), it is unlikely that declines in floodplain groundwater level are due to atmospheric flux. Instead, the floodplain groundwater aquifer establishes a downstream hydraulic gradient causing parallel sub-surface flow through the valley-fill (Sophocleous, 2002). Under these conditions, if the pond water level becomes higher than the floodplain aquifer then enriched water from the ponds can disperse into, and locally enrich, the waters of the proximal floodplain. Greater discharge will take place from the pond into the floodplain aquifer where coarser layers of sediment occur in the stratigraphy of the pond banks and valley-fill. However, the impact of this process on the chemistry of the broader distal floodplain aquifer is minimal (*sensu*, Ferone and Devito, 2004).

3.4.2. Surface water–groundwater interaction

The findings of this study reveal that precipitation and evaporation dominate the hydrological function of the Mulwaree chain-of-ponds system, but the relative role of each varies depending on whether the system is in a high-flow or no-flow state. Shallow groundwater flow into and out of the ponds from the surrounding floodplain aquifer is minor compared to evaporation and overland flow. Also, as the ponds in this study do not extend below the alluvial sediment or floodplain aquifer these systems are unlikely to be directly connected to deep groundwater or spring-fed. However, there may be interaction between the alluvial aquifer and deeper groundwater sources that have not been tested as part of this study. During wet periods when the ponds are recharged, the hydraulic gradients dictate that they will lose water to the surrounding floodplain aquifer. During dry periods, the ponds are weak gaining systems with pond water becoming enriched via evaporation. The functionality of the system changes between states but, on average, water levels between the ponds and the floodplain aquifer follow each other closely (Jolly et al., 2008). The findings suggest that the hydrology of these systems could be highly sensitive to local-scale water extraction and shallow groundwater aquifer interference. The functionality of these systems is not dissimilar to those found in other settings, including boreal, temperate and dryland areas (Cartwright and Gilfedder, 2015; Ferone and Devito, 2004; Jolly et al., 2008).

Multiple lines of evidence suggest that the ponds are not recharged from the groundwater in a sufficient volume to alter the isotopic composition or radon levels. The loss of water from the ponds during no-flow is predominately through evaporation with additional small losses to the surrounding groundwater when there is sufficient hydraulic gradient. This is shown by the slightly higher rate of water level decline compared to atmospheric flux. The groundwater levels decrease at a similar rate to the atmospheric flux, yet most of the time groundwater is isolated from evaporation suggesting that the coincident rates of change are not directly correlated.

During periods below zero discharge, increases in water level beyond atmospheric flux at The Towers gauging station all occur during winter. The continued increase in electrical conductivity, unlike the sharp decline that occurs during high-flow events, suggests that the inputs are slow moving surface water, or shallow groundwater influx. These may be due to the lower evaporation and evapotranspiration over winter leading to relatively higher runoff and increased infiltration rates to the alluvial aquifer during winter (Jasechko et al., 2014). This shows that the Mulwaree River and alluvial aquifer are closely linked to high-flow events over winter and winter rainfall in general. Groundwater recharge is vulnerable to decreases in rainfall, especially in winter (Jasechko et al., 2014), and increases in evaporation and evapotranspiration reduce antecedent soil moisture decreasing runoff and through-flow into the alluvial aquifer (Wood et al., 1990). Winter rainfall is predicted to decline in southeast Australia over the 21st century due to climate change, along with higher evaporation and evapotranspiration due to increased temperatures (Dowdy et al., 2015; Grose et al., 2015). This puts the Mulwaree River floodplain aquifer at risk of lower inputs and reduced water levels, thereby impacting pond water levels, base-flow inputs to downstream discharge, and pond and floodplain aquifer ecosystem function.

Another chain-of-ponds (Deep Creek) in southeast Australia receives between ~14% (of 300 ML/day) and ~100% (of ~7 ML/day) of its downstream discharge from groundwater inflow, during high and no flow, respectively (Cartwright and Gilfedder, 2015). The Mulwaree River may have a similar relationship, with the shallow groundwater discharging into the Wollondilly River after overland flow has ceased. The longitudinal gradient and permeability of the coarse sedimentary layers may allow the groundwater to move downstream and produce a water level decline approximately equal to that of the atmospheric flux. The coincident decline in groundwater (from downstream discharge) and pond water (as they decrease at a rate near to evaporation less rainfall) creates a near zero hydraulic gradient. In Deep Creek, the majority of the groundwater is added to the system where reaches are close to bedrock hillslopes where there is likely steeper hydraulic gradient. Little, or no, groundwater is added where the ponds are in the middle of the floodplain of a broad alluvial reach (Cartwright and Gilfedder, 2015) that is similar to the planform of the lower Mulwaree River.

Although it was not observed during this study, it is possible that groundwater could enter the ponds, particularly if the floodplain aquifer was recharged from successive large rainfall events and the level were to decline more slowly than the pond water evaporated. This could cause groundwater influx to the ponds due to the resultant hydraulic gradient. So, while the ponds and their aquatic communities may not be directly dependent on the particular water chemistry of adjacent groundwater, they are dependent on groundwater to maintain the water level in the ponds, making them GDEs that have little or no groundwater exchange.

The geomorphic evolution, and resultant structure, of the Mulwaree River supports a hydrological setting that is unlike others across (at least) southeastern Australia. The scale of these ponds is greater (in both area and depth) than anything else reported for a discontinuous river. To explain their continued form (i.e. deep ponds in an aggrading system), it is hypothesised that the ponds are maintained through two processes. Firstly, there is very little sediment transferred into, or along, the Mulwaree River due to the low stream gradient, dense channel and floodplain vegetation, and the wide floodplains acting as buffers (Fryirs et al., 2007). Secondly, any fine-grained sediment is kept from consolidating owing to the pore pressure from the aquifer, as seen by relatively depleted $\delta^{18}O$ and $\delta^{2}H$ levels in the unconsolidated fine-grained benthic surface sediment. It is subsequently 'flushed' by higher flows, keeping the pond volumes at an approximate equilibrium.

Further work is needed to explain the changes in groundwater levels. Stable isotope sampling when the groundwater levels are toward a minimum would clarify the relationship with atmospheric flux. The expectation is that the values would fall to the lower end of the evaporation line near the LMWL, similar to those from April and October 2015, indicating a disconnection from atmospheric flux. Tritium may also help explain the movement of groundwater through the alluvial aquifer and indicate the sources of water in the ponds during no-flow (Cartwright and Morgenstern, 2016; Cook and Böhlke, 2000).

3.5. Conclusions

The lower Mulwaree River has evolved over more than 100 ka to form a unique surficially-discontinuous fluvial environment. The deep ponds and sharp changes in stratigraphy are features of the rapid evolution from a higher-energy gravel-bed river to the present low-energy system. This has resulted in the surface water having dichotomous states of a continuous river during high-flow and disconnected ponds during no-flow. Unlike the surface flow, the groundwater maintains a longitudinal flow, punctuated with pulses after high rainfall events. This longitudinal flow appears to bypass the ponds with a preferential flow path through the coarse sediment of the deeper gravelly alluvium. The ingress of water from the alluvial aquifer to the ponds is minor compared to their large volume and the repeated flushing with surface water during high-flow events. However, the ponds maintain a weak lateral connection with alluvial aquifer when there is sufficient hydrological gradient, meaning that impacts to the adjacent groundwater, will affect the aquatic communities. The findings suggest that the hydrology and ecosystem function of these large-scale chains-of-ponds, and discontinuous fluvial systems more generally, could be highly sensitive to local-scale water extraction, shallow groundwater aquifer interference and changes to groundwater recharge due to climatic changes. The surficial appearance of discontinuity masks the continuous longitudinal flow of the alluvial aquifer during both high-flow and no-flow stages, highlighting the importance of subsurface and hyporheic processes in defining the hydrological character of a river.

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Chapter 4

Diversity of Chains-of-Ponds and Reach-Scale Sensitivity Analysis

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4.1. Introduction

Chains-of-ponds consist of steep-sided ponds separated by densely vegetated, alluvial valley-fill sediments that contain shallow ephemeral channels or preferential flow paths (Eyles, 1977a; Hazell et al., 2003). They form on low-gradient drainage lines through scour or deposition and are often found in, or called, swampy meadows (Mactaggart et al., 2008). These discontinuous systems are noted as a previously ubiquitous landform in many upland drainage lines, but land-use changes and direct modification has seen the loss of many chains-of-ponds systems (Eyles, 1977b; Mould and Fryirs, 2017; Prosser et al., 1994). Channel incision is the most common process in the shift from a discontinuous channel form and has been linked to land-clearing and over-grazing, and also direct modification to drain 'swampy' areas (Eyles, 1977b; Mould and Fryirs, 2017). The chains-of-ponds that remain are of (geo)ecological significance as they provide habitat to species dependent on permanent (or longer-term), lentic water (Hazell et al., 2003) and are representative of pre-European small to medium-sized rivers (Eyles, 1977b; Rutherfurd et al., 2000).

Catchment and river management requires an understanding of the character and behaviour of a system to be able to develop processes for protecting, maintaining or rehabilitating these important landscape ecosystems (Brierley and Fryirs, 2005). Beyond a rivers current state, it is important to be able to predict the impacts on character and behaviour of a river due to changes from landscape modification and climate change (DeFries and Eshleman, 2004; Fryirs and Brierley, 2016). For example, will changes to the intensity and duration of storm events result in greater geomorphic change than the system may be able to accommodate? A key geomorphic concept in understanding how a system behaves is sensitivity; i.e. the way in which it responds to a disturbance, relative to the magnitude of the disturbance (Downs and Gregory, 2004; Fryirs, 2017). There have been studies on intermittent and ephemeral fluvial systems with discontinuous channels using long-term evolution to understand the response (or resilience) of a system to disturbance, with the aim of predicting future adjustment. These systems include; cut and fill (Erskine and Melville, 2008; Fryirs and Brierley, 1998; Johnston and Brierley, 2006; Prosser, 1991), arroyos (Bull, 1997), swampy meadows (Prosser et al., 1994) and chains-of-ponds (Eyles, 1977a; Mould and Fryirs, 2017). This process has provided useful insight into the formation and processes of discontinuous systems allowing those in river management to forecast future trajectories and make better informed decisions on the recovery potential or pathways available (Fryirs and Brierley, 2016).

The next step in using sensitivity for managing discontinuous watercourses, and specifically chains-of-ponds, is being able to use semi-quantitative assessments of reach sensitivity to identify those at risk (Reid and Brierley, 2015). The measures need to incorporate their sensitivity to disturbance, their resilience and potential of changing to a new river type. This is covered by three measures: *event sensitivity* is the preconditioning that increases the likelihood of geomorphic adjustment or change to a generally resilient landform (Crozier, 1999; Phillips, 2006); *morphological sensitivity* is a reaches resilience or recovery potential (Brunsden, 1993b; Fryirs, 2017); and, *change sensitivity* is the likelihood or potential to shift to a new behavioural regime (Brierley and Fryirs, 2016; Brunsden, 1993b).

The relatively small body of work focused on evolutionary and geomorphic processes of chains-of-ponds have identified measurable characteristics relating to ponds size and valley slopes, along with historical changes (Eyles, 1977a; Mould and Fryirs, 2017; Williams and Fryirs, 2016 – Appendix 5). However, quantitative measures or indices that describe the morphodynamics, such as a braid index (Brice, 1960), or sinuosity in meandering rivers, are not available for these river types. To extend the applicability of semi-quantitative sensitivity analysis to discontinuous rivers types, quantitative values measured from geomorphic features or geomorphic change are required. This is so that the features or rates of change can be objectively measured, and then used to compare discontinuous rivers of the same type.

Chains-of-ponds are susceptible to changes in hydrology due to anthropogenic landuse changes and direct modification (Eyles, 1977b; Mould and Fryirs, 2017; Wasson et al., 1998). Climate change is also likely to affect streamflow and vegetation structures in chains-of-ponds due to changes in the amount, intensity and variability of precipitation and increases in temperature, evaporation and evapotranspiration across southeastern Australia (Dowdy et al., 2015; Grose et al., 2015; Reinfelds et al., 2014). To understand how chains-of-ponds will respond, there needs to be an understanding of how the hydrology of a system influences their characteristic form and function.

The aims of this paper are to provide a better understanding of the hydro-geomorphic processes, controls and sensitivity to geomorphic change of chains-of-ponds. This is achieved in a series of steps:

1) describe and measure the geomorphic structure, planform and stratigraphic character, and diversity of a range of headwater chains-of-ponds (section 4.4.1);
2) describe the hydrological function by identifying surface water–subsurface water interactions and use flow-modelling to quantity stream power (sections 4.4.2 and 4.4.3);

3) identify the variability of reaches and the process of pond and channel formation, evolution and loss (sections 4.5 and 4.6);

4) analyse statistical relationships between impelling forces (unit stream power) and quantitative planform metrics (e.g. ponds size) (section 4.7);

5) use the sedimentary structure, long-term evolution and historical changes of seven morphologically distinct chain-of-ponds reaches to analyse geomorphic sensitivity (section 4.8) and;

6) create measurable geomorphic planform characteristics to quantify event, morphological and change sensitivity for chains-of-ponds (section 4.8)

This understanding will provide for improved interpretation and assessment, and therefore better management of these unique and important discontinuous watercourse ecosystems.

4.2. Setting

The Northern Tablelands of NSW have been relatively tectonically stable for the past 20 million years and low rates of denudation (~10 m/Myr) (Bishop, 1985) have resulted in elevated, low relief plateaus with low gradient headwaters. Tableland geology is dominated by late Palaeozoic sedimentary and low-grade felsic metamorphic units, punctuated by intrusive granites and diorites, with Cenozoic basaltic caps on many of the highest regions. The climate is temperate, with mean minimum and maximum temperatures ranging from 12°C to 27°C in summer and 0°C to 12°C in winter. Annual precipitation of 750–1200 mm is summer-dominated with moderate inter-annual variability (Bureau of Meteorology, 2017).

Prior to European settlement, the Northern Tablelands were seasonally inhabited by multiple aboriginal peoples during the warmer months before moving to the coast or western plains for the cooler parts of the year (Godwin, 1983; Kerr et al., 1999; Rosen, 2009). Land use changes began in 1830s when the region was settled by European squatters and pastoralists, with increased stocking rates of sheep and cattle, pasture improvement (new grass types and superphosphate), and tree clearing through the 19th century (Starr, 1978).

The seven study reaches, on the property 'Eastlake' (near Uralla NSW) in the headwaters of the Macleay catchment, are all on the adjacent Jacks and Mihi Creeks, which have catchment areas of ~19 km^2 at their confluence (Figure 1). There are over 180 ponds on the studied reaches with between 2 and 29 on each of seven reaches. Flow through both creeks is episodic with overland flow typically achieved after rainfall events greater than 25 mm in a day. All the reaches are on land that is grazed for cattle or sheep. These reaches incorporate a range of chain-of-ponds morphologies with varying stratigraphy, valley confinement, slope and lithology.

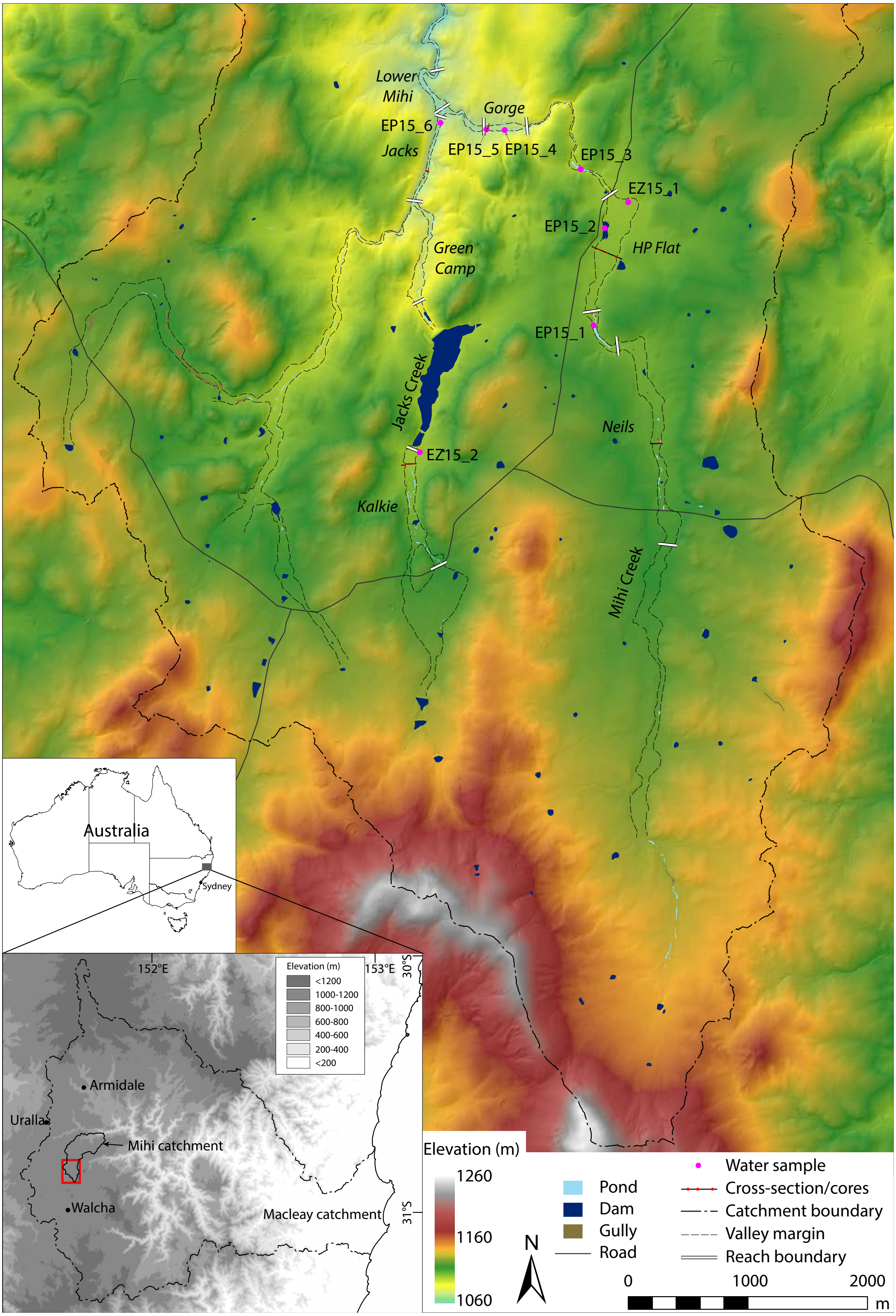

Figure 1. Map showing the location and elevation of Mihi and Jacks Creek in upper Macleay Catchment, Northern NSW, Australia; including dams, ponds and gullies, water isotope sample locations (filled black circle), cross sections and cores (black line and red dots). Reach names are shown in italics. Refer to reach diagrams for details (Figures 5 and 7–9)

4.3. Methods

4.3.1. Cross-sections Survey and Geomorphic Mapping

Core locations, cross-sections and long profiles were surveyed using a Leica TCR700 total station, adjusted to Australian Height Datum from a 2 m LiDAR-derived DEM (Spatial Services, 2015). The DEM was also used, in conjunction with 0.5 m ground sample distance ADS40 aerial imagery (Spatial Data Services, 2013), to create geomorphic maps. The valley width was measured from the resultant maps and ground truthed during site visits. Long profiles were interpolated from the LiDAR-derived DEM at cross-section every ten metres. Values for the floodplain and channel/pond beds were taken from mean and minimum cross-section elevation, respectively. Slope was calculated using a moving 100 m regression (50 m either direction) to account for negative slope values when exiting ponds and floodplain anomalies, such as farm dams. Current geomorphic planform was compared to historical parish maps (Land and Property Information, 2017) and later aerial imagery from 1956 to 1979 (Land and Property Information, 2016). Catchment area was extracted from the output of the Flow Accumulation tool using ArcGIS 10.4 (ESRI, 2016).

4.3.2. Stratigraphy

The stratigraphy was revealed through examination of two bank exposures and thirty-two sediment cores, across six transects and one longitudinal profile. Core locations were chosen as they were representative locations on five morphologically distinct reaches where access was available. Sediment from the initial three holes were extracted using a Dormer 50 mm sand auger, with only shallow depths (<1.2 m) obtained as the sediment was not collected by, or fell from the auger at the gravel layers. The majority of core samples were collected using a Geoprobe 54LT percussion corer, with optically stimulated luminescence (OSL) samples collected in black opaque tubes and opened under dim red light to preserve the trapped signal. Using a hand corer, two cores were collected in 50 mm PVC tubes and again opened under dim red light for the extraction of sediment for OSL analysis. Further samples were taken from each stratigraphic layer for field texture analysis (Northcote, 1979).

4.3.3. Geochronology

Alluvial sediments were dated using single-grain OSL. Burial doses were determined using single-aliquot regenerative-dose protocol (SAR) (Murray and Wintle, 2000; Wintle and Murray, 2006). Samples were analysed on an automated Risø TL/OSL-DA-20 reader (Bøtter-Jensen et al., 2000) fitted with an EMI 9235QA PMT and Hoya U-340 detection filters. Optical stimulations were performed using blue LEDs (470 nm) or green laser (532 nm) for single-aliquot and single-grain analysis, respectively. Laboratory irradiations were performed by a calibrated $^{90}Sr/^{90}Y$ source, with uncertainties in the dose received at each single-grain location incorporated in the equivalent dose. Lithogenic radionuclide activity concentrations were determined using Compton suppression gamma spectrometry at the Australian Nuclear Science and Technology Organisation. Dose rates were calculated using dose-correction factors from Adamiec and Aitken (1998), with beta-dose attenuation factors taken from Mejdahl (1979), cosmic dose rates calculated following the procedures of Prescott and Hutton (1994) and adjustments for moisture content after Aitken (1985) and Readhead (1987). OSL equivalent doses were calculated using a minimum-age model (MAM) if the over-dispersion was high due to partial bleaching in a higher energy environment, or using a central-age model (CAM) if the over-dispersion was low from a well-bleached sample in a low-energy depositional environment (Galbraith et al., 1999; Rhodes, 2011; Vermeesch, 2009).

4.3.4. Hydraulic Modelling

Two-dimensional (2D) hydraulic models were created in HEC-RAS 5.0.3 (USACE, 2016) for the seven reaches on Jacks and Mihi Creeks calculating, water surface elevation, depth, velocity, shear stress and unit stream power. Values were calculated using a full momentum (conservation of energy) model over a 5 m grid mesh, with break lines added to align flow on barriers and depressions. The model was run with a 10 second computation interval for six flows of varying annual exceedance probabilities (AEP). Downstream boundary conditions were set as normal depth with the water surface slope equal to the floodplain slope measured from a 2 m LiDAR-derived DEM (Spatial Services, 2015). Upstream boundary conditions were flow hydrographs over a 48-hour period with the duration and flow pattern estimated from NSW Office of Water gauging stations Mihi Creek at Abermala (station 206034, catchment 117 km^2) and Pipeclay Creek at Kirby Far (station 206027, catchment 9 km^2) (Office of Water, 2017). Peak discharges were estimated using the Australian Rainfall and Runoff Regional Flood Frequency Estimation Model (Rahman and Haddad, 2017) for AEPs of 50%, 20%, 10%, 5%, 2% and 1% (Figure 2).

The width of flow along with mean, standard deviation, minimum and maximum values for the modelled outputs were extracted using Zonal Statistics in ArcGIS 10.4 (ESRI, 2016) along cross-sections at 10 m intervals on each Mihi and Jacks Creek longitudinal profile. Unit stream power values shown in the longitudinal plot were averaged using a 100 m moving window. Plotted water surface elevation were smoothed using a linear regression over a 100 m moving window.

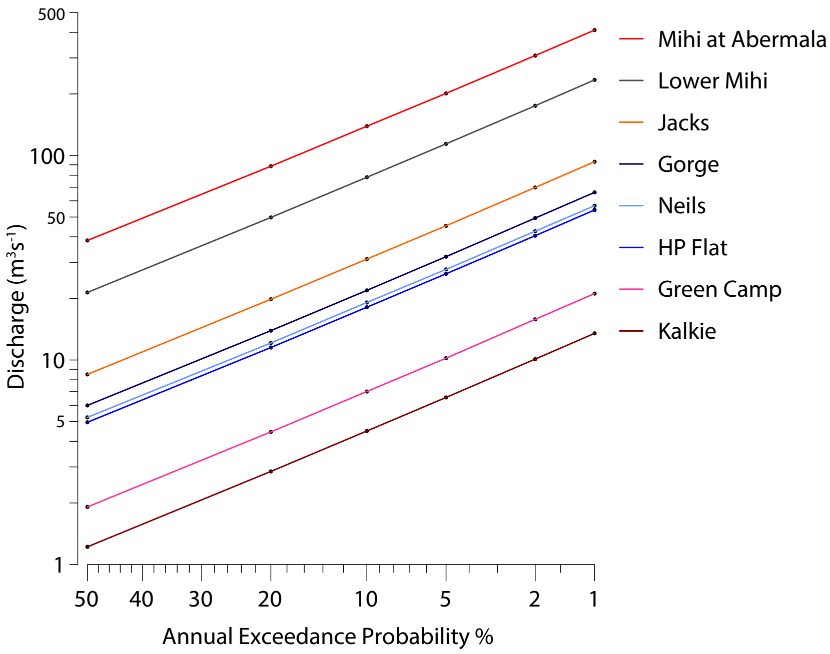

Figure 2. Discharge annual exceedance probability plot for seven reaches. Estimated using the Australian Rainfall and Runoff Regional Flood Frequency Estimation Model (Rahman and Haddad, 2017).

4.3.5. Stable Isotopes and Groundwater

Stable isotope (δ^2H and δ^{18}O) samples were collected from the ponds and piezometers using a Solinst 425 discrete interval sampler or from the surface directly into high-density polyethylene (HDPE) bottles, leaving no headspace, and sealed tightly. Samples were taken from the surface and base of open-water ponds and groundwater was sampled from 100 mm diameter piezometers installed during the 1980s by New South Wales Soil Conservation. Between October 2015 and January 2016, 18 rainwater samples were collected from separate events lasting 0.5–24 hours with varying rainfall intensity (0.02–6 mm/h). Immediately after cessation of rainfall, samples were decanted from open collection containers into HDPE bottles and sealed with no head space. Prior to analysis, samples were extracted from the HDPE bottle and passed through Minisart 0.22 µm polyethersulfone filters, to remove any sediment, in to 2 ml glass vials. All samples were analysed using isotope ratio infrared spectroscopy (IRIS) (Kerstel and Gianfrani, 2008; Lis et al., 2008) on a Picarro L2130i cavity ring down spectrometer, accurate to ± 1 ‰ for δ^2H and ± 0.2 ‰ for δ^{18}O at

Australian Nuclear Science and Technology Organisation (ANSTO). Results are expressed in per mil (‰), reported relative to VSMOW and normalised using ANSTO in-house standard reference material, which are standardised against VSMOW2-SLAP2, with a quality control reference standard included in each run.

Groundwater depths were taken every 30 minutes using a Solinst Levelogger 3001 (accuracy ± 0.01 m), with barometric pressure changes compensated using 9 am and 3 pm barometric pressure values from the Armidale Airport AWS, station 56238 (Bureau of Meteorology, 2017).

4.4. Results

4.4.1. Geomorphic planform and stratigraphy

Along the two creeks, nine morphologically distinct reaches are described in detail below. These include the upper reaches of each creek, and the seven reaches that have been hydrologically modelled including; Neils, HP Flat and Gorge on Mihi Creek; and Kalkie, Green Camp and Jacks on Jacks Creek; with Lower Mihi below the confluence of the two creeks (Figure 1, 3 and 4).

Figure 3. (Page 99)

The valley width (filled grey line) compared to the effective valley width, for the 1% (black line) and 50% (red line) AEP flows extracted from the HEC-RAS outputs, highlight the relative portion of the floodplain and adjacent hillslopes that are inundated during flows.

Unit stream power values are shown for 1% (black line), 10% (dark red line) and 50% (red line) AEPs with reach mean values (dashed lines) listed.

Slope (blue line), calculated using linear regression of elevation values within a 100 m moving window and reach mean slope (dashed horizontal lines) with values shown. Water surface slopes for 1% and 50% AEPs were calculated using the same 100 m linear regression window.

Pond surface area (y-axis) relative to the locations along the longitudinal profile (x-axis) also shows the length of each pond represented by the length of the dash (to the nearest 10 m). Colours showing their setting and or modification (see key for details). The longitudinal density is also shown below the valley width on the top most y-axis using the same colours.

The longitudinal profile (think black line) is the valley-wide surface mean elevation. The dash-dot line linking the two profiles shows where Jacks Creek joins Mihi Creek. Spikes in elevation, particularly noticeable on the upper part of Jacks Creek (far right) are associated to farm dams. The bottom of the grey shaded area under the longitudinal profile is the valley-wide minimum elevation, highlighting ponds, channels and flow paths. Bedrock elevation under the alluvial surfaces (dashed black line) interpolated from sediment cores. Estimates only extend to reaches where cores were taken to sufficient depth.

Catchment areas (red line) for each creek with the dashed-dot line showing where Jacks Creek flows into Mihi Creek.

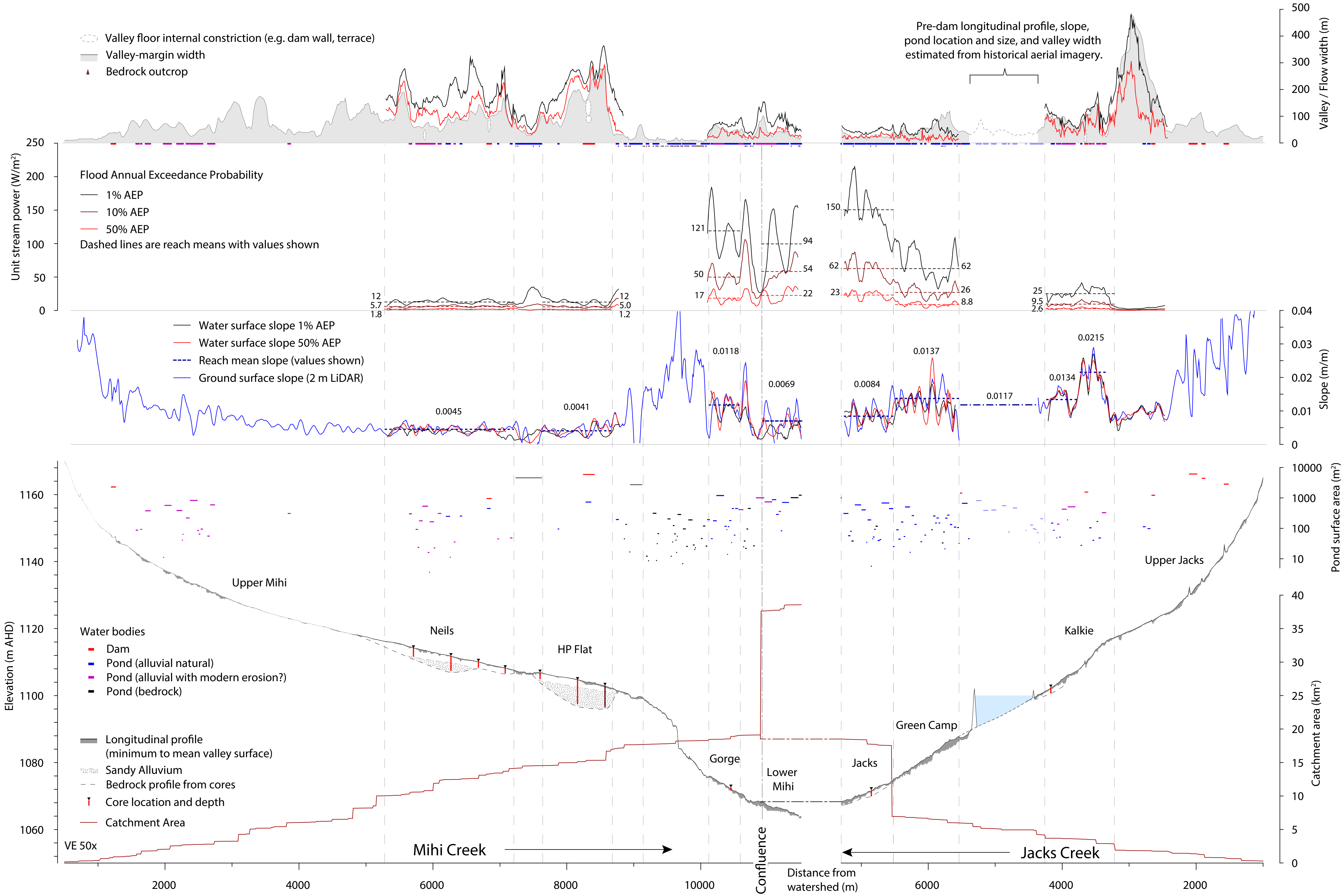

Figure 3. Longitudinal variability on the adjacent Mihi Creek (downstream from left to centre) and Jacks Creek (downstream from right to centre). The plots associated to the y-axes, starting from the top, are detailed opposite.

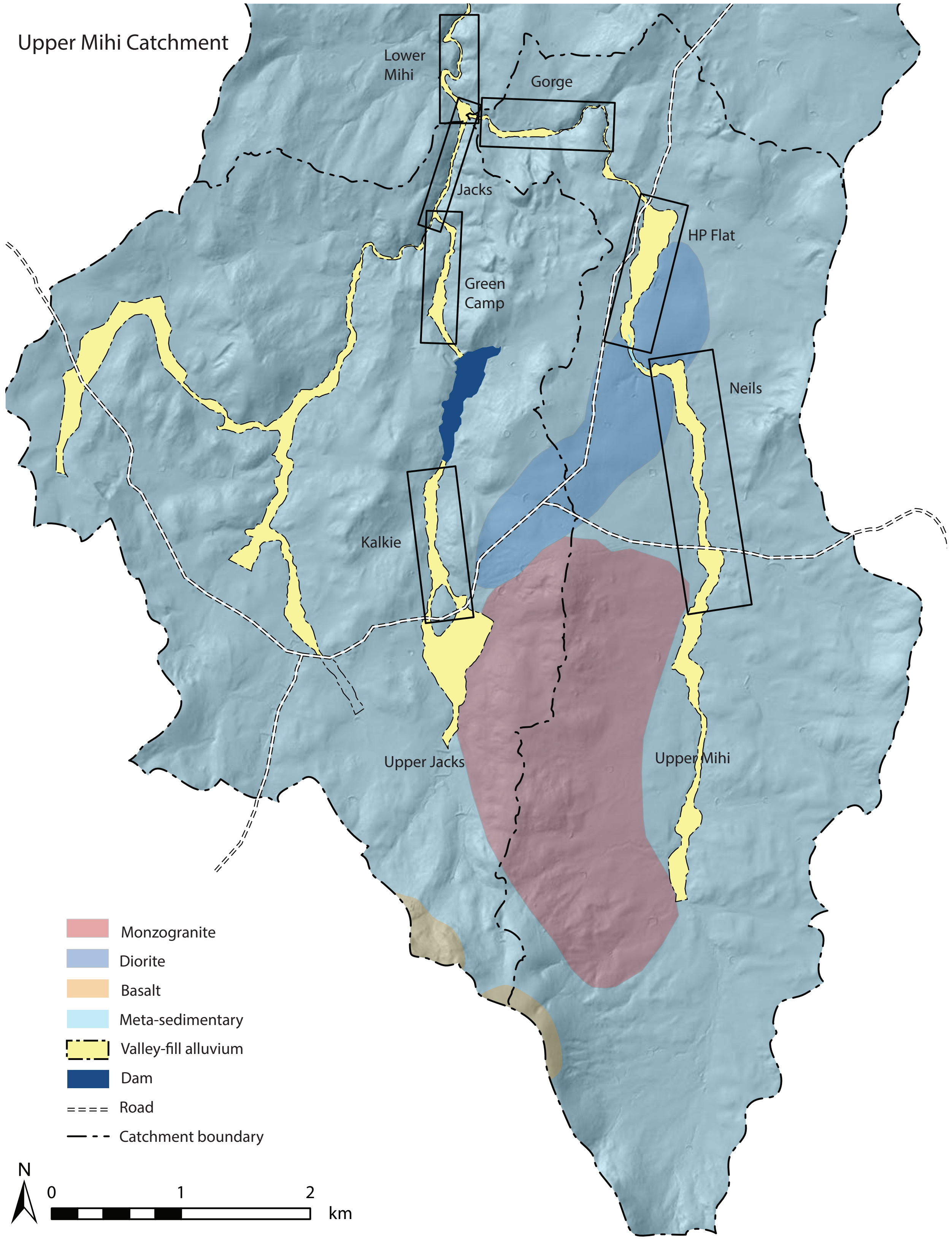

Figure 4. Surface geology modified after Geoscience Australia (2012). Black rectangles show the location of the seven planform reaches. See Figures 3, 5 and 7–9 for detail.

Upper Mihi Creek

The long profile of the upper most reach of Mihi Creek is concave, reducing from a slope of 0.075 m/m to 0.01 m/m through the first 2 km, then continues to reduce to 0.005 m/m until 5.5 km (Figure 3). The steep upper section runs off the basalt capped watershed divide in narrow concave valleys (Figure 4). This gives way to a reach that has valley margins 25–140 m wide, with a mean slope generally less than 0.015 m/m (Figure 3). Along this reach at a catchment area from 1.8 km^2 to 4 km^2, there are 16 incised gullies or ponds, with surface areas of 40–800 m^2 and lengths of 11–110 m. The longer of the incised features have head cuts that occur when the valley margin narrows, ending mostly by being dammed with small splay deposits as the valley widens. These gullies are visible in aerial photographs from 1956 and are noted on the 1936 parish map, but are not shown on the 1906 or 1887 maps, both of which show drainage lines both upstream and downstream. This may indicate that the gullying on this alluvial section occurred in the early 20th century. The small oval ponds are in the broader valley margins and have no head-cuts. Once the slope is consistently below 0.008 m/m, there is only one pond at a constriction point where the valley margin is 35 m wide and a catchment area of 6 km^2.

Neils

Neils reach begins approximately 5.5 km downstream from the watershed on Mihi Creek, with a catchment area of 10 km^2, and is the first unconfined reach to contain ponds (Figures 3, 4, and 5A). The upper two thirds of the reach has a small concave artificial channel connecting most of the ponds. It is 1 m wide at the top and 0.3 m deep, and generally aligned with the natural flow paths. There are no natural channels and during flow events the water is distributed over the 45–150 m wide floodplain, across which the cross-sectional elevation changes by less than 0.1 m. The floodplains are covered by tussocks and dense pasture grasses, with a distinct change in vegetation at the hillslope–floodplain margins. The ponds are shallow with gently sloped sides and fill only during flow events, but are dry the majority of the time. The creek flows northward along the fold-axis of the underlying low-grade metasedimentary bedrock. Slope is a near constant 0.0045 m/m, with a bedrock control point at the lower end of the reach where Mihi Creek cuts westward through an elongate diorite intrusion (Figure 4).

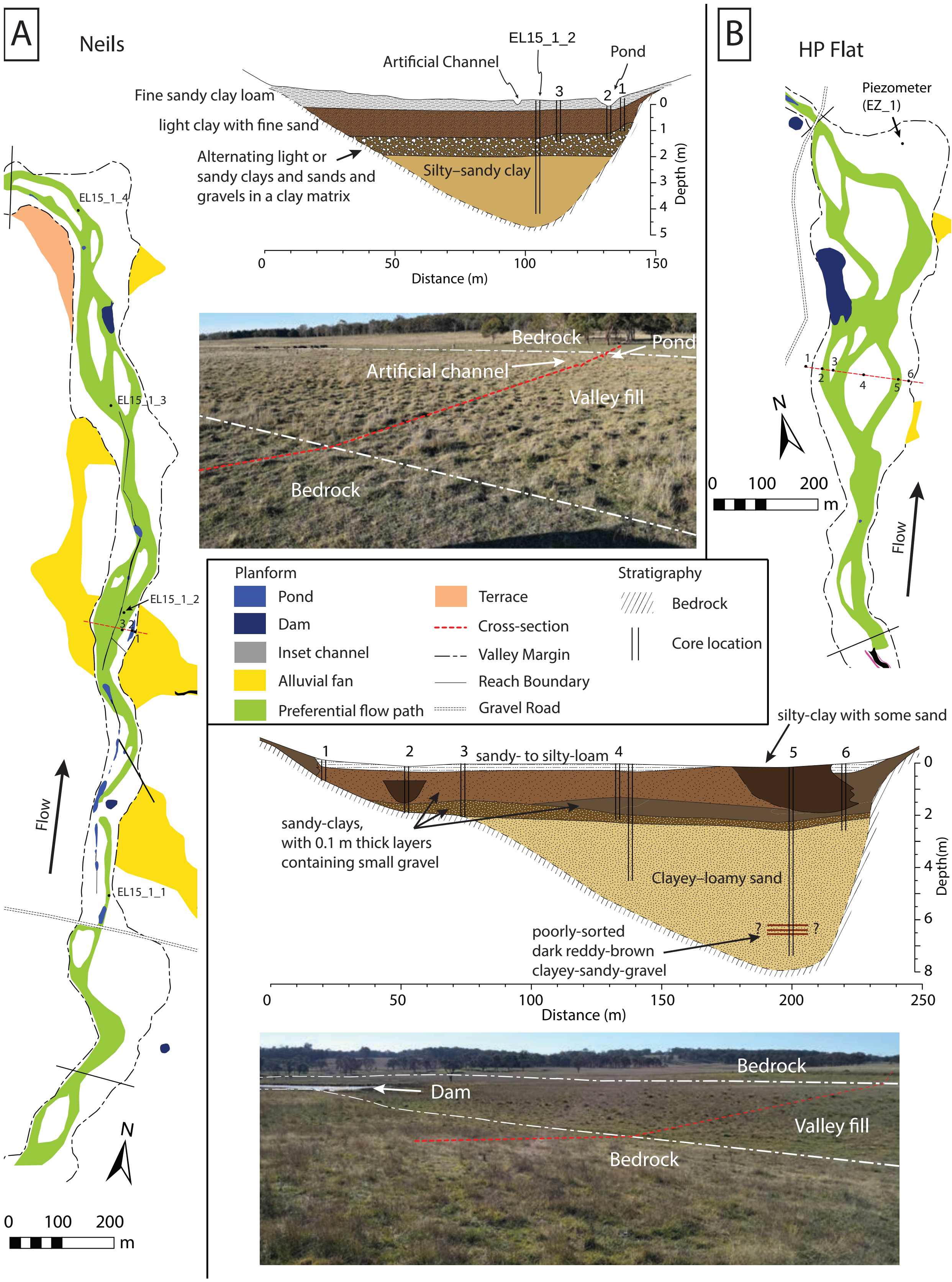

Figure 5. Planform and stratigraphy of **A)** Neils and **B)** HP Flat on Mihi Creek. Photos R. Williams. Detailed stratigraphic columns and images of sediment cores in Appendix 3

The deepest core on the cross-section, EL15_1_2, has over 4 m of fill above bedrock, with the lower 2 m being silty sandy clay (Figure 5A). Overlying this to a depth of 1.4 m, are light or sandy clays alternating with sands and gravels in a clay matrix. The clay layers are thinner than 0.05 m, while the coarser layers are 0.1–0.25 m thick. Above this is a 1 m layer of light clay containing fine sand, topped with 0.3–0.6 m of fine sandy clay loam. An OSL sample (EM15_1_2_100) taken on the same transect as core EL15_1_2 at a depth of 1 m has an age of 18.3 ± 1.4 ka (Table 1, Figure 6). A second OSL sample was taken from core EL15_1_2 at a depth of 4.2 m but failed to provide a reliable natural luminescence signal in all but one quartz grain and therefore an age could not be calculated.

Table 1. Depth, water content, Dose rate (D_R), over dispersion (σD), burial (equivalent) dose (D_E) and calculated burial ages. Radial plots in Figure 6

Sample	Reach	Depth (m)	Water content (wt. %)	Dose Rate (Gy/ka)					Burial Dose		Age (ka)
				Gamma	Beta	Cosmic	Internal	Total D_R	σD	D_E (Gy)	
EG15_1_NB_80	Gorge	0.8	18 ± 5	0.66 ± 0.04	1.01 ± 0.08	0.20 ± 0.02	0.03 ± 0.01	1.90 ± 0.12	15%	1.82 ± 0.08	0.96 ± 0.08
EM15_1_2_100	Neils	1.0	17 ± 5	0.95 ± 0.07	1.1 ± 0.1	0.19 ± 0.02	0.03 ± 0.01	2.30 ± 0.16	58%	42.1 ± 1.1	18.3 ± 1.4

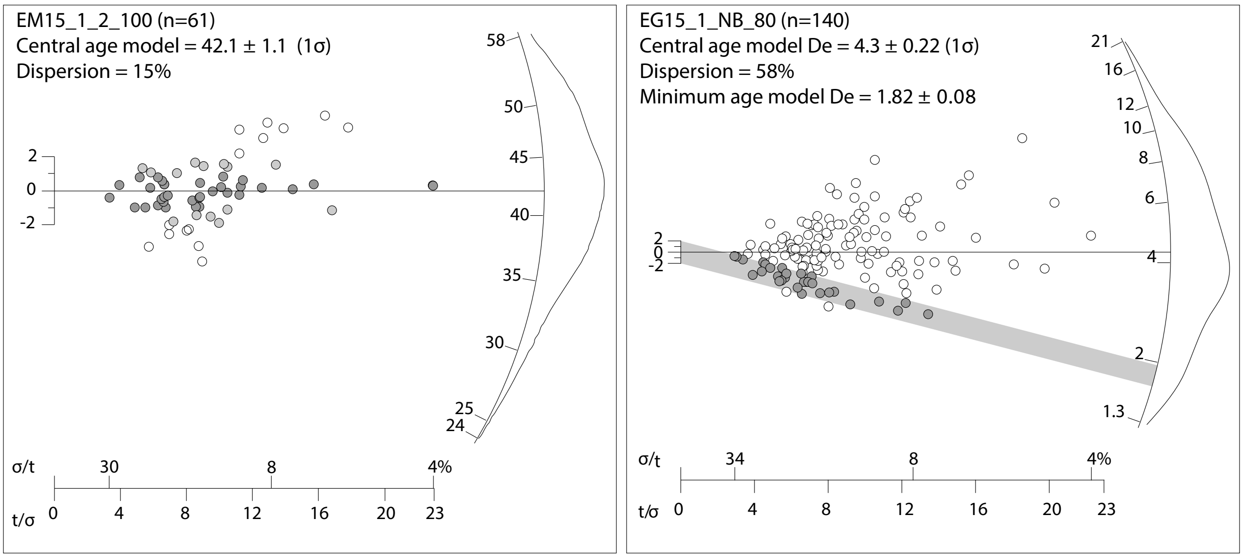

Figure 6. Radial plot (x-axis error, radial (y) axis equivalent dose) of single-grain OSL results, showing the central age model equivalent dose (horizontal line) for sample EM15_1_2_100 (Neils) with dark grey dots within 1σ and light grey dots within 2σ. Central age model equivalent dose (horizontal line) and minimum age model equivalent dose (shaded bar at 2σ) for sample EG15_1_NB_80 (Gorge).

The majority of the ponds (15 of 18) are in the upper half of the reach, where the valley margins are narrower (mean ~60 m) than the downstream portion (mean ~90 m). An 1887 parish map of the area shows the upper part of the reach as swampy with no channel line. In both 1956 and 1965 aerial imagery, the pond features are not visible, with only the artificial channel showing. By 1979 there are some scour features beginning to expand along the artificial channel, and by 2008 they have increased in size, along with the formation of new scour ponds. In the lower half of the reach, one of the older ponds that has since been enlarged to increase water storage for stock, is located immediately downstream of a protruding bedrock hill that constricts the floodplain, forcing two shallow flow paths to merge. The other smaller scours are located in the shallow flow path depressions that remain saturated for longer after flows and where smaller discharges are concentrated.

Between Neils and following reach, HP Flat, a long pond that runs through the diorite bedrock behaves like a confined channel when the creek flows (Figure 4). As the floodplain width increases after the bedrock constriction, it remains channelised with low levees on both sides, before the coarse sand and small gravel is deposited in a splay that dams the elongated bedrock-base pond.

HP Flat

HP Flat is a broad alluvial valley-fill that begins immediately after the bedrock constriction with a catchment area of 14.5–17 km^2. The mean floodplain slope of the reach is 0.0041 m/m, with upper two thirds and lower third ~0.003 m/m and ~0.006 m/m, respectively (Figure 3). The flow tends northward along preferential drainage lines atop the valley-fills that overly the boundary between the diorite intrusion to the east and low-grade metasedimentary units to the west (Figures 4 and 5B). The surface is covered with large (up to 30 cm) tussocks and dense pasture grasses (Figure 5B).

There are only two ponds along the reach. The first, with a surface area of 50 m^2, is a small shallow, rounded scour feature on the main flow path. The second, set in the wider part of the valley-fill, was an elongate scour pond that was originally ~600 m^2, but has since been dammed and excavated to a surface area of 2750 m^2 for livestock water supply. While the floodplain at this point is 180 m wide, the flow was confined to 27 m between the left-hand valley margin and a floodplain/terrace mound that is elevated 0.8 m above the low-flow path and 0.4 m above the adjacent floodplain. The slope of the channel increases to 0.006 m/m at this point and continues to a bedrock control point 300 m downstream. The 1887 parish map shows a drainage line that extend through the lower three-quarters of reach, loosely connecting some of the preferential drainage lines, but also crossing an elevated part of the floodplain. There is no evidence of this feature from field investigations or visible in aerial imagery from 1956, 1965 and 1979.

Cores through a cross-section at one of the broadest parts of the floodplain reveals valley-fills greater than 7.2 m in depth (Figure 5B). From the base of the core to a depth 2.4 m below the surface was dominantly yellow-grey clayey- to loamy-sand, with most of the sand being coarse to very coarse. At depths from 6.6 m up to 5.2 m there were alternating sequences of this sediment and poorly sorted dark-red–brown clayey sandy gravel (up to 20 mm b-axis). The upper 2.4 m of sediment varies across the valley, being a mix of red-brown to grey-brown sandy clays, with 0.1 m thick layers containing small gravel and occasional pieces up to 10 mm. The top 0.3–0.4 m is sandy–silty loam except for the main flow path (EHP15_1_5 – Core 5, Figure 5B) where it is a finer silty clay with some sand. The unconsolidated alluvial sediments are at an elevation that is over 4.5 m lower than the downstream bedrock control point. The downstream bedrock elevation is similar to the top of the deep yellow-grey clayey sand unit (Figure 3).

Two OSL samples were taken at depths of 3.8 m and 2.15 m below the surface. However, a reliable luminescence signal was only given in nine grains (with extremely high over-dispersion) in one sample, and one grain in the other; consequently, providing no reliable age estimates for the deeper valley-fill.

Gorge

This relatively short (350 m) reach of Mihi Creek, 1.5 km downstream from HP Flat with a catchment area of 18.4–19 km^2 and near the confluence of Jacks Creek, is constrained upstream and downstream by confined bedrock gorges (Figures 3, 4, and 7A). The upstream gorge between the two sites cuts across north–south trending low-grade metasedimentary bedrock, forming a series of step pools, with an average slope of ~0.02 m/m. The bedrock margin then widens to 30–60 m at the site, and the slope reduces to 0.008 m/m and 0.011 m/m for the floodplain and channel, respectively.

The floodplain has large plate-like cobbles that are up to 300 mm distributed through the profile and can be seen in the bank exposures and scattered on the surface (Figure 7A). The cobbles also line the bed of the ponds at the upstream end and are scattered over the bed of the downstream ponds. Separating two flow paths is a cobble bar, differentiated from the rest of the floodplain by its elevated position and cobbles exposed on the surface.

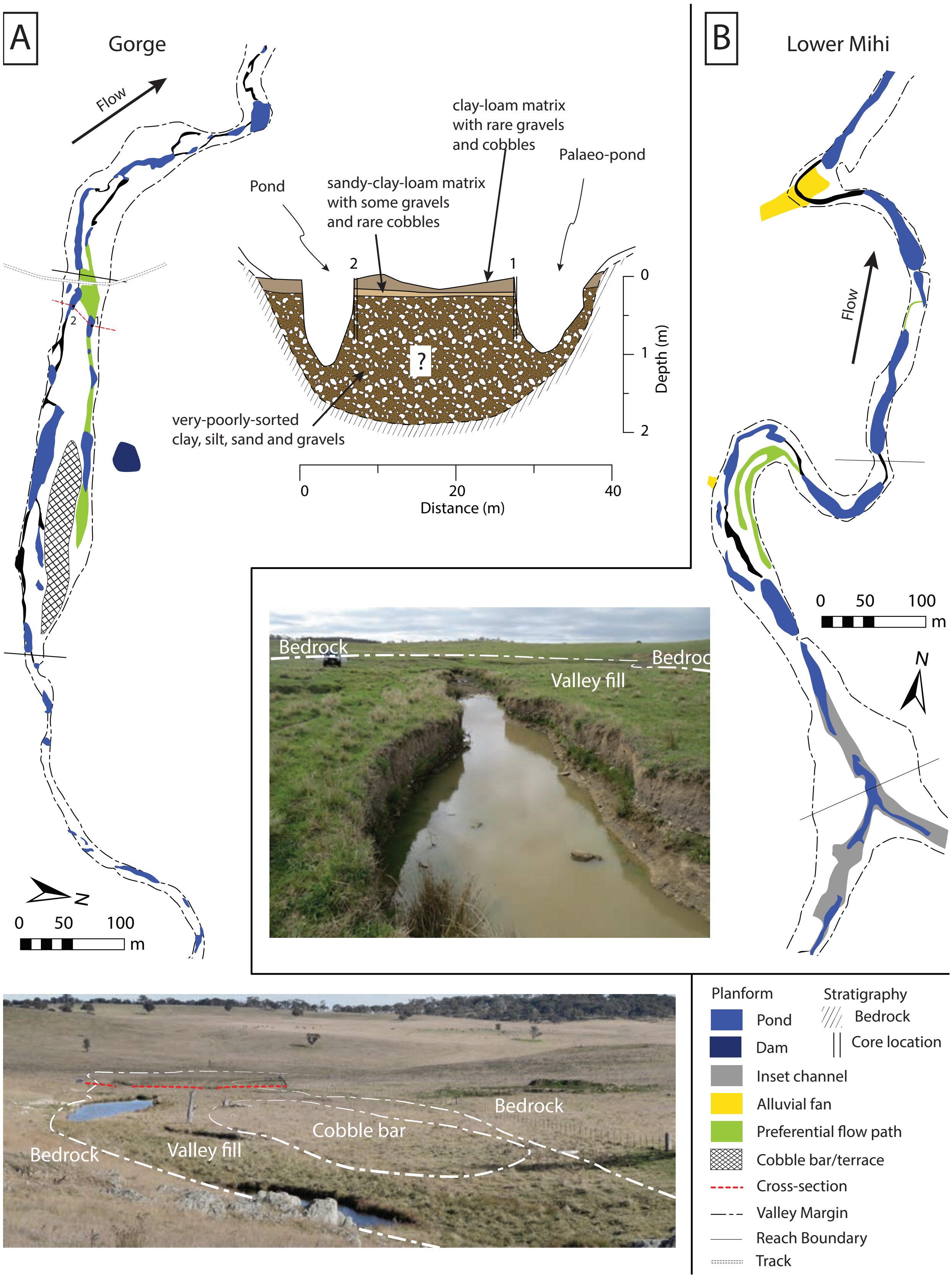

Figure 7. A) Planform and stratigraphy of Gorge on Mihi Creek and **B)** Planform of Lower Mihi below the confluence of Jacks Creek on Mihi Creek. Photos R. Williams. Detailed stratigraphic columns and images of sediment cores in Appendix 3.

The lower flow path contains six ponds between 11 m and 105 m in length, with surface areas of 46–1200 m^2 and contain water except during extended dry periods. All are steep sided and 0.4–1.2 m deep with the lower three having narrow (<0.5 m) incised (~0.4 m deep) channels connecting the ponds. These channels are not linear and wind around the dense tussocks. In areas where erosion is more recent, for example the head cuts on the ponds, there are larger amounts of cobbles on the channel or pond beds with the fine-grained material moved further downstream. These cobbles that are distributed through the profile do not appear to limit bank erosion as they are in a finer-grained matrix that is more easily eroded. However, after they fall from the eroding banks and line the ponds bed, they armour the bed and may limit further incision.

Along the upper (northern) flow path, there are four ponds 6–60 m in length, with surface areas of 15–415 m^2. They are also steep sided, but only 0.4–0.8 m deep and contain water after heavy rainfall or high flow events, but are dry for the majority of the time. Unlike the ponds on the lower flow path, the banks and beds of the ponds have vegetation, which establishes during the longer non-inundated periods. There have no clearly identifiable changes to the planform of the reach since the earliest aerial imagery in 1956.

The stratigraphy of the lower part of the reach is limited to the upper metre from banks exposures (Figure 7A). The lower 0.3 m consists of very poorly sorted clay, silt, sand and gravels, with occasional cobbles. Above this is a dark grey-brown sandy clay loam matrix with some gravels and rare cobbles. In some bank exposures there is a distinct layer from ~0.4 m to ~0.2 m where it is dominated by gravels and cobbles (20–100 mm b-axis). The upper 0.2 m is typically a loam matrix across most of the floodplain, but again contains gravels and occasional cobbles. Sediment from the poorly sorted lower unit, at a depth of 0.8 m, has an OSL age of 0.96 ± 0.08 ka (sample EG15_1_NB_80 – Table 1, Figure 6).

Lower Mihi

Below the confluence of Jacks Creek with a catchment area of 37.6–38.6 km^2, Mihi Creek has floodplains that are typically 20–50 m wide but up to 100 m wide at a tributary junction (Figures 3, 4 and 7B). It contains ponds that are set into valley-fill and connected by narrow channels, or sit behind bedrock outcrops or bars of sediment in the channel, similar to Eyles (1977a) fixed bar ponds. The floodplain slope over the 0.9 km reach is 0.0069 m/m. There are no clear planform changes from 1956 to 1979. Between 1979 and 2008, a 70 m a head cut extension has occurred, consuming two additional ponds. Downstream from this reach the river becomes a partly confined valley with bedrock-controlled discontinuous floodplains and a low sinuosity channel. The slope oscillates between 0.007 m/m and 0.004 m/m over at least the next 6 km.

Upper Jacks Creek

Upstream of the field site, Kalkie, Jacks Creek has three sections with distinct long profile and valley characteristics (Figures 3 and 4). The first section runs off the basalt capped watershed divide in a narrow concave valley that has a slope of ~0.09 m/m. Below this is a section that has a mean slope of ~0.024 m/m and sits between valley margins that are 10–50 m apart. There are five dams along this 1 km reach, often with gullies upstream and downstream, incising into the shallow alluvium, the majority of which are visible in the 1956 aerial photographs and also drawn on the earlier parish maps. The third section is after the creek exits the valley confinement and forms a broad alluvial fan up to 500 m wide. The elevation across this fan varies by less than 0.5 m and has a slope of ~0.008 m/m.

Kalkie

Kalkie is a reach on Jacks Creek at a channel distance of 3.2–4.2 km from the watershed divide, with a catchment area from 2.7 km^2 to 4.2 km^2 (Figures 3, 4, and 8). The slope increases to 0.0215 m/m at the toe of the upstream alluvial fan before declining to 0.0134 m/m and continues to a bedrock outcrop at the head of the 500 Ml dam that was built in 1969. At the start of the reach, the alluvial valley floor bifurcates a small bedrock hill, narrowing the valley width to 25 m either side (Figure 8). The valley margin widens again to 100 m as the valleys converge before narrowing to ~40 m approximately half way down the reach. There are numerous ponds and isolated or connecting channel features through the narrow sections, but become less frequent where the valley widens. Similarly, the scoured ponds and natural channels are less frequent as the margin again expands to 100 m for the lower third of the reach.

A spring, located two-thirds down the reach, provides a near permanent water source. Prior to the installation of low embankments and an artificial channel, the spring maintained high water tables that resulted in boggy ground over the alluvial valley floor. The artificial channel was then extended downstream to the end of the reach to lower the water table. The ponds in the narrow-valley section mid-way through the reach are up to 1.5 m deep, relatively narrow, with head cuts, connecting channels and bank slumping. They are 15–105 m in length, with surface areas of 50–500 m^2. The two scour ponds in the lower, broad-valley part of the reach are <0.6 m in depth, have no head cuts or channels and are 20 m and 25 m in length, with areas of 85 m^2 and 150 m^2. In areas where it currently has no channels or elongate ponds the 1906 parish map shows it as unchannelised with broad valley margins. There are no marks on the parish maps for the areas that currently have ponds and historical aerial imagery shows no identifiable changes to the planform since 1956.

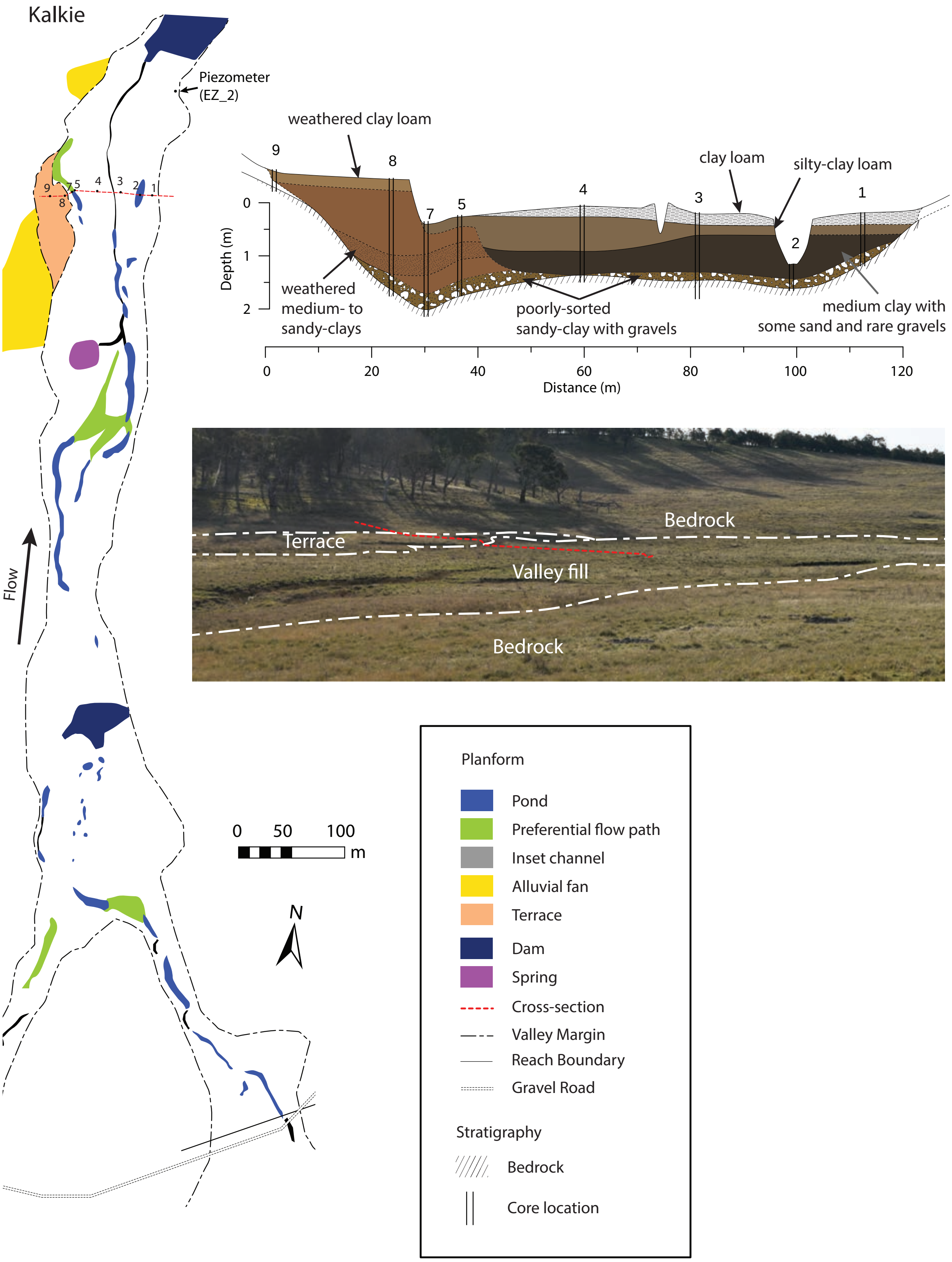

Figure 8. Planform and stratigraphy of Kalkie on Jacks Creek. Photos R. Williams. Detailed stratigraphic columns and images of sediment cores in Appendix 3

Across the broadest cross-section on the lower third of the reach, the metasedimentary bedrock is 1–2 m below the surface (Figure 8). Cores 8 and 9 are elevated above the rest of the floodplain on a terrace. Core 9 is on the margin of the valley with bedrock 0.35 m below the surface, but core 8 reveals heavily weathered alluvium that has bedrock at a similar depth to the remainder of the floodplain cores. On the western side (sites 5–8), the sediment above bedrock is ~0.3 m of poorly sorted sandy clay with gravels followed by medium–sandy clays to within 0.2 m of the surface. These clay units have a much paler orangey grey colour and are weather compared to sediment in the eastern cores (1–4), which are darker greys and browns (see Appendix 3 for images of the cores). Above bedrock, cores 1 and 3 have a layer (~0.4 m thick) of poorly sorted sandy clay with gravels, similar to the western terrace. This is overlain by a medium-clay unit that contains some sand and rare gravels to a depth of 0.4 m, followed by 0.2 m of silty clay-loam and 0.2 m of clay loam. Core 2 is the same except the surface has been scoured to a depth of 1 m. Core 4, near the middle of the cross-section, has a similar bedrock elevation, but does not have the lower sandy clay with gravel unit. Instead bedrock is overlain with medium-clay with some sand and gravel, to a similar thickness as the other cores, and a deeper (0.6 m) silty clay-loam layer that is topped with 0.2 m of clay-loam. This separates the stratigraphy in to four main units; the lower sandy gravelly clay across the valley (except in core 4), a finer-grained terrace on the west, the middle medium-clay unit on the east, and a (silty) clay-loam covering the floodplain.

Green Camp

Green Camp begins below the large dam on Jacks Creek at a channel distance of 5.4 km and catchment area of 6 km^2 (Figures 3, 4, and 9A). The reach ends 1.1 km further downstream where the catchment area is 6.9 km^2. The reach trends northward along the fold axis of the metasedimentary bedrock and consists of a series of floodplain pockets as the channel generally abuts one of the valley margins. The channel is highly varied in its width and depth, with a reach-average slope of 0.0137 m/m. At some locations, the channel is 10 m wide and 1.5 m deep, continuously for 300 m; in other sections the channel is 1–5 m wide and ~0.5 m deep connecting 1.5 m deep ponds. The ponds have surface areas of 20–250 m^2 and lengths of 7.5–30 m. There are numerous bedrock outcrops exposed in the base of the ponds and where the channel has incised. The valley margin is typically ~30 m wide, but in a 200 m length, midway down the reach, it is up to 80 m wide. There are also two alluvial fans encroaching past the bedrock margin from unchannelised tributaries. In both cases the outside of the bend of the channel has eroded the fan, creating a sharply defined floodplain boundary. Similar pond and meandering channel features in 2008 aerial imagery appear in the 1887 parish map and later historical aerial imagery from the 1950s to 1970, suggesting only possible minor changes. There were no cores taken from Green Camp to characterise the stratigraphy.

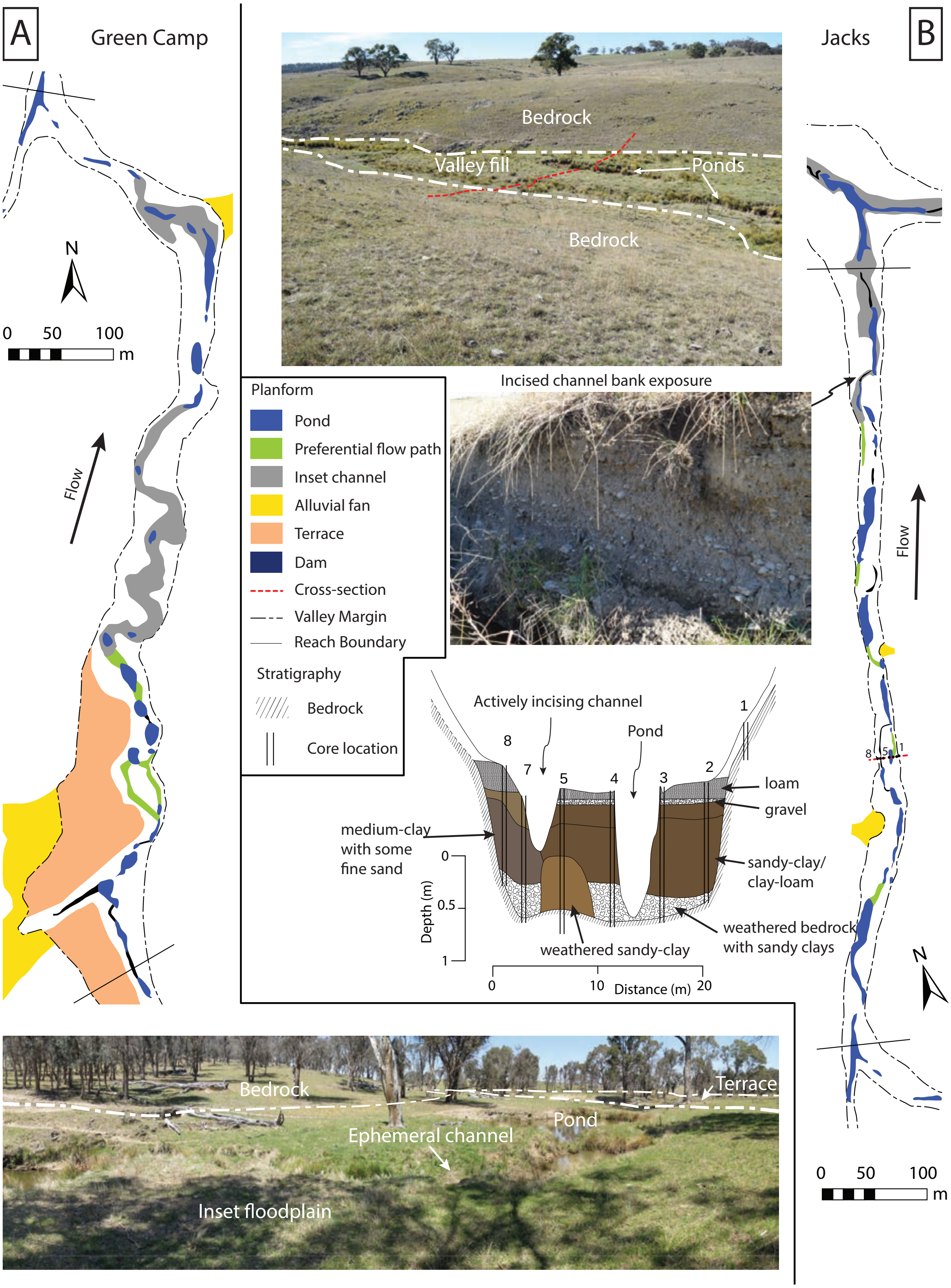

Figure 9. Planform and stratigraphy of **A**) Green Camp and **B**) Jacks on Jacks Creek. Bank exposure showing gravel layers from a location downstream of cross-section. Photos R. Williams. Detailed stratigraphic columns and images of sediment cores in Appendix 3.

Jacks

Jacks continues on from the end of Green Camp where the western arm of Jacks Creek joins and trends NNE along the metasedimentary bedrock fold axis. It is at a channel distance of 6.6–7.2 km from the watershed divide, with a catchment area from 17.5–18.5 km^2 (Figures 3, 4, and 9B). The slope of the channel and floodplain lowers to 0.0084 m/m. It is the narrowest and most uniform valley width ranging from 12 m to 30 m. There are bedrock outcrops visible in the incised channel and some of the downstream ponds beds and banks, but the majority of the reach's surface is alluvium. Jacks has several bedrock controls through the reach but not at the downstream end where is meets Mihi Creek. This alluvial section at the confluence is, however, controlled by bedrock on Mihi Creek ~400 m downstream. Additional valley margin controls are from two very poorly sorted (clay–gravel) alluvial fans that debouche on to the narrow floodplain. Pond size varies, ranging in surface areas from 5 m^2 to 590 m^2 and lengths of 5–75 m, with most ponds having shallow connecting channels that wind through the resistant tussocks. The topography in the upper third of the reach consists of a more uniform floodplain elevation with shallow incised ponds and narrow channels, whereas the lower sections are more complex, with deeper and wider channels cut into terraces, inset floodplains and fixed-bar ponds (from deposition at the downstream end) that have armoured cobble or bedrock beds. Historical aerial imagery and parish maps show very little identifiable change over the past 130 years.

The bedrock under the floodplain is at a similar elevation through the cross-section, creating a flat-bottomed, steep-sided valley that has been overlain with alluvium (Figure 9B). On the left side of the floodplain (cores 7 and 8), the lower 0.8 m is a brown-grey, medium-clay with some fine sand. On the right (cores 2–4), the lower 0.8 m is a dark-brown sandy clay to clay loam. Dividing these is core 5, which has a weathered, orangey brown sandy clay for 0.5 m above bedrock, overlain by the same dark-brown sandy clay to clay-loam in cores 2–4 to a depth of 0.2 m. The top 0.2 m across the floodplain is loam, with two cores having isolated 0.05 m thick gravelly deposits. These deposits appear isolated in the cores, but in bank exposures of many on the ponds there are multiple gravel layers through the profile. An example is shown in the bank exposure image in Figure 9B.

4.4.2. Stable Isotopes and groundwater levels

The local meteoric water line (LMWL), calculated from rainfall samples collected between October 2015 and January 2016 during a range of rainfall intensity events of 0.02–6 mm/hr, aligns closely with the LMWL derived from mean monthly and annual estimates for the site using the Online Isotopes in Precipitation Calculator (Bowen, 2017; after Bowen and Revenaugh, 2003; and Bowen et al., 2005) (Table 2 and Figure 10).

Table 2. Stable isotope (δ^2H and $\delta^{18}O$) values relative to VSMOW (‰) for rainfall, surface water (ponds) and shallow groundwater (piezometers). Sample locations shown on Figure 1.

Sample name	Location	Reach	δ^2H VSMOW (‰)	$\delta^{18}O$ VSMOW (‰)	D excess	Depth below surface (m)
EP15_1_0	EP15_1 Pond	Neils/HP Flat	-13.5	-1.4	-2.4	0.0
EP15_1_50	EP15_1 Pond	Neils/HP Flat	-13.5	-1.4	-2.2	0.5
EP15_2_0	EP15_2 Pond	HP Flat	-11.3	-1.0	-3.4	0.0
EP15_2_30	EP15_2 Pond	HP Flat	-11.1	-1.0	-3.2	0.3
EP15_3_0	EP15_3 Pond	Below HP Flat	-11.8	-1.2	-2.6	0.0
EP15_3_0	EP15_3 Pond	Below HP Flat	-12.0	-1.2	-2.6	0.0
EP15_3_60	EP15_3 Pond	Below HP Flat	-11.8	-1.1	-2.7	0.6
EP15_4_0	EP15_4 Pond	Gorge	-5.0	0.2	-6.4	0.0
EP15_4_30	EP15_4 Pond	Gorge	-5.1	0.2	-6.9	0.3
EP15_5_0	EP15_5 Pond	Gorge	-7.0	-0.1	-6.4	0.0
EP15_6_0	EP15_6 Pond	Jacks	-0.6	1.4	-11.7	0.0
EP15_6_35	EP15_6 Pond	Jacks	-1.1	1.3	-11.8	0.35
EZ_1_270	Piezometer	HP Flat	-42.3	-7.0	13.3	2.7
EZ_1_440	Piezometer	HP Flat	-42.5	-7.0	13.7	4.4
EZ_2	Piezometer	Kalkie	-36.0	-6.1	13.1	2.0
E15_1	Rainfall	n/a	7.6	-1.2	17.2	n/a
E15_2	Rainfall	n/a	31.4	3.5	3.4	n/a
E15_3	Rainfall	n/a	18.0	0.1	17.2	n/a
E15_4	Rainfall	n/a	12.7	-0.2	14.3	n/a
E15_5	Rainfall	n/a	17.8	0.8	11.4	n/a
E15_6	Rainfall	n/a	-1.0	-1.7	12.6	n/a
E15_7	Rainfall	n/a	-10.1	-3.1	14.7	n/a
E15_8	Rainfall	n/a	-24.0	-5.0	16.0	n/a
E15_11	Rainfall	n/a	-34.7	-5.6	10.1	n/a
E15_12	Rainfall	n/a	-28.1	-3.9	3.1	n/a
E15_13	Rainfall	n/a	-40.2	-5.6	4.6	n/a
E15_14	Rainfall	n/a	-22.3	-5.0	17.7	n/a
E15_15	Rainfall	n/a	4.8	-1.7	18.4	n/a
E15_16	Rainfall	n/a	-5.8	-3.2	19.8	n/a
E15_17	Rainfall	n/a	-31.4	-6.3	19.0	n/a
E15_18	Rainfall	n/a	-6.0	-2.8	16.4	n/a
E15_19	Rainfall	n/a	-10.3	-3.8	20.1	n/a
E15_20	Rainfall	n/a	-21.2	-3.0	2.8	n/a

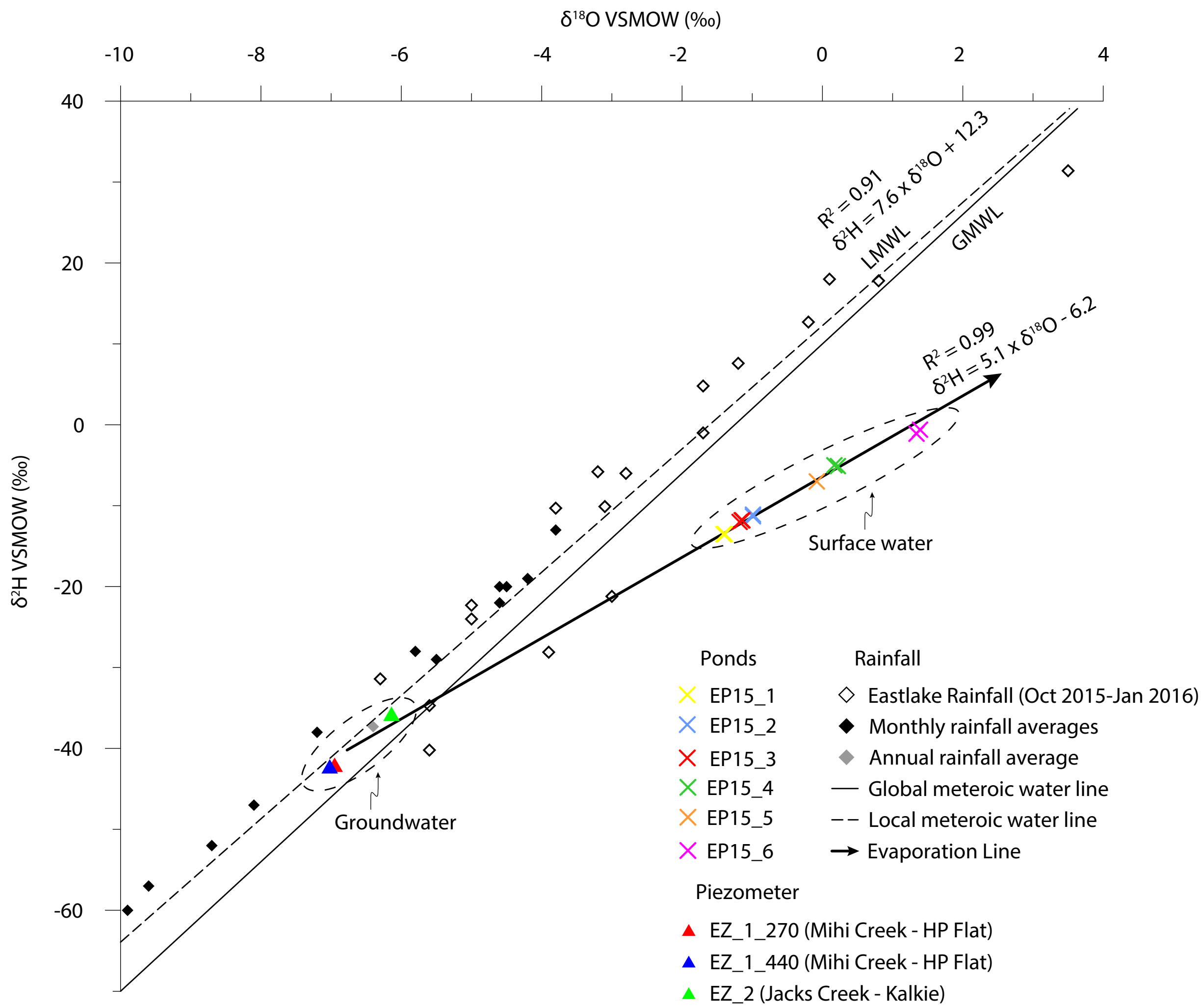

Figure 10. Stable isotope values for rainfall, surface water (ponds) and groundwater (piezometers). Ponds (×) create the evaporation line (thick line with arrow). Groundwater samples (Δ) are close to mean annual rainfall value (grey ◊) (Bowen and Revenaugh, 2003) and sit near the LMWL (dashed), which is fit through mean monthly rainfall estimates(black ◊) (Bowen et al., 2005) and the measured rainfall values (hollow ◊). See Figure 1 for locations.

The three shallow groundwater samples (EZ) have δ^2H and $\delta^{18}O$ values that cluster close to the estimated annual precipitation isotope average, showing that the shallow groundwater is derived from local precipitation (Gat and Gonfiantini, 1981) (Table 2, Figure 10, see Figure 1 for locations). Prior to sampling, the ponds had received no overland flow for at least two months with no measurable rainfall in the previous four weeks. Stable isotope values for the surface (pond) water define a clear evaporation line and were separate from the underlying shallow groundwater values (Figure 10). The smaller, shallower ponds (EP15_4–6), which are subject to proportionally greater water losses from evaporation, have a lower D excess (further from the LMWL) (Gat, 1996) and plot toward the right on the evaporation line (Figure 10), illustrating that fractionation during evaporation is the main reason for the stable isotope values in the ponds, indicating no ingress of shallow groundwater at this time. The level of the shallow groundwater, measured from the piezometer in HP Flat (EZ_1) that was installed to a depth of 6.54 m through alluvial sediments, remained below the elevation of the pond base, during the one year record (Figure 11). This confirms the isotope results showing that ponds are filled by surface flows, and during no-flow periods remain disconnected, with water levels declining due to evaporation.

Successive higher rainfall events that lead to stream flow at the downstream gauging station (Mihi at Abermala, station 206034) (Office of Water, 2017) coincided with an increase in shallow groundwater level at HP Flat (Figure 11). This shows that, at least during higher rainfall events, the meteoric waters are moving into the shallow groundwater through infiltration and throughflow. There were greater increases in shallow groundwater level, from similarly sized rainfall events, during the colder months (April to September), compared to events between October and March. This seasonal distinction is also seen during dry periods with the water level declining at a slower rate through the cold months compared to the summer months. This is likely due to the increased evaporation and evapotranspiration, reducing infiltration during hotter periods (Jasechko et al., 2014).

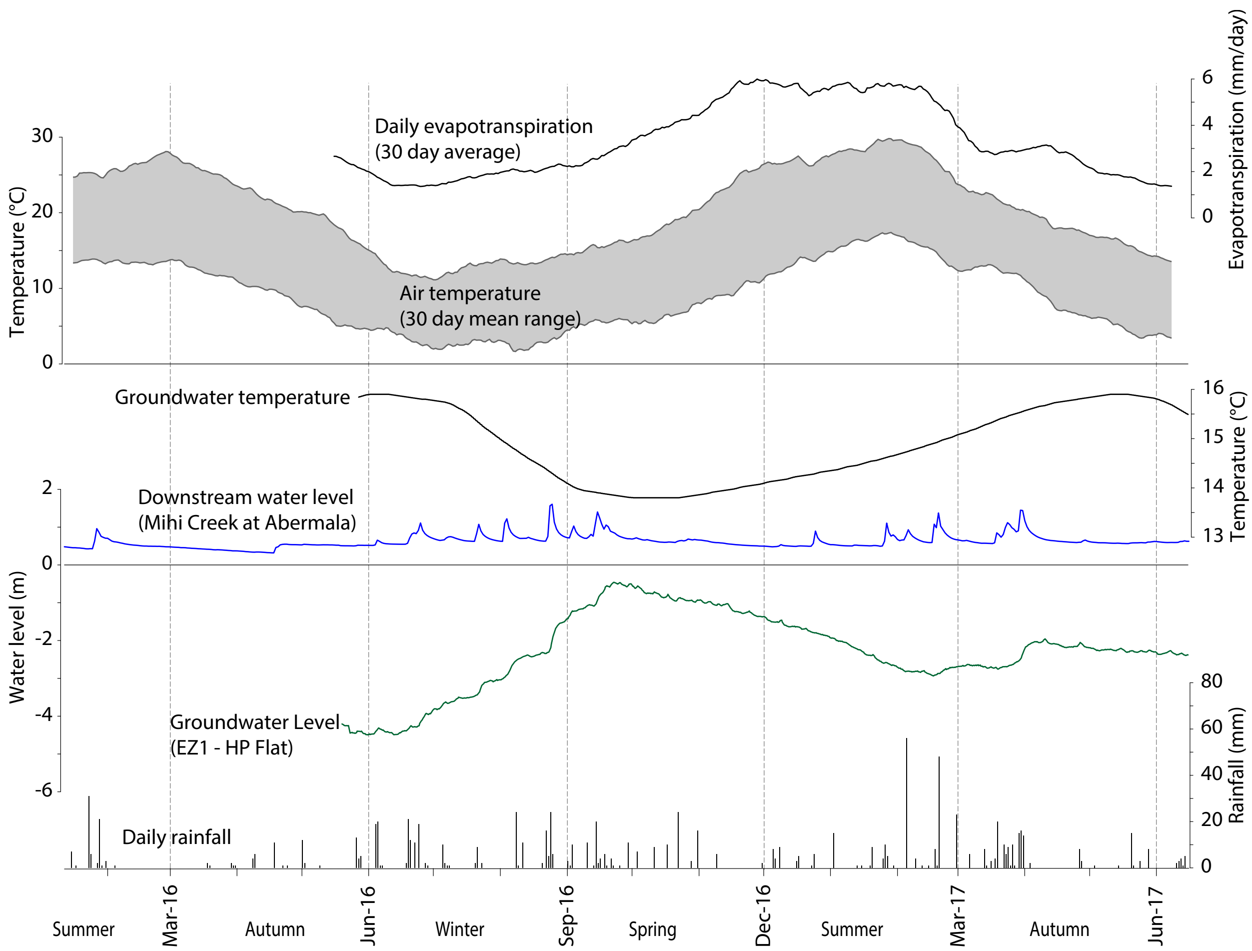

Figure 11. Groundwater levels and temperatures under the broad floodplain at HP Flat (EZ_1), see Figures1 and 3 for location. Rainfall from daily totals at 'Eastlake' and correspond closely to those at nearby Bureau of Meteorology weather station at Emu Creek (56010) 16 km SSE and Armidale Airport AWS (56238) 30 km N. Daily evaporation and air temperature from Armidale Airport AWS (Bureau of Meteorology, 2017). Water levels from downstream NSW Office of Water gauging station Mihi at Abermala (206034) (Office of Water, 2017).

4.4.3. Hydraulic modelling – unit stream power and shear stress

Unit stream power

The upper reaches on Mihi creek have mean unit stream power values that range from less than 2 Wm^{-2} up to 12 Wm^{-2} for the 50% and 1% AEP, respectively (Table 3 and Figure 3). The higher mean and peak values through Neils compared to HP Flat for lower flows are due to the concentration of flow through the small artificial channel (particularly in the 50% AEP flow) and constriction due to dam walls built on the floodplain. Another notable feature of these two reaches is the shallow slope of the valley margin that allows floodwater to dissipate energy over further over adjacent hillslopes (Figures 12–15 and Appendix 4).

Table 3. Summary of peak discharges used for the HEC-RAS 2D hydraulic modelling and the resultant mean and maximum unit stream power values for each reach.

							HEC-RAS 2D flow modelling											
	Peak discharge (m^3s^{-1})						Mean unit stream power (Wm^{-2})						Maximum unit stream power (Wm^{-2})					
AEP (%)	50	20	10	5	2	1	50	20	10	5	2	1	50	20	10	5	2	1
Kalkie	1.2	2.9	4.5	6.6	10	14	2.6	6.6	9.5	14	20	25	73	141	154	191	246	266
Green Camp	2.3	5.8	8.6	14	21	28	8.8	10	26	36	50	62	127	146	237	260	276	305
Jacks	8.0	17	25	37	61	80	23	37	62	83	120	150	147	221	306	367	500	608
Neils	5.2	12	19	28	42	51	1.8	3.9	5.7	7.7	11	12	16	28	37	58	85	96
HP Flat	5.0	12	18	26	41	54	1.2	3.2	5.0	6.8	9.9	12	12	22	36	48	79	97
Gorge	6.0	14	22	32	49	66	17	34	50	66	96	121	124	167	231	303	424	525
Lower Mihi	15	33	53	77	119	159	22	40	54	68	84	94	123	169	214	243	340	416

The small increase in discharge between HP Flat and Gorge is not reflected in the 10-fold increase in average unit stream power of 17 Wm^{-2} and 121 Wm^{-2} for the 50% and 1% AEP, with peaks exceeding 100 Wm^{-2} and 500 Wm^{-2}, respectively (Table 3, Figure 3). The valley margin is less than half that of both upstream reaches and the longitudinal slope increases from 0.0041 m/m to 0.0118 m/m (Figure 12) accounting for the some of the increases. There is also far greater variability over the length of the reach due to the more complex topography and geomorphic units that constrain flow (Figure 7).

The uppermost reach on Jacks Creek, Kalkie, has a catchment area of less than 4 km^2 but has mean unit stream power values double those of Neils and HP Flat that have catchments of 10–15 km^2 (Figure 3). Much like the shifts from HP Flat to Gorge, there are three reasons for this disparity; firstly, the slope is approximately four times greater (reach mean of 0.0167 m/m – Figure 12); secondly, the valley margin is narrower being generally less than 100 m, but as little as 30 m; and lastly, the valley sides are steeper and do not allow the larger flows to dissipate energy over a wider flow area (Figure 12). The peaks in unit stream power are also greater through Kalkie due to the deeper ponds and incised channels that concentrate flow (Figures 12–15 and Appendix 4).

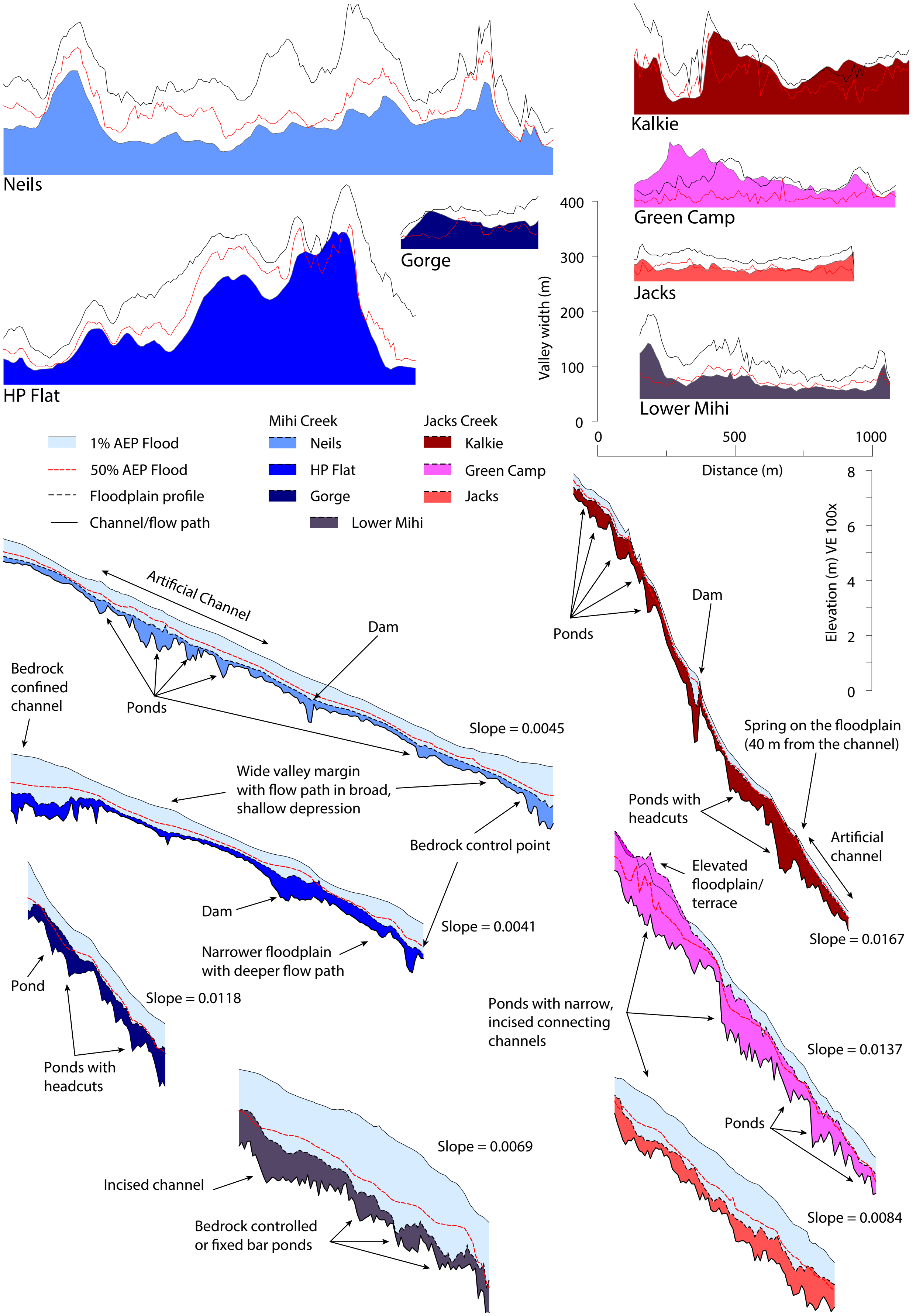

Figure 12. Comparison of channel, floodplain and water surface elevation long profiles, and valley and flow widths, on two adjacent headwater chain-of-ponds systems. Filled colour shows the depth of the channel below the floodplain. Floodplain and channel/pond elevations calculated from the mean valley wide and minimum elevations, respectively. Flow widths and water surface elevations (light blue shading) for 1% (black) and 50% (red) annual exceedance probability flows modelled in HEC-RAS 5.0.3.

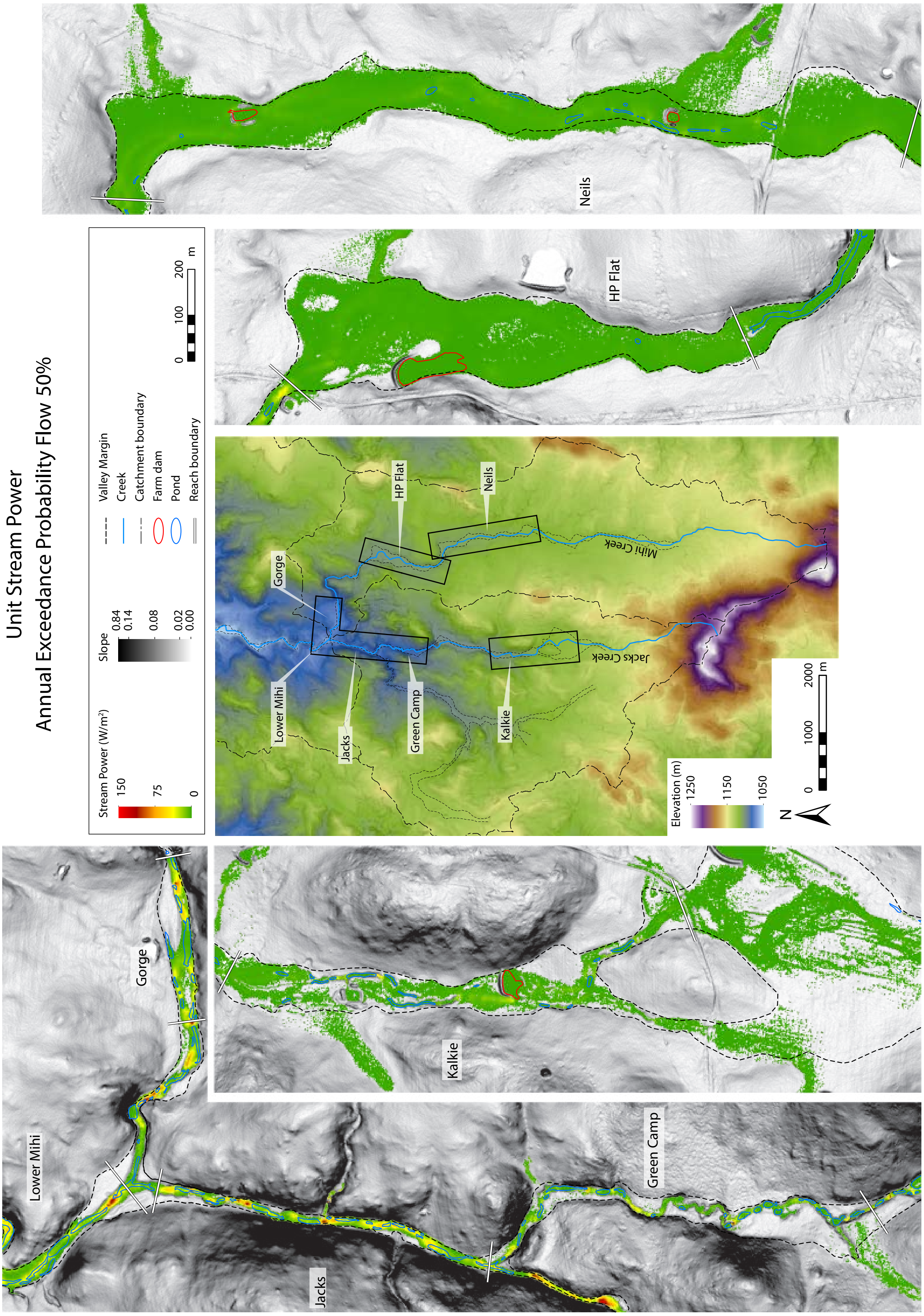

Figure 13. Unit stream power (Wm^{-2}) for 50% AEP flows. See methods for details

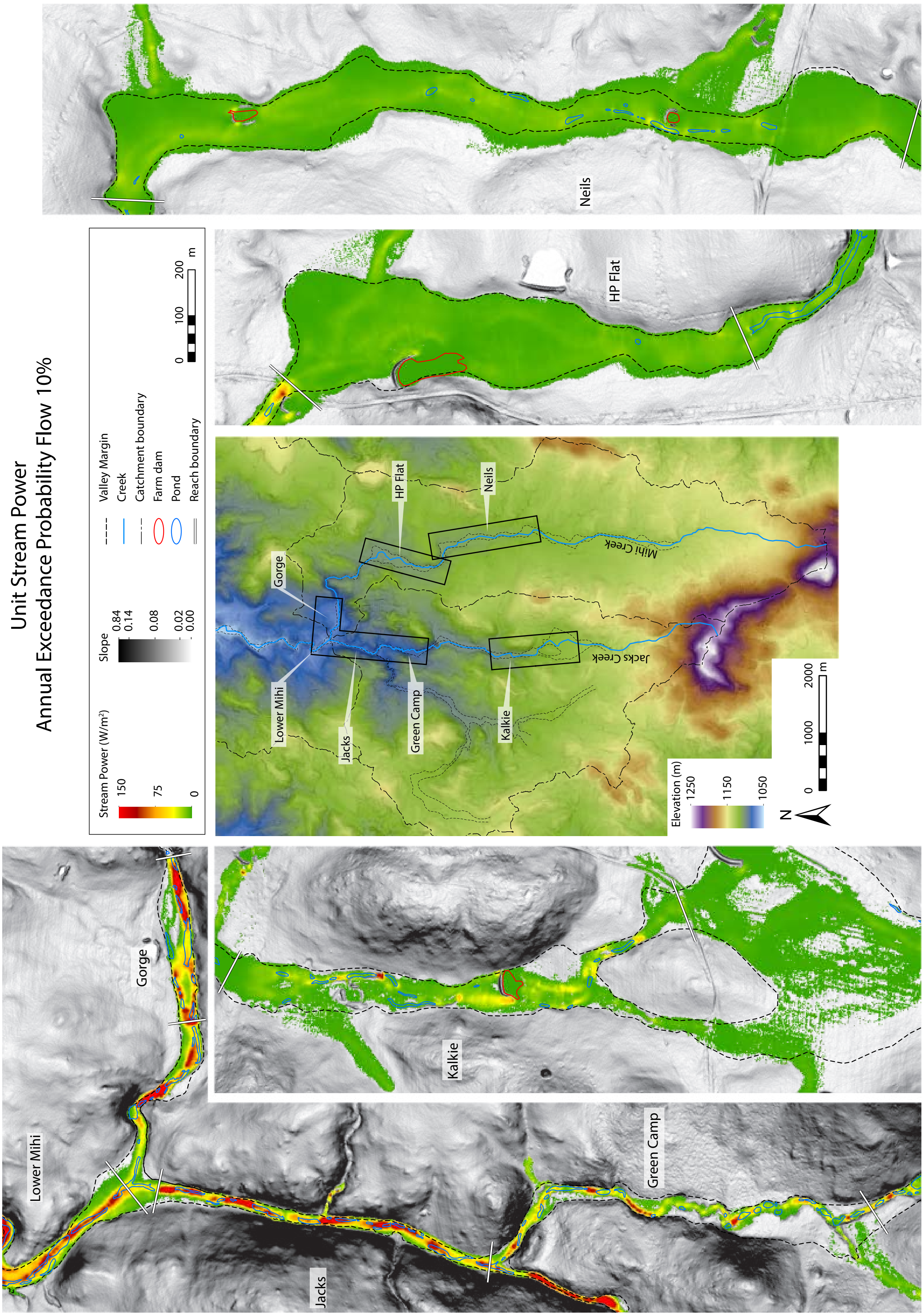

Figure 14. Unit stream power (Wm^{-2}) for 10% AEP flows. See methods for details.

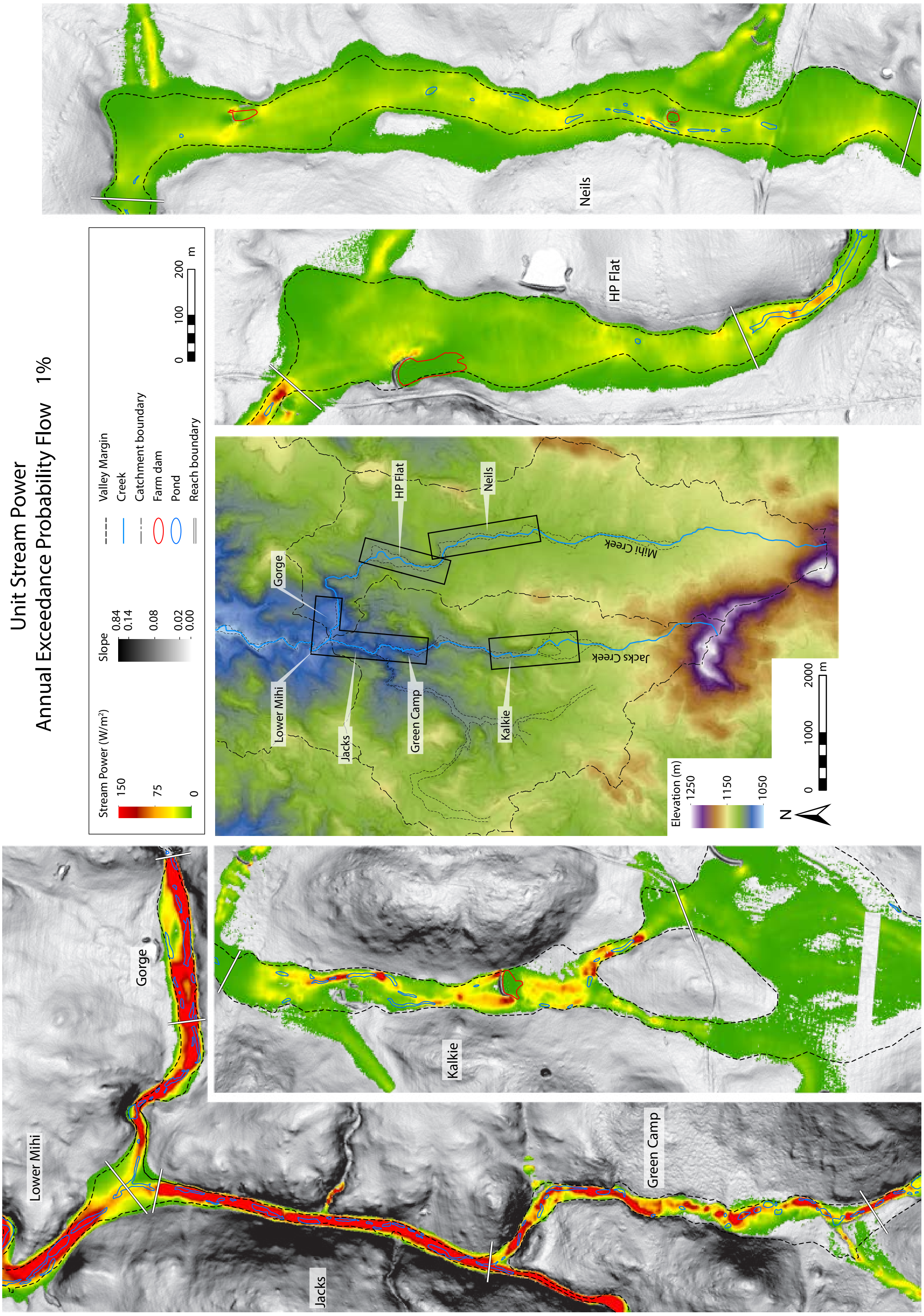

Figure 15. Unit stream power (Wm^{-2}) for 1% AEP flows. See methods for details.

Being immediately downstream from a 500 Ml dam (built in 1969), Green Camp only receives the flows expected of its catchment area (6–6.9 km^2) once the storage upstream is filled through sustained wet periods or successive floods. If the effects from the dam are discounted, unit stream power has a greater increase, relative to the discharge, compared to Kalkie (Table 3, Figure 3). This is due to the variability along the reach as the slope changes and flows are confined in a more planform-controlled setting (Figures 9 and 12). This is especially noticeable in the 10% AEP unit stream power values as the flows alternate from being confined to the channel or inset features, to overtopping the elevated floodplain/terrace (Figure 12). In contrast, the flows of a 50% AEP are similar in width along the reach as the flows are generally confined between the elevated floodplain/terrace (Figure 12). Similar to Kalkie and Gorge, higher peak values are associated with geomorphic features that concentrate flow (Figures 13–15 and Appendix 4).

Downstream, the peak discharge at Jacks is more than triple that of Green Camp as the larger western arm of the creek merges (Figure 3, Table 3). The unit stream power values are slightly lower than the change in discharge due to the decrease in slope from 0.0137 m/m to 0.0084 m/m (Figure 12). While the valley width is less than Green Camp, the flow widths are similar as the valley floor of Jacks does not contain elevated geomorphic features until the downstream third. The large variability in unit stream power can be seen in the lower half as the flows are more channelised (Figures 3 and 9).

Below the confluence of Mihi and Jacks Creek the catchment area doubles, but the mean unit stream power is slightly lower than each of the upstream reaches (Figure 3, Table 3). This is due to the slope decreasing to 0.0069 m/m, a wider valley margin and lower slope valley sides (Figure 12). Peak unit stream power values result from local geomorphic features including deeply incised channels near the confluence and steep valley sides downstream (Figures 7 and 13–15 and Appendix 4).

Shear Stress

Shear stress, τ (Nm^{-2}), is calculated using the equation;

$$\tau=\gamma dS \qquad (1)$$

Where γ is the specific weight of water (9807 Nm^{-3}), d is depth (m) and S is slope (m/m), and is related to unit stream power, ω (Wm^{-2});

$$\omega=\gamma QS/w \qquad (2)$$

Where Q is discharge (m^3s^{-1}) and w is width. Using equations (1) and (2);

$$\tau=\omega/v \qquad (3)$$

Where v is velocity (ms^{-1}).

Equation 3 highlights why shear stress values follow a similar trend to unit stream power along both creeks, with broad low-slope reaches of Neils and HP Flat having the lowest median and peak values (Table 4, Figures 16–19 and Appendix 4). The five-fold increase to the next reach downstream (Gorge) is not as great as the 10-fold increase in unit stream power due to the higher velocities of the downstream reach as the water flows over the increased slope and narrower valley margins. Large increases in shear stress are also recorded moving downstream on Jacks Creek as the effective valley width narrows with resultant increases in flow depth. This is illustrated in Figure 12 where the water surface elevation shows the depth above both the channel/pond and mean floodplain elevation.

Table 4. Summary of maximum and median shear stress results from HEC-RAS 2D hydraulic modelling for each reach. The additional reach (Kalkie (modified)) was from a second modelled flow over an altered DEM that removed channels, ponds and anthropogenic structures to simulate intact valley-fill sediments.

	HEC-RAS 2D flow modelling											
	Maximum Shear Stress (Nm^{-2})						Median shear stress (Nm^{-2})					
AEP (%)	50	20	10	5	2	1	50	20	10	5	2	1
Kalkie (modified)	32	47	58	71	86	93	7.9	13	16	20	26	30
Kalkie	68	96	101	121	138	147	5.7	11	14	17	22	25
Green Camp	93	99	134	139	147	149	11	12	25	31	40	46
Jacks	92	120	139	155	187	211	24	33	47	57	73	85
Neils	25	36	40	50	60	73	5.2	8.6	11	13	16	18
HP Flat	25	34	65	76	75	82	4.3	8.2	11	13	16	18
Gorge	95	120	134	152	187	213	20	33	42	51	64	74
Lower Mihi	273	332	351	375	412	447	22	36	44	49	52	53

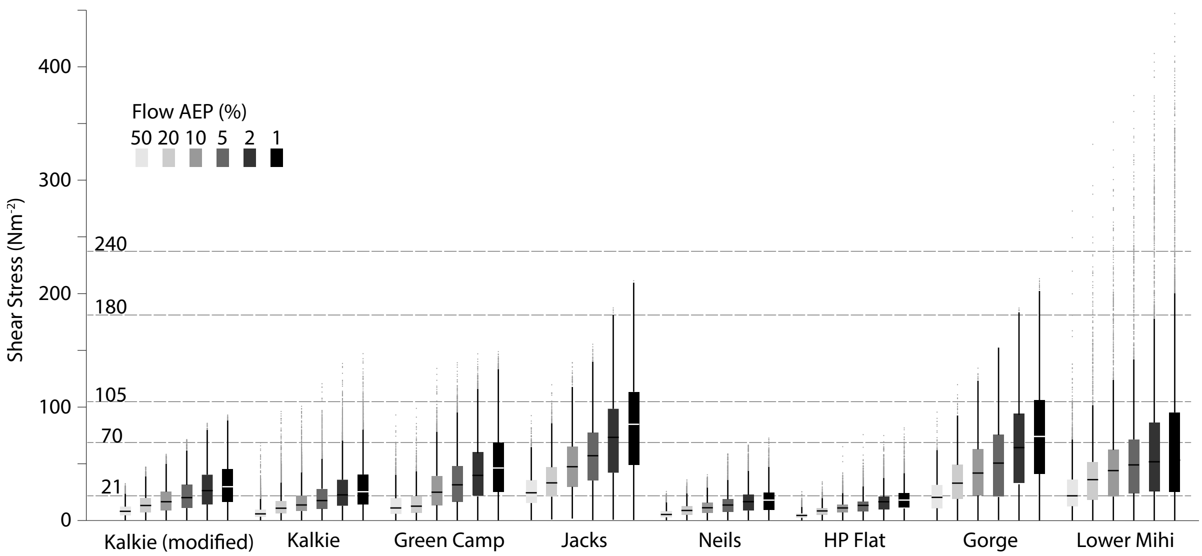

Figure 16. Box plot shear stress values from a 2×2 m grid output from HEC-RAS 2D flow model for AEP flows of 50%, 20%, 10%, 5%, 2% and 1%. The horizontal line is the median and the box shows the inter quartile range (Q1 to Q3 – IQR) with whiskers to lower (Q1-1.5×IQR) and upper (Q3+1.5×IQR) limits. Outliers are grey dots. Horizontal grid lines are the shear stress threshold of erosion for each surface disturbance/vegetation type detailed in Prosser and Slade (1994) (values converted from $dyn.cm^{-2}$); tussock grass and sedge (240 Nm^{-2}), lightly degraded tussock grass and sedge (180 Nm^{-2}), aquatic plants (105 Nm^{-2}), heavily degraded tussock grass and sedge (70 Nm^{-2}) and bare clay (21 Nm^{-2}). The additional reach (Kalkie (modified)) was from a second modelled flow over an altered DEM that removed channels, ponds and anthropogenic structures to simulate an intact valley-fill.

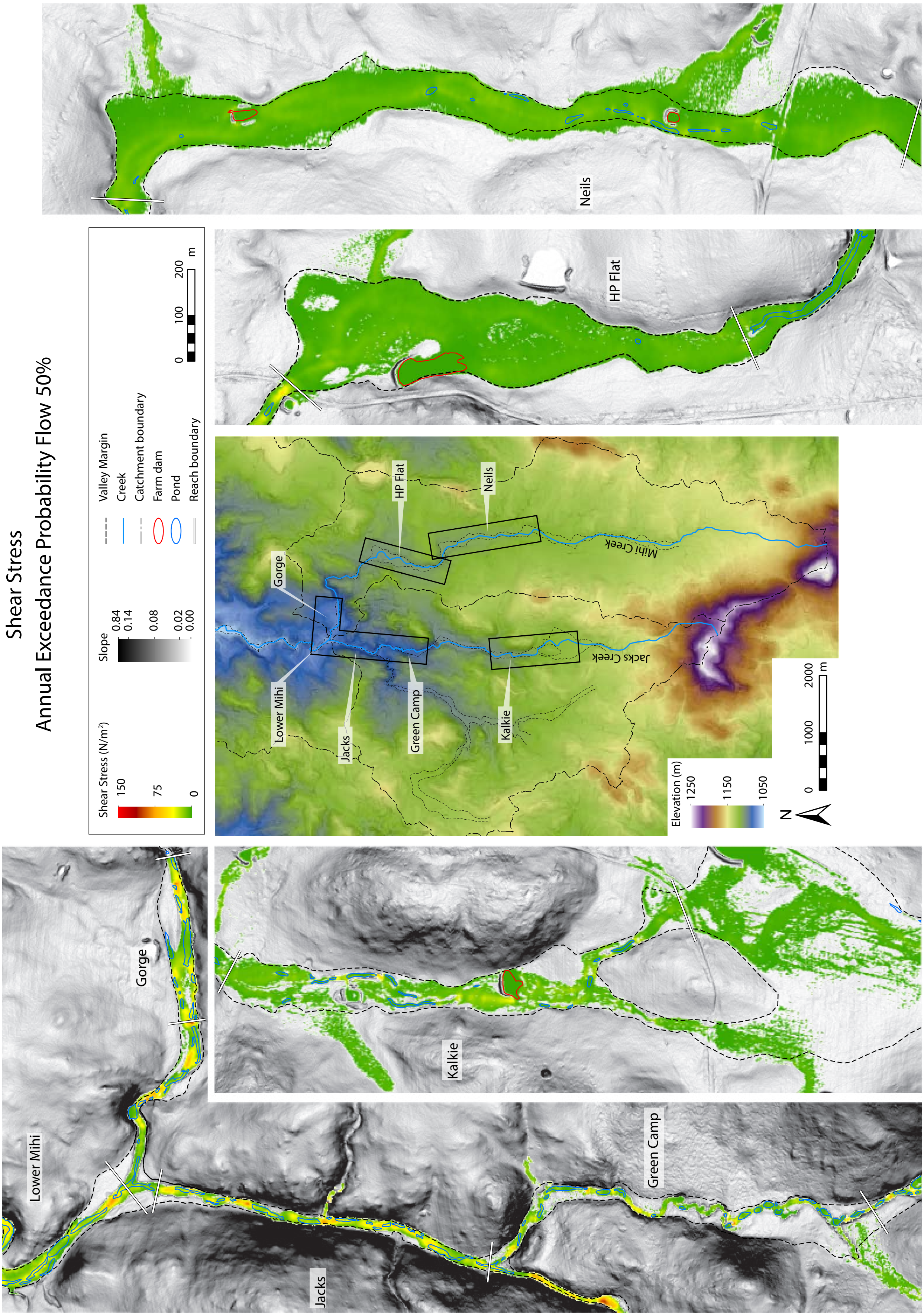

Figure 17. Shear stress (Nm^{-2}) for 50% AEP flows. See methods for details.

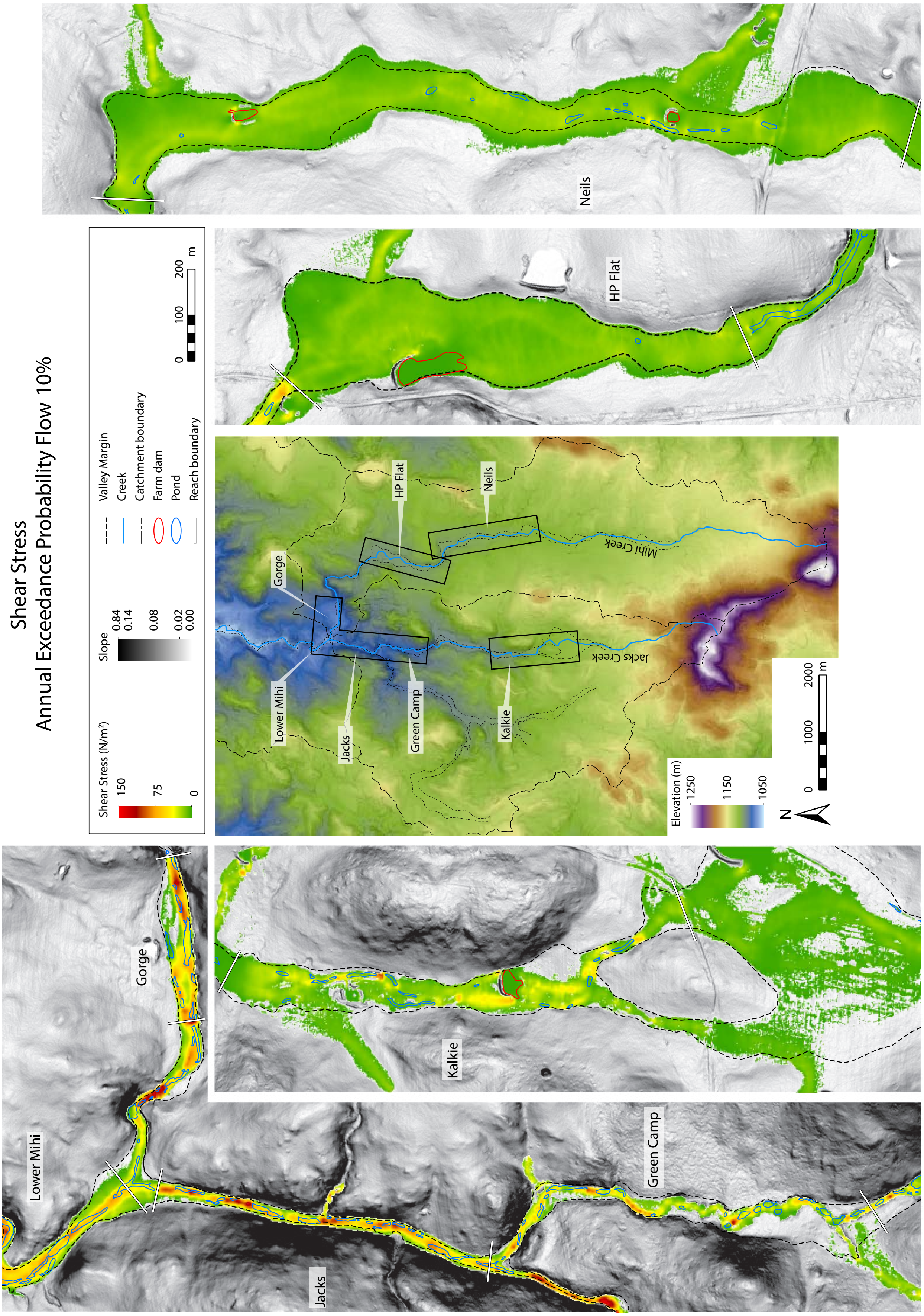

Figure 18. Shear stress (Nm^{-2}) for 10% AEP flows. See methods for details.

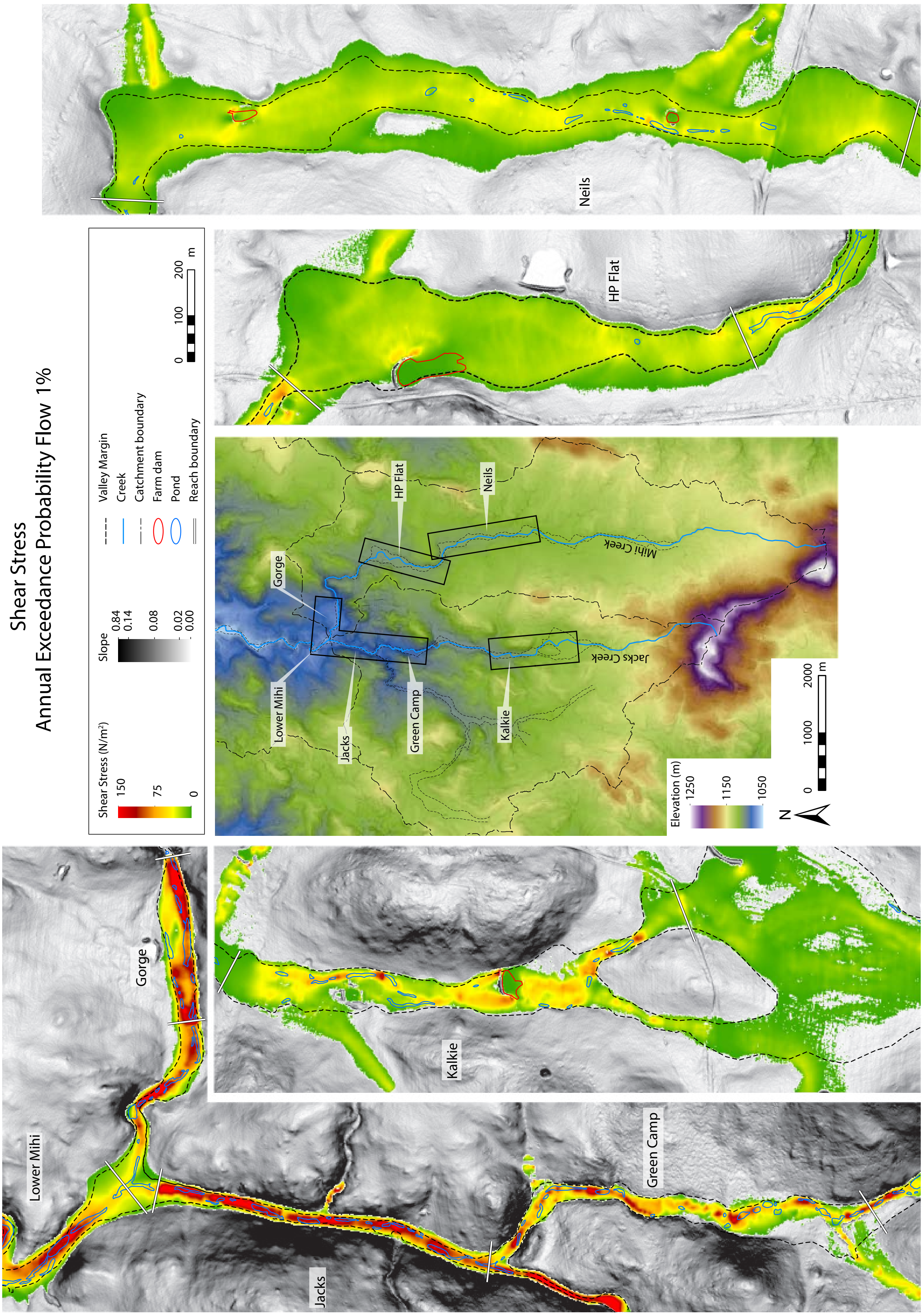

Figure 19. Shear stress (Nm^{-2}) for1% AEP flows. See methods for details.

The more consequential values for shear stress are the peaks or those above the threshold for erosion (Figures 16 and 20 and Appendix 4). Hydraulic modelling of shear stress on all reaches, when compared to the calculated values from Prosser and Slade (1994), show that flows with a 1% AEP will not cause erosion on areas of the valley floor that are intact and vegetated with tussock and/or sedge (Figure 20). Areas that are lightly disturbed from fire or light grazing by livestock also remain intact. Additionally, it is only the downstream and confined reaches that would see small areas of erosion once the surface has been heavily disturbed from ploughing or animal trampling (Figure 20). However, when the ponds, incised channels and areas surrounding floodplain structures are included there is likely to be erosion associated with these un-vegetated features during flows as low as 50% AEP. This occurs in all reaches except for the broad, low slope valleys, which may have minor erosion above 10% AEP flows. To test the likelihood of erosion in an undisturbed reach an altered DEM of the Kalkie reach was created by removing ponds, channels and dams. The modelling of this altered reach showed an overall increase in shear stress, with a 6% increase in the area that would erode if it were bare clay. There was a reduction in the number of high values, therefore limiting erosion to a small number of places only if the surface was heavily disturbed (Figure 20).

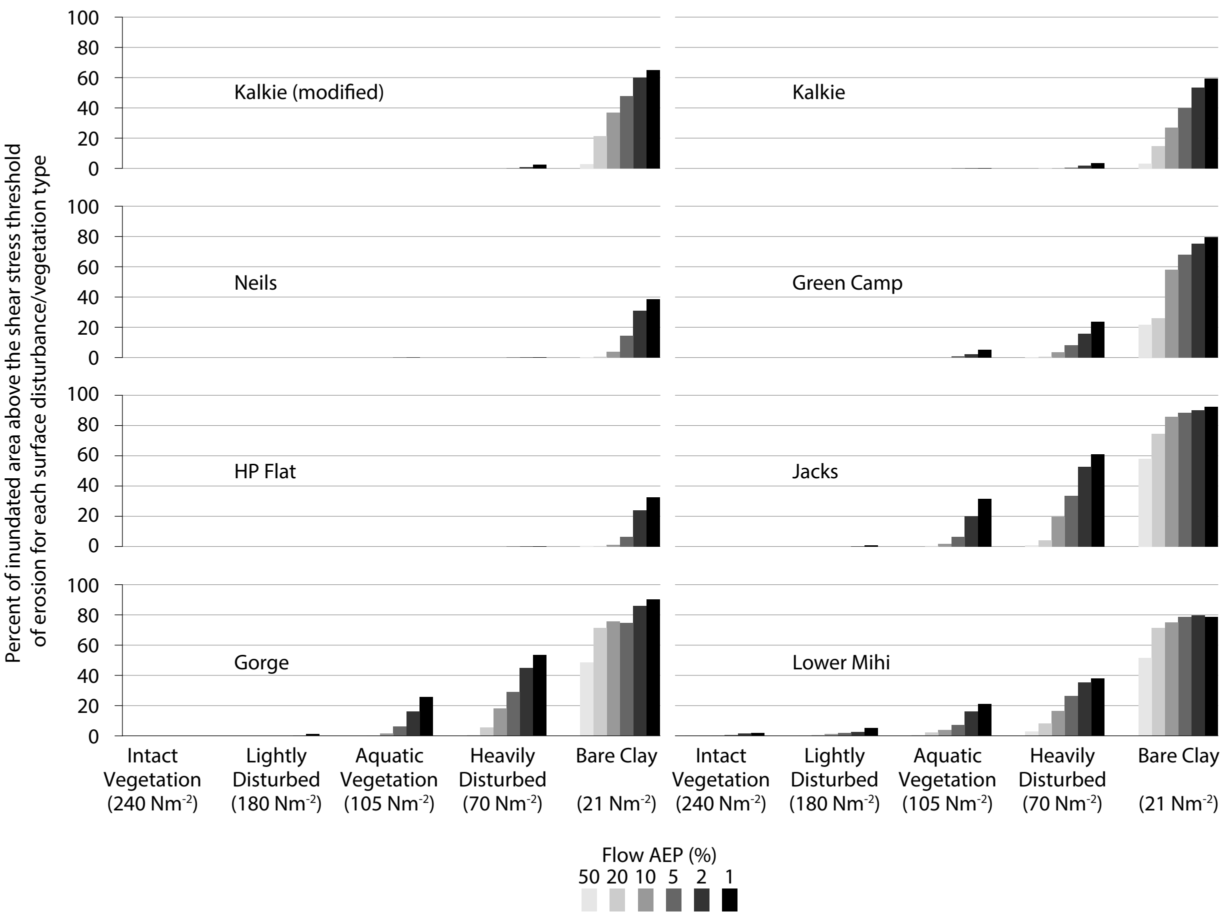

Figure 20. Percent of inundated area above the shear stress threshold of erosion for each surface disturbance/ vegetation type detailed in Prosser and Slade (1994). Shear stress values for each reach from HEC-RAS 5.0.3 2D model. The reach Kalkie was modelled twice with the second run, Kalkie modified, using an altered DEM that removed the channel, ponds and dam wall to simulate an intact valley-fill

4.5. Planform and stratigraphy of chains-of-ponds

Varied reach-scale characteristic planform and slope along Mihi and Jacks Creeks are associated with the position of downstream control points. In most of the reaches, the control is a bedrock outcrop that has restricted incision, limiting slope and allowing the alluvium to be deposited over the incised valleys. The location of the control points is associated with the underlying geology of the region, with narrower valley margins and bedrock outcrops at places where the creeks trend east–west, cutting across the north–south fold axis of the low-grade metasedimentary units or through the elongate diorite intrusion.

In general, the reaches have a basal layer of coarser-grained sediment at a depth of 1–2 m overlain by finer-grained sandy clays with some gravels, and topped with organic-rich loams that contain sands or small gravels. The basal layer has different characteristics in each reach with gravelly clays or clayey gravels and the downstream, higher-energy reaches also contain cobbles. The mid layers contain higher clay percentages compared to the surface, but are less well sorted with higher sand and gravel content. The cores through the floodplain do not show the layering that is evident in the few bank exposures, particularly at the downstream reaches, where the gravels are deposited in sheets during higher flows and covered by finer suspended sediment from successive lower-energy flows. The density of these gravel deposits also reduces towards the surface suggesting a gradual reduction in peak energy over time as the floodplain aggraded. The sand and gravel content in this layer also increases downstream in both Mihi and Jacks Creeks. The top layers are consistently loamy through all sites, but with an increasing sand content in the downstream reaches. This trend is expected with increasing discharge downstream.

The variation over the cross-section of each reach illustrates different evolutions. The weathered terrace on the western side of Kalkie suggests a minimum of two phases of aggradation separated by incision across 70% of the valley. Downstream on the higher energy reaches there is also evidence of reworking with changes in alignment of the flow path, erosion of ledges and head-cut incision in ponds. An OSL sample from a bank exposure of an active pond at a depth 0.8 m has an age of ~1 ka, suggesting that, like other lower-energy environments that have incised or been reworked over the Holocene (e.g. Fryirs and Brierley, 1998; Nanson and Cohen, 2014), some chain-of-ponds reaches are able to be reworked under climatic conditions similar to present. In contrast, the absence of unconformities in the stratigraphy of Neils and an OSL age from 1 m below the surface suggests no reworking other than pond scour for more than 18 ka.

The ponds in partly confined and unconfined reaches can be separated into two broad categories; ponds that are shallow with relatively gently sloped sides, and those that are deep and steep sided often with evident bank slumping. The first category is found in the upper reaches of Mihi Creek (Neils and HP Flat) and on Jacks Creek on the broad sections of Kalkie where there are no planform controls. They are situated anywhere from the margins to the centre of the valley. The second category occurs in the steeper and confined section of Kalkie and the higher energy reaches, Jacks and Gorge; typically abutting the valley margins or other planform controls, such as a terrace. There are examples of shallower ponds on these reaches, but they are associated with sections of localised low slope and are not on the main flow path. These lower energy environments may not scour the bed as quickly, allowing vegetation to recolonise and further stabilise the shallow form (*sensu* Gurnell et al., 2012).

4.6. Surface disturbance and pond formation

Vegetation plays an important role in resisting erosion in these discontinuous systems and the shear stress required to initiate erosion varies greatly under different vegetated or disturbed conditions (Prosser and Slade, 1994). Shear stress calculations from hydraulic modelling (Figures 16–20) illustrate that the disturbance of this surface 'armour' will not only expose the underlying dispersible loamy soils (Eyles, 1977a), but will concentrate flow and increase velocity through reduced resistance, thereby increasing scour with a positive feedback over successive flows. Many chains-of-ponds are located on agricultural land opening them up to greater risk of vegetation disturbance from grazing and trampling. In addition, where there are already ponds, livestock may cause added bank slumping, increasing the width of the ponds and drawing flows from the adjacent densely vegetated floodplains, further decreasing their stability. Overall, the hydraulic modelling confirms Eyles (1977a) interpretation that it is damage or removal of vegetation and/or damage to the floodplain surface that will lead to the initiation of pond development. Unit stream power then influences whether these scour features will enlarge and elongate, making them susceptible to gullying. The frequency of overland flow and the duration of inundation of the scour features or ponds may also impact the ability of vegetation to recolonise the disturbed area (Gurnell et al., 2012). For example, a shallow scour pool may dry quickly due to evaporation, and without further extended inundation will allow surrounding grasses to establish that will hinder further erosion. The increased flow resistance may also help to entrain sediment (Van Dijk et al., 1996). Alternatively, a permanent pool may encourage reedy vegetation growth that stabilises the banks. However, the majority of ponds along all reaches contained very little tussock or pasture grass on the shallow pond beds, or aquatic/reedy vegetation in the deeper ponds, possibly due to the temporal variability of water levels. Additionally, some of the ponds that maintain water for extended periods have aquatic macro fauna, such as *Cherax Destructor* (freshwater crayfish), and their burrowing into the banks contributes to the ponds enlargement (Eyles, 1977a).

In a reach where there is no channel, larger flows are more likely to initiate change, especially at points of valley constriction where unit stream power is increased. Any anthropogenic modification to the valley floor, either through artificial channels or the creation of dams, will increase the chance of triggering a disturbance due to increased unit stream power.

4.7. Hydrology, unit stream power and planform metrics for chains-of-ponds

There are four factors that determine unit stream power. 1) Discharge, which is closely related to catchment area, but depends on numerous other factors including the shape of the catchment and rainfall intensity (Rahman et al., 2015). 2) The ability to dissipate flows over the width of the valley. This also includes the adjacent valley-sides that may be engaged during higher flows, with shallower slopes allowing further dissipation, or floodplain impediments such as dam walls. These can be combined into the term effective valley width at each flow stage. 3) The water surface slope, or energy slope of the reach. This may also be influenced by the valley width, as narrower margins may cause flow to back up, thereby reducing the slope upstream and increasing it downstream. 4) Local geomorphic features such as ponds and channels or anthropogenic structures including dam banks and drainage channels, all of which have localised effects on the slope and effective valley width.

Unlike rivers with longitudinally continuous channels that have measurable characteristics such as bankfull discharge (Wolman and Miller, 1960), there is no longitudinally continuous characteristic that can be applied to discontinuous rivers as a comparable measure across reaches to explain geomorphic change. These sites are in close proximity and tend to flood during the same events, so the unit stream power values at each AEP flow can be compared across reaches as they have been preconditioned by the same climatic drivers (e.g. previous floods or droughts). A comparison of planform and pond characteristics relative to the same AEP flows between reaches highlights metrics that can be used to identify those at risk of incision or change to a new river type (Figure 21).

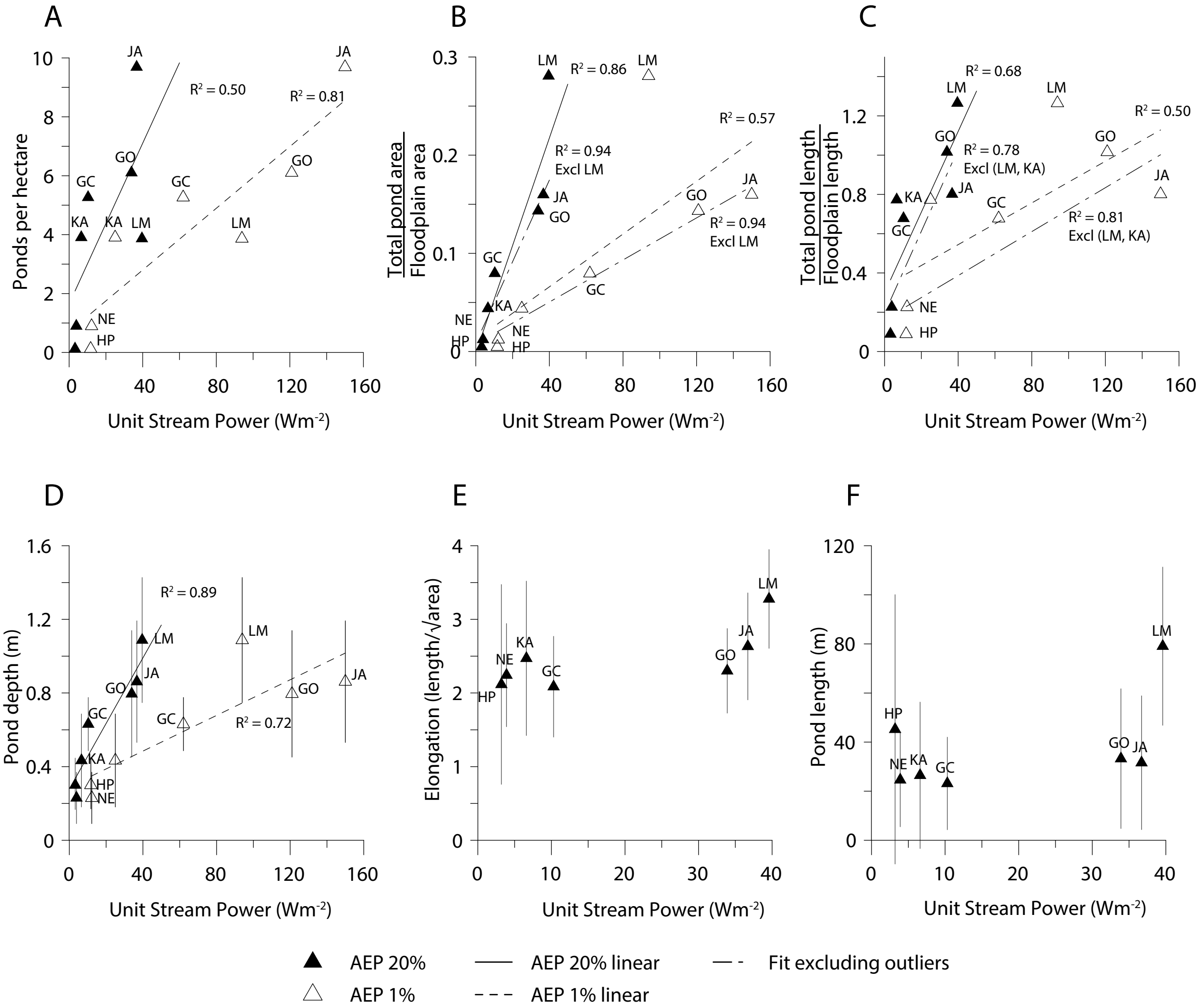

Figure 21. Planform and ponds metrics for the seven reaches — Neils (NE), HP Flat (HP), Gorge (GO), Kalkie (KA), Green Camp (GC), and Lower Mihi (LM) — relative to unit stream power for 20% AEP (▲) and 1% AEP (△). Error bars are one standard deviation.

The correlation between the number of ponds per unit area and mean unit stream power is poor for AEPs of 50% and 20% (R^2=0.5-0.58), but increases for AEPs of 5% and 1% (R^2=0.70 and R^2=0.81, respectively) (see Figure 21 A), suggesting that the higher unit stream power values of the larger flood may be enough to initiate scour through the densely vegetated floodplains. The correlation between the total area of ponds relative to the area of the valley floor and mean unit stream power (Figure 21 B) decreases as the flow AEP decreases, due to one outlier with a high positive residual (Lower Mihi). Excluding the outlier, it is correlated with mean unit stream power (R^2=0.94–0.98) over a range of flow AEPs (Figure 21 B). The excluded reach has a much greater pond and channel area relative to the floodplain area than the other reaches as it has begun to channelise and is at risk of losing its ponds and longitudinal discontinuity. Therefore high positive residuals may be a usable metric for identifying at-risk reaches. However, it does not necessarily identify the risk for those with broad floodplains, with relatively large areas, that have single thread flow path that may channelise the intact valley-fill. To partly account for the valley width of a reach, the total length of the ponds relative to the reach length may be suitable as a measure of risk. There is a correlation to unit stream power, (R^2=0.50–0.72 Figure 21 C), but this lower value is largely due to high positive residuals from reaches (KA and LM) that have several elongate ponds and strong planform controls.

For individual ponds, depth is not correlated with unit stream power (R^2 = 0.09), but this may be due to new ponds in the higher energy reaches that have not had the time to deepen through scour. However, reach-mean pond depths are significantly different (p=0.001) and correlated with reach mean unit stream power ($R^2 > 0.72$) over multiple AEP flows (Figure 21 D). The reaches with armoured pond beds have lower depths relative to unit stream power ratio and if they are excluded the correlation increases to R^2>0.92.

The unmodified shallower ponds of the upper reaches are, on average, shorter and less elongate than the deeper ponds. However the variety of size and shape means that (excluding the elongate, incised ponds below the confluence on Lower Mihi) there is no significant difference in length (p=0.489) or elongation (length/√area) (p=0.299) between the reaches (Figure 21 E and F). In addition, there is no correlation between length or elongation and unit stream power for either individual ponds or reach averages. This suggests that localised factors such as planform features, bedrock outcrops, soil, vegetation and aquatic macro-fauna may be more important in controlling the length/elongation of the pond (Eyles, 1977a; Prosser et al., 1994). This can therefore provide a measure of a reach's resilience to channelisation, at least partly independent of external forcing.

4.8. Assessment of sensitivity for chains-of-ponds

Prediction of the timing and rates at which rivers change is aided by an understanding of their evolution and the historical changes in morphology and behaviour, compared with external forcing (Fryirs, 2003). Such forcing may include anthropogenic modification of the morphology, vegetation or hydrology of the reach or catchment, and climatic changes over various temporal scales. This information provides an understanding of how these systems adjust and their natural range of variability within the existing flux boundary conditions, or their trajectory to crossing thresholds to new states (Brierley and Fryirs, 2005; Fryirs et al., 2012).

Geomorphic sensitivity can be assessed using the process of Reid and Brierley (2015). This entails that each river style is assigned a *potential* sensitivity of low, medium or high based on the potential range of adjustment. All seven reaches on Mihi and Jacks Creeks can be assigned low (L) *potential* sensitivity as they are generally resilient systems (Fryirs, 2003) (Table 5). This is because these laterally unconfined alluvial-fills, with discontinuous channels and ponds, have imposed boundary conditions of downstream bedrock controlling slope, and relatively broad valley floors to dissipate energy (Table 6). The unchannelised form and position in the headwaters of catchments create low unit stream power and low sediment supply. The greatest risk to a change in river type is channelisation, which will incise the ponds, increase unit stream power, and transport sediment downstream, significantly altering the ecosystem.

Each reach is then assigned a *specific* sensitivity of I, II or III based on its contemporary history of adjustments. A further classification (T) can be added if the reach is close to the threshold of change to a new river type. However, assigning a specific sensitivity for each reach is a problem for many chains-of-ponds, as the rates and size of change of geomorphic adjustments in these discontinuous headwater streams is typically very low (Johnston and Brierley, 2006; Mould and Fryirs, 2017). Thereby, making it difficult to identify measurable changes from historical imagery to compare against the longer-term evolution. While larger gullies may be identified, it is often difficult to determine smaller, post-European changes in this system as historical aerial imagery is not always of sufficient resolution, and older parish and plan maps (e.g. Land and Property Information, 2017) do not include enough geomorphic detail (especially where there is no channel) to identify changes. Also, it does not take into account the period of post-European landuse-change prior to the first available parish maps. This is likely to be the case for the majority of chains-of-ponds and other discontinuous headwaters systems. Therefore, it may not always be possible to conduct historical analysis, so other metrics or characteristics need to be identified to be able to examine the sensitivity of chains-of-ponds. In addition, extracting and quantifying descriptors of planform change (Step 5, Figure 4 in Reid and Brierley (2015)) presents a problem, as unlike other fluvial systems (e.g. braid index (Brice, 1960)) there is a lack of information about what are a suitable descriptors and what measurable planform values are 'expected'. Therefore, quantitative and measurable characteristics that can be used to estimate *specific* sensitivity for chains-of-ponds needs to be created. For this study, identifiable historical geomorphic changes from aerial imagery, field investigations and anecdotal evidence is used to assign *specific* sensitivity values to each reach. It is also used to explain the variation in the pond and planform metrics between sites that has yielded a range of values that help assign reach-specific sensitivity to other chains-of-ponds. Some of these geomorphic changes include changes to the size, shape and number of ponds and channels, and natural and anthropogenic modification of the floodplain.

Table 5. Valley and pond characteristics for each reach. Sensitivity Rank applied using the semi-quantitative method from Reid and Brierley (2015) and field investigations.

	Valley/Reach						Ponds						
Reach	Sensitivity Rank	Catchment area (km²)	Valley width (m) Min	Mean	Max	Slope (m/m)	Ponds/ Hectare	Surface area (m²)	Length (m)	Elongation	Floodplain area %	Floodplain length %	Depth (m)
Kalkie	L–II	2.7 – 4.2	23	83	152	0.0167	**3.9**	112 ± 155	**26 ± 30**	**2.5 ± 1.0**	*4.4 %*	**77 %**	0.67
Green Camp	L–II	6.0 – 6.9	17	56	119	0.0137	**6.0**	125 ± 115	*21 ± 16*	2.1 ± 0.7	8.0 %	68 %	0.97[a]
Jacks	L–II	17.5 – 18.5	13	23	34	0.0084	**9.7**	165 ± 208	**32 ± 27**	**2.6 ± 0.7**	16.0 %	**80 %**	0.57
Neils	L–I	10.0 – 14.1	42	94	190	0.0045	*0.9*	154 ± 162	25 ± 19	2.2 ± 0.7	*1.2 %*	*22.7%*	0.42
Neils Upper	L–II	10.0 – 12.0	42	64	92	0.0069	**3.3**	149 ± 161	**26 ± 21**	**2.3 ± 0.7**	*5.0%*	**57%**	0.45
Neils Lower	L–I	12.0 – 14.1	70	109	190	0.0045	*0.3*	166 ± 182	*22 ± 14*	1.9 ± 0.7	*0.5%*	*9.0%*	0.37
HP Flat	L–I	14.5 – 17.0	43	153	279	0.0041	*0.1*	388 ± 506	**45 ± 55**	2.1 ± 1.4	*0.5 %*	*8.9 %*	0.54
Gorge	L–II	18.4 – 19.1	23	49	68	0.0118	**6.1**	235 ± 338	**33 ± 28**	**2.3 ± 0.6**	14.3 %	**102 %**	0.54
Lower Mihi	L–III–T	37.6 – 38.6	20	40	100	0.0069	**3.9**	582 ± 343	**74 ± 32**	**3.3 ± 0.7**	28.1 %	**127 %**	**1.26**

[a] measured from the valley wide terrace elevation. Metrics highlighted by bold text are high sensitivity or risk, and italics are low sensitivity or risk.

Table 6. Summary of characteristics related to the impelling and resisting forces, pond formation and historical change for the reaches of Mihi and Jacks Creeks. The descriptions of high, moderate and low are relative to what may be expected in a chain-of-ponds system.

Reach	**Neils Lower HP Flat**	**Neils Upper**	**Kalkie**	**Green Camp**	**Gorge, Jacks**	**Lower Mihi**
Slope (m/m)	Low (<0.07)	Low (<0.07)	High (>0.012)	High (>0.012)	Moderate (0.07–0.012)	Low (<0.07)
Effective Valley Width						
Confinement	Unconfined	Unconfined	Planform confined/ Unconfined	Planform confined	Partly confined	Partly confined
Valley Width (m)	80–200	80–200	30–80	20–100	20–50	20–100
Valley margin slope	Low	Low	High	High	High	Moderate
Planform controls	Low (flow paths)	Low (flow paths)	Moderate (flow paths/terrace)	High (inset)	High (complex)	High (channel)
Discharge						
AEP50 (m^3s^{-1})	1–6	1–6	1–2	2–3	5–10	20–40
AEP1 (m^3s^{-1})	10–60	10–60	10–30	15–40	60–100	150–300
Energy (relative)	**Low**	**Low**	**Moderate**	**Moderate**	**High**	**High**
Vegetation	Tussock and pasture grass	Tussock and pasture grass	Tussock and pasture grass	Pasture grass	Tussock and pasture grass	Pasture grass
Lithology	Fine–sandy	Fine–sandy	Fine–sandy	Fine–sandy	Fine–gravel, armoured	Fine–gravel, partly armoured
Bedrock controls	Downstream	Downstream	Downstream	Multiple	Multiple	Downstream
Aquatic macrofauna (Yabbies, tortoise etc.)	No	No	Unknown	Yes	Yes	Yes
Resistance (relative)	**Moderate**	**Moderate**	**Moderate**	**Moderate**	**High**	**Moderate**
Pond formation	Scour	Scour	Scour	Scour/Fixed bar	Scour/Fixed bar	Scour/Fixed bar
Historical change						
Since 1887 Parish map	**Low**	**Moderate**	**Moderate (?)**	**Low (?)**	**Moderate (?)**	**High**
Since 1956 aerial imagery	**Low**	**Moderate**	**Low (?)**	**Low (?)**	**Low (?)**	**High**

(?) indicates changes that are not clearly visible on parish maps of historical aerial imagery

The number of ponds relative to the valley area is used to indicate the reach's sensitivity to events due to preconditioning that initiate geomorphic change to a generally resilient landform. This *event sensitivity* is a measure of any disturbance (anthropogenic, climatic, etc.) and intrinsic controls related to unit stream power (discharge, valley width, and slope) or resistance (vegetation and stratigraphy) that increase the likelihood of exacerbating the disturbance (Crozier, 1999; Fryirs, 2017; Phillips, 2006). If it is possible to identify the changes over time, it can highlight the changes in sensitivity to events, and be linked to causation. For example, a reach that has had an increase in the number (or increase per unit of time) of scour features since European settlement may be attributed to altered grazing or farming practices that have preconditioned the system, increasing its sensitivity. This can serve as an early detection of change and may only require minor intervention to stop further incision. The size and elongation of the ponds, combined with the channelisation of a reach, can be used to indicate the *morphological sensitivity*. That is, the more elongate a pond and more channelised a reach, the less likely it is to maintain a stable form. Combining this with a measure of the total channelisation of the reach (the ratio of the summed length of the ponds and significant channel features to the length of the reach), indicates the reach's *change sensitivity* (the likelihood or potential to shift to a new behavioural regime) (Brierley and Fryirs, 2016; Brunsden, 1993a). Positive feedbacks from concentrating flow and increasing unit stream power will lead to the channelisation of currently discontinuous reaches, thereby moving beyond its current behavioural regime to a channelised river type. Consideration should be given to the linearity of these ponds; that is, are they connected by the same preferential flow path? This is because multiple flow paths with ponded features will return higher *change sensitivity* values, even though some may be inactive and only inundated during larger flows.

These values must also be explored in the context of what is expected of this system. In some cases, river change is a natural adjustment for discontinuous systems, resulting from both autogenic and allogenic factors (e.g. Fryirs and Brierley, 1998; Johnston and Brierley, 2006; Prosser, 1991; Prosser et al., 1994). Therefore, for the purpose of measuring sensitivity, suitable quantifiable descriptors for this discontinuous river style are; 1) the number of ponds per unit area, 2) the length and/or elongation of the ponds, and 3) the sum total length of the ponds relative to the reach's valley length (see Figure 22). There is no weighting applied to any of these sensitivity metrics as a high result in any will indicate that some form of adjustment beyond what may be expected has, or is occurring. However, a high value for *change sensitivity* is more likely to suggest that the reach is at the threshold (T) of change to a new river type. Combining the metrics for each reach with the reach scale controls of discharge, valley slope, valley confinement (or effective valley width) and bed material, they can be assigned a reach sensitivity value. A combination of these metrics and any identifiable historical changes has resulted in I, II or III rating for sensitivity (see Tables 5 and 6).

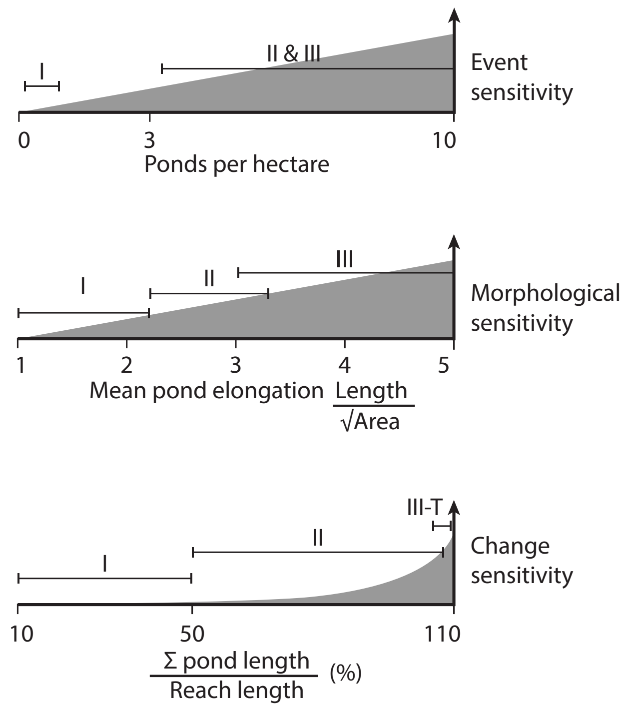

Figure 22. Conceptual diagram of sensitivity metrics (x-axes) and their relationship to the sensitivity of a reach. Floating bars show range of values for the assigned sensitivity rankings (I, II and III) for the seven reaches in this study.

The reaches with the lowest reach specific sensitivity value (I) have a low number of ponds per hectare (<0.3), were shorter and less elongate, with no identifiable historical change to the length or elongation of the ponds and a low proportion of the length is ponded or channelised (<10%) (Table 5, Figure 22). These are found on the upper parts of Mihi Creek and have the lowest slopes and broadest valley margins with relatively little anthropogenic modification to the valley floor. The absence of reworking of the valley floor over the past 18 ka and the rarity of ponds suggest that these reaches sit toward the lower unit stream power threshold for pond formation (Figure 23). The reaches with moderate specific sensitivity values (II) showed a higher number of ponds per hectare (3–10), were on average more elongate, and a much higher proportion of the length was scoured or incised (57%–102%) (Table 5, Figure 22). These reaches have a wide range of catchment areas, unit stream power values, valley widths and slopes (Table 5).

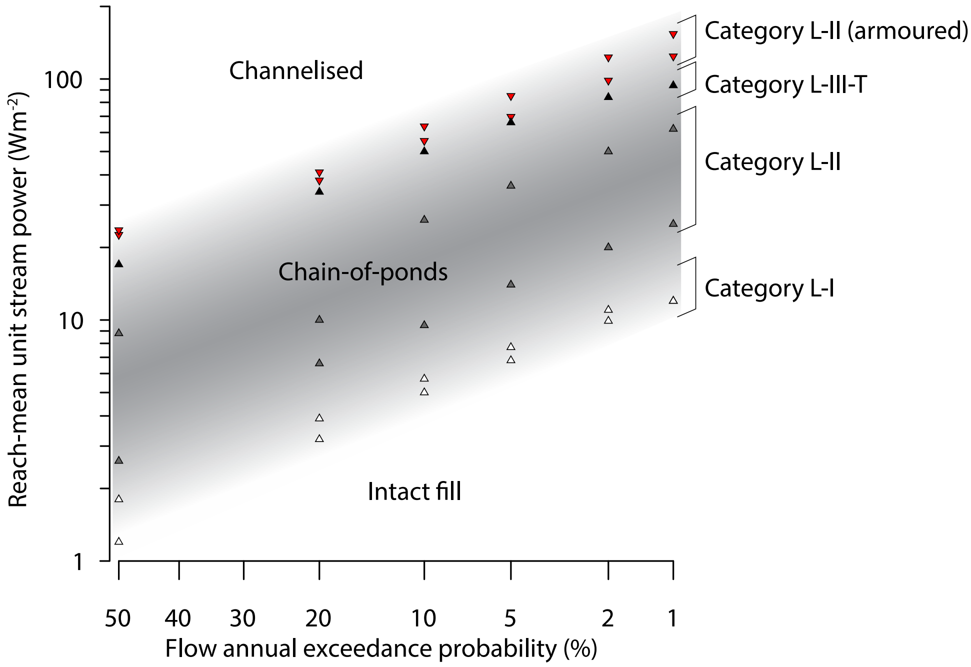

Figure 23. Indicative thresholds of unit stream power required for chains-of-ponds formation.

The upper one third of Neils, Neils Upper, has many comparable reach planform characteristics to those with the lowest reach specific sensitivity value. However, it has been modified with a shallow drainage channel and a dam wall across a significant proportion of the valley, both of which constrict flow and increase unit stream power. This has resulted in an increase in the number of ponds, and the elongation of new and existing ponds over the past 50 years, highlighting the increased event sensitivity (Crozier, 1999; Fryirs, 2017), and reduced resilience that is likely due to anthropogenic modification. In contrast, the artificial channel in the lower section of Kalkie does not show any sign of disturbance, but this may be due to the natural spring maintaining higher water tables, supporting vegetation growth that armours the surface against erosion. The reaches of Jacks and Gorge have the highest mean stream power across the sites (Figure 23), but moderate sensitivity values due to the armouring that is evident in both reaches.

The highest reach specific sensitivity value (III–T) (Table 5, Figure 22) is only assigned to one reach, which has seen large historical changes to the planform. The number of ponds per hectare (3.9) is not high because multiple ponds have merged due to headcut incision, recorded in much longer and more elongate ponds than any other reach. While this reach has lower unit stream power values than the immediate upstream lower sensitivity reaches (Figure 23), it also does not contain bedrock outcrops and well-armoured beds that protect the upstream reaches from incision. With pond extension over the past 70 years, there are only a few short areas that are not incised, and the depth of the incision is greater than any other reach. This capacity to concentrate flows and the higher peak discharges means that Lower Mihi is the reach most at risk of complete incision and change to a new river style. This change is likely to result in a system that is similar to the mostly channelised reaches immediately downstream.

4.9. Implications for river management

Channel discontinuity in chains-of-ponds results from a balance of impelling and resisting forces across a range of temporal (e.g. flood events and climatic oscillations to climate change) and spatial scales (e.g. geomorphic unit to reach). The energy to initiate scour and channelisation (generally) increases with catchment area due downstream increasing discharges. However, longitudinal variations in slope and effective valley width alter the reach and intra-reach unit stream power, leading the fluctuations that move above the threshold of channel formation. Resistance to scour and channelisation ranges in scale from the individual plant to reach scale vegetation or sediment structure, and can significantly alter the threshold of energy required to initiate scour or form channels. Relatively minor changes to the impelling or resisting forces can dramatically alter the geomorphic form of these discontinuous systems as they are inherently near the threshold of channel formation. There are generally distinct processes in headwater streams due to the highly variable discharge and close coupling with hillslope processes (Gomi et al., 2002). Changes to hydro-geomorphic form and processes will impact in situ biotic structure and function, as seen in chain-of-ponds (Hazell et al., 2003) and other upland discontinuous systems in southeast Australia (Hose et al., 2014; Pemberton, 2005). The connectivity of these headwaters to higher order streams will also result in downstream changes to ecological function (Finn et al., 2011; Freeman et al., 2007; U.S. EPA., 2015). This is particularly relevant for many of these landscapes as they may be affected by regular land use changes as a result of farming or grazing practices.

The sensitivity metrics quantified here enable a semi-quantitative geomorphic assessment of chains-of-ponds and may be used to guide the identification of similar metrics for other discontinuous river types. This process will assist managers in identifying reaches that are sensitive to disturbance or impacts from climate change, or changes to discharge from stream modification or instream storage such as farm dams. In combination with assessing recovery potential through forecasting future trajectories (Brierley and Fryirs, 2016; Fryirs and Brierley, 2016; Mould and Fryirs, 2017), it will guide approaches to maintaining or restoring these unique ecosystems. For example, the lowest reach (Lower Mihi) has seen the greatest change in channelisation so appears to be a priority for intervention. However, there are other factors to consider including: the depth and length of incision that will require a large amount of sediment or structures to restore; there are bedrock control points protecting upstream reaches from headcuts limiting the risk to other reaches; and importantly, the downstream reaches are a different river type, suggesting this reach will likely remain at the threshold for river change and any work will probably be of little consequence. Alternately, the upstream reach of Neils (sensitivity L–II) will likely only require minor intervention in filling or blocking the small artificial channel, which will re-engage the floodplain at all flow stages and reduce unit stream power through the ponds.

4.10. Conclusions

The reaches along Jacks and Mihi Creeks provide a range of chain-of-ponds morphologies in varying stages of adjustment (or modification) since post-European landuse change. Hydraulic modelling produced a range of unit stream power values relative to flow annual exceedance probabilities that provide indicative limits within which chains-of-ponds can form and persist. This can help understand the likelihood of a reach enduring adjustments to any of the controls on unit stream power (discharge, slope and effective valley width) and can guide the protection and management of these ecosystems. These results are applicable to similar discontinuous systems in temperate climates that have variable flows and water tables, including swampy meadows (e.g. Mactaggart et al., 2006), dambos (e.g. Mäckel, 1973) and alluvial valley-fills (e.g. Fryirs and Brierley, 1998). Having the same external forcing from climate and landuse across all the reaches has allowed a comparison of intrinsic controls on geomorphic change and the ability to identify measures of sensitivity. These metrics provide a basis for the semi-quantitative assessment of geomorphic sensitivity (*sensu* Reid and Brierley, 2015) for small-scale chains-of-ponds and a process for creating similar quantifiable metrics in other discontinuous watercourses. To further develop a robust set of criteria for assessing their sensitivity and capacity for repair or restoration, analysis of additional intact and incised reaches will enhance the reliability and identify critical thresholds or turning points.

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Chapter 5

Discontinuous Watercourses in River Science and Policy

Chapter in preparation as:

Williams, R.T. and Fryirs, K.A., In Prep. A commentary on the recognition of discontinuous watercourses in river science and policy in Australian law

5.1. Introduction

The international call to understand the function and connectivity of headwater streams, especially those displaying discontinuity of flow and channel form (Acuña et al., 2014; Acuña et al., 2017; Bauer et al., 2017; Creed et al., 2017; Davies et al., 2011; Meyer et al., 2007; Wohl, 2017), has stemmed from the uncertainty of their protection under policy and legislation (Doyle and Bernhardt, 2011; Kalen, 2007; Lamaro et al., 2007; Murphy, 2007; Taylor et al., 2011) and their under representation or inadequate management (Gomi et al., 2002).

In Australia, fluvial systems with discontinuity of flow and/or channel make up 50–70% of the channel network (Downing et al., 2012; Sheldon et al., 2010) and many of these are rare or at risk, making them geo-ecologically important (Bennett et al., 2002; Dunn, 2000). While these important ecosystems should be protected, discontinuous rivers and streams have long been overlooked under Australian legislation, with a lack of continuity in both flow and channel form a key factor (Davies et al., 2011; Lamaro et al., 2007; Taylor and Stokes, 2005b). This has contributed to the loss of many headwater ecosystems through urbanisation (Davies et al., 2011; Vietz et al., 2014), agriculture (Brierley et al., 1999; Eyles, 1977b), forestry (Zavadil and Ivezich, 2011) and mining (Fryirs et al., 2016).

This paper examines the scientific, legal and cultural, meanings and definitions of a watercourse, with a specific focus on those with ephemeral flow and at a threshold of channel formation. It then examines the extent to which various forms of discontinuous watercourse, in particular chains-of-ponds, can be better considered as part of water resources law and management.

5.2. How do we define a watercourse in Australia?

To understand the extent to which rivers are protected under the law, there needs to be an understanding of how rivers or watercourses are regarded from cultural, legal and scientific perspectives.

> *'When the term 'river' is considered with respect to biophysical, social and economic issues that impinge on river environments, it is apparent that the meaning of a river is as much a construct of an individual's experience as it is a specific and definable physical reality.'*
>
> *(*Taylor and Stokes, 2005b p.183*)*

The varied perceptions that people have of the same river may lead them to expect different outcomes, depending on whether they see it as an impediment to development, a resource to be utilised, or a valuable social or environmental ecosystem in need of protection.

5.2.1. Cultural understanding

(Australia's) cultural understandings of a river can be broadly separated into two perspectives; Indigenous and European. While this separation is not clean, with many non-indigenous people building their own experiences from their interactions with the landscape, it encompasses the views on the separation of land and water. Indigenous Australians have long viewed that there is no distinction between rivers and the surrounding landscape.

> *Aboriginal peoples have never drawn a distinction between the land and the waters that flow over, rest upon or flow beneath it. The land and waters are equal components of 'country', all that require care and nurturing, and for which there are ongoing responsibilities (*Lingiari Foundation, 2002 p.6*)*

This connection moves beyond the physical where their 'spiritual and religious connection to country are directly linked to, and cannot be separated from, the environment' (J. Crew cited in Weir et al., 2013 p.5). This innate connection to the natural environment is in contrast to the early European settlement on Australia where settlers who came with the intent of land 'ownership' (as opposed to stewardship) and imposed their views upon the landscape, seeing it as a resource to be used (McKay and Marsden, 2009).

It is understandable that people assign importance to a place where sufficient water forms a permanent or at least a predictable intermittent watercourse, as it provides certainty of an essential resource. Nonetheless, a watercourse is a sum of its upstream parts and a disturbance in the headwaters will affect downstream flow, water quality and ecological connection (Freeman et al., 2007; Gomi et al., 2002; U.S. EPA., 2015; Wohl, 2017). Due to the scale of ephemeral drainage lines or watercourses compared to the larger perennial stream to which they contribute, their importance may be underestimated (Armstrong et al., 2012) and inadequately managed (Gomi et al., 2002). However, the cumulative impact from the disturbance of many upstream reaches will alter the hydrological and ecological function of the downstream reaches (Freeman et al., 2007). This occurs in both rural (e.g. Nathan and Lowe, 2012; O'Connor, 2001) and urban environments where the current approaches will 'perpetuate the demise of river environments via "death by a thousand pipes"'(Davies et al., 2011 p.331).

From an Anglo-European perspective, watercourses are typically considered independent of land. In Australia, this separation was carried through in the policy of riparian rights, where ownership of the water that flowed through, or along, a person's land remained with the State. This distinction may result from the way water moves through the land and is seen as greater (or timelier) consequence than other parts of the landscape, particularly if you have the capacity (and desire) to modify or control the flow. Aboriginal people generally relied on water in an uncontrolled form, with reports of relatively small landform modification (Builth et al., 2008; Rowlands and Rowlands, 1969). They lived within the means of the landscape as there were no population centres like the cities of Europe that relied on ever increasing yields of agricultural imports to sustain the inhabitants (Boserup, 1965). With European settlement in Australia, many of these ideas and approaches were brought to a vastly different landscape resulting in rapid changes to vegetation and landuse (Brock et al., 1999; Butzer and Helgren, 2005; Portenga et al., 2016; Rustomji and Pietsch, 2007).

5.2.2. Scientific knowledge

The term 'discontinuous watercourses' is used here to encompass spatial and temporal discontinuity in both flow and channel form. Watercourses with temporal discontinuity of flow, termed 'temporary waterways' (Acuña et al., 2014), including those with intermittent and ephemeral flow (among others descriptors (Uys and O'Keeffe, 1997)), have seen an increase in attention over the last 20 years, particularly in ecological research (Datry et al., 2014; Leigh et al., 2016). Much of this has resulted from a growing understanding of the importance that temporary waterways have in maintaining biodiversity and providing ecosystem services (Larned et al., 2010), but also from legislation, such as the European Water Framework Directive (Logan and Furse, 2002; Munné and Prat, 2004) and changes to the United States Clean Water Act definition of 'Waters of the US' (Leibowitz et al., 2008; Nadeau and Rains, 2007). There are still large research gaps in our understanding of the functional processes, including the spatial extent, resilience, hydrology and connectivity of temporary or discontinuous watercourses (Wohl, 2017). In addition to temporal flow discontinuity, channel discontinuity is common in some headwater systems including arroyos, dambos, cut and fill, swampy meadows and chains-of-ponds, and while there is a growing body of research (e.g. Bull, 1997; Cartwright and Gilfedder, 2015; Eyles, 1977a; Fryirs and Brierley, 1998; Hazell et al., 2003; Mactaggart et al., 2006; Mould and Fryirs, 2017; Prosser et al., 1994; Wasson et al., 1998), there remains uncertainty in the processes of channel formation and stability, and the delineation of their lateral and upstream extent (Wohl, 2017).

An understanding of hydro-geomorphic structure and function is essential in ecological restoration and conservation of discontinuous watercourses as they are the physical template for creating habitat mosaics through a range of flow stages (Brierley et al., 1999; Larned et al., 2010; Poole, 2002). Rivers are dynamic in their adjustment of form across a range of temporal and spatial scales and this applies to both the flow of water and their geomorphic character and behaviour (Brierley and Fryirs, 2005). This variability is especially evident in headwater streams as flow and geomorphic form adjust to highly variable extrinsic and intrinsic forcing (e.g. weather, climate, landuse change, preconditioning, etc.), which act upon an area in the landscape that is inherently at the threshold of channel formation (Wohl, 2017). The identification of where watercourses begin can be difficult in rivers with temporal and spatial discontinuity as the form of the fluvial environment may not contain bed and banks or a clear high water mark (Mersel and Lichvar, 2014; Taylor et al., 2011; Wohl, 2017), and this can become more complex when considering how they change over time. As an example of spatial adjustment, the planform of a reach may alter longitudinally between an intact valley-fill and channelised, as changes to slope, valley width, stratigraphy or vegetation effect stream power (e.g. Bull, 1997). Additionally, the spatial extent of a channel network may change over various time scales through gradual adjustment or threshold behaviour (Church, 2002; Knighton, 1998; Phillips, 2006). How the rate of change is viewed is also dependent on the perspective. For example, a channel that incises through an unchannelised reach over a period of 50 years may appear gradual to the observer, but from an evolutionary timescale may be a rapid geomorphic change before a long process of accretion begins again (e.g. Fryirs and Brierley, 1998; Johnston and Brierley, 2006; Mould and Fryirs, 2017; Prosser et al., 1994).

Flow of water is linked to a range of short- to long-term climatic forcing (e.g. an isolated storm, seasonal weather patterns, decadal oscillations or climate change), along with the geomorphic form over which it flows. Therefore the spatial extent of flow will vary over a range of temporal scales such as, ephemeral flow after rainfall, seasonally intermittent flow from predictable weather patterns (e.g. monsoon) (Datry et al., 2014; Doyle and Bernhardt, 2011; Stanley et al., 1997) or the possible gradual decline resulting from climate change (Döll and Schmied, 2012). An additional factor in the change of flow patterns is through anthropogenic alterations including water storage or extraction that can result in the shift from perennial to intermittent rivers (Gleick, 2003).

The dynamic process of river evolution, be it natural or enhanced through anthropogenic influence (Brierley and Fryirs, 2005), opens the definition of a 'river' or watercourse to a litany of questions. If a watercourse has continuous bed and banks because it has been channelised due to anthropogenic changes, what happens if the watercourse is rehabilitated to a swamp or meadow with channel discontinuity or no channel? Does it lose protection? Do the lack of 'channel' features and flow no longer afford it protection?

Conversely, if a creek is incised, does it now receive protection, or do we look at how it was historically as a point of reference? How far does this go back? Do we look at the oldest aerial photos, personal recollections and word of mouth, estimations of pre-European character, or its entire evolutionary sequence? Does an intact valley-fill (such as a swampy meadow or chain-of-ponds) that was incised one thousand years ago receive protection because of its history or because it will one day again incise and create channels? Additionally, in headwater areas with poor channel definition, the natural riparian conditions may have been modified or replaced with pasture grasses leaving no clear 'riparian vegetation'. Does the acceptance of modification in relation to a natural channel then transfer to the modified riparian vegetation, and if so, how can previous riparian conditions be known? Much like defining where a watercourse begins, the spatio-temporal considerations for the protection of a variety of dynamic landforms means that the time scales over which each watercourse is interpreted must be suitable to each type.

5.2.3. Legal definition

It is noted by Acuña et al. (2014) that legislation in many parts of Australia have definitions that include temporary waterways and therefore may afford them protection. Unfortunately, the term 'intermittent', which often serves well in affording protection to watercourses with seasonally-discontinuous flow, does not legally encompass many of the 'ephemeral' watercourses in Australia (Taylor and Stokes, 2005b).

This has resulted in legal uncertainty, particularly in NSW where no definition of a 'watercourse' is provided in the *Water Management Act 2000* (NSW) (Taylor and Stokes, 2005a). The definitions of watercourses or waterways in all other states include the concept of discontinuity of flow with the word 'intermittent' or equivalent (see Table 1). However, none use the widely accepted term 'ephemeral' (e.g. Knighton, 1998), which describe the majority of Australia's fluvial environments (Sheldon et al., 2010), instead choosing the terms 'from time to time' (SA, Commonwealth), 'occasional' (WA) or the broader 'whether or not the flow is continuous' (Vic, NT) and 'regardless of the frequency of flow events' (Qld). The second point of argument comes from the definition of a 'channel', or the landscape feature through which the water flows. The High Court ruling in *Knezovic v Swan-Guildford* (1968) 118 CLR 468 requiring a watercourse to have 'continuity, permanence and unity' extends not only to flow but to geomorphic form, along with the expectation of a channel to have a 'defined bed and banks'. All states and territories share similar terms in defining a watercourse, such as river, creek, stream or brook, and most have a requirement similar to the federal *Water Act 2007* (Cth) of 'a natural watercourse (whether modified or not)' and include the terms 'bed' and 'banks'. The questions then arise; what is a natural channel, and where does it begin both longitudinally and laterally? For perennial or larger intermittent streams it can be problematic, let alone the issues that arise for ephemeral and headwater streams (Lamaro et al., 2007). Queensland's legislation, (*Water Act 2000* (Qld)) makes this clearer with definitions that include geomorphic terms like 'in-stream islands', 'benches' and 'bars', and also 'scour' or 'depositional features' to identify bank margins. For clarity on the longitudinal commencement of a watercourse, the definition specifically excludes 'drainage features', which are, in short, erosional features that are formed by short duration flows immediately after rainfall events that do not create a 'riverine environment' such as an absence of riparian vegetation (see Table 1). These conditions can have almost as much ambiguity as to the point where a watercourse begins, because there may not be a defined change in channel morphology, but a gradual transition. This transition may also not be linear or unidirectional, with discontinuous channels or scour features forming in alluvial valley-fills, before the threshold of channel continuity is reached (Chapter 4). Discontinuity of a watercourse was tested in NSW in *Narrambulla Action Group Inc. v Mulwaree Council* [1996] NSWLEC 199, where Bannon J found it was not a watercourse but:

> *At best it can be classified as a drainage line with gullies to the East and West, together with intermittent ponds and flood plane [sic] where water flows are rare intervals, under the influence of rain.*

Channel discontinuity means that chains-of-ponds, swampy meadows, and other unchannelised forms (see Mactaggart et al., 2008) may not receive protections afforded to other watercourses; that is until (ironically) they become degraded through incision and acquire the necessary geomorphic features of continuous bed and banks. Some chain-of-ponds may have protection under the Water Management Act 2000 (NSW) through the definition of a lake being 'any collection of still water, whether perennial or intermittent'. However, like the definition of a river, it excludes the term ephemeral.

There is one exception in Australian legislation where policy specifically includes 'chain of ponds' in the definition of a waterway. The *Standard Instrument (Local Environmental Plans) Order 2006* (NSW) prescribes the form and content of a principal local environmental plans under the *Environmental Planning and Assessment Act 1979* (NSW). Part 2 contains the land use zoning for natural waterways with objectives:

- *To protect the ecological and scenic values of natural waterways.*
- *To prevent development that would have an adverse effect on the natural values of waterways in this zone.*

However, there are no requirements in Local Environmental Plans (LEP) to identify or map watercourses, but rather the guidance given by the NSW Department of Planning suggests only perennial watercourses be specifically zoned:

> *Q: Should small creeks etc be zoned one of the Waterway zones?*
>
> *A: No. Small and intermittent waterways should generally be zoned according to the surrounding zone.* (Department of Planning, 2007 p.3)

Therefore, the definition as it applies to non-perennial streams appears to fall back to that of a 'river' in the *Water Management Act 2000* (NSW) (see Table 1) and the Water Management (General) Regulation 2011 (NSW). This regulation relies on the 'blue lines' that indicate watercourses on old topographic maps — with a median year of publication of 1979 — to identify stream order, which then determines the restrictions that apply to 'controlled activities', such as building and the removal or deposition of material, on the watercourse and riparian zones.

Much of Australia's current legislative and legal system came from England, and with it came the doctrine of riparian rights relating to the use of water being granted to a property that bordered a river (McKay and Marsden, 2009). Some of this remains with extraction permitted for domestic and stock rights under various water policies of the states. The *Water Management Act 2000* (NSW) also provides regulation for building dams on 'minor streams' to collect runoff. A 'minor stream' has a similar definition as prescribed for NSW LEPs using the same 'blue lines' on older topographic maps to identify 1st and 2nd order streams. The erroneous nature of this regulation has been discussed, noting that the blue lines are 'often little more than a cartographer's interpretation of reality' (Taylor and Stokes, 2005a p.210) and that channel discontinuity and ephemeral flow are a feature of many headwater streams and should be included in legislation and planning policy (Davies et al., 2011; Taylor and Stokes, 2005b).

Of greatest concern is the disconnection of scientific understanding from both policy and law. The *Water Management Act 2000 (*NSW) was written to replace the *Rivers and Foreshore Improvement Act (1948)* (NSW) in a time when there was a well-developed understanding of the nature of flow and channel discontinuity in Australia, along with the impacts resulting from European settlement (Brierley et al., 1999; Eyles, 1977a; Rutherfurd et al., 2000; Wasson et al., 1998). Yet, unlike water legislation in all other states, there is no definition of a watercourse included. There also was the awareness that case law had previously excluded ephemeral streams as a watercourse (e.g. *Narrambulla*) and future judgements may continue to follow the High Court's archaic Anglo-American definition of a watercourse;.

> '*the watercourse, in my opinion, must exhibit features of continuity, permanence and unity, best seen, of course, in the existence of a defined bed and banks with flowing water.*'
>
> *Knezovic v Swan-Guildford* (1968) 118 CLR 468 s18 derived after Angell (1854)

An acknowledgement of the disconnect between science and law is shown in Narrambulla by Bannon J, who noted an expert witness (Dr E.M. O'Loughlin, previous Chief Research Scientist with CSIRO)

> '*thinks of waterbodies in a scientific way, which includes waters such as Coopers Creek, but does not fit the definitions given by the Courts, taken as they are, from European conditions.*'

The European landscape and climatic conditions, which influenced Australia's early post-European policy and management of rivers, are vastly different to Australia's climate and riverine landscape. The modified nature of Britain's waterways is illustrated in the *Water Act 1914* (UK) definition of a watercourse which includes '*all rivers, streams, ditches, drains, cuts, culverts, dykes, sluices, sewers and passages through which water flows*'. It is surprising that these attitudes remained for so long considering the vast differences in landscape, climate and water resources.

5.3. Discussion

5.3.1. Intention of the policy

In Australia, all legislation related to water use and riverine ecosystems have objectives aligned to ecologically sustainable development, and the protection of water resources and their associated ecosystems. The definitions of a watercourse or waterway and other aspects of the riverine ecosystem, such as riparian zones, are intended to provide both boundaries for protection and certainty for land users. However, these definitions did not always align with the scientific understanding of riverine ecosystems when the Acts were written, let alone as scientific understanding evolved. There is a spectrum of geomorphologically complex continuous and discontinuous channel forms and equally varied riparian areas, or associated ecological footprints, that make up fluvial environments (Brierley and Fryirs, 2005; Davies et al., 2011).

The application of a strict definition is not always suitable, and imposing a fixed approach is unlikely to appropriately consider the complexity and specific needs of each ecosystem. To ensure that watercourses are protected, the definitions need to be explicitly inclusive of flow and channel form variability by adding ephemeral flow and channel discontinuity, along with a definition of riparian areas (Davies et al., 2011). Beyond the statutory definitions, guidelines need to be in place with the respective government departments or agencies to provide clarity on the identification of watercourses and the decision making process (e.g. the 9-part test (Taylor and Stokes, 2005b)) for both landholders and environmental protection. The guidelines must also be flexible so that approaches can be tailored to local and regional climatic and hydro-geomorphic conditions.

A lack of protection has led to the loss or damage of many headwater streams in urban environments, either being actively modified (e.g. piped for stormwater) or severely altered due to the changed hydrograph from an increase in impervious surfaces (Davies et al., 2011). Similar losses have occurred in rural areas from the channelisation of discontinuous or swampy headwaters, or the installation of dams. For example, under 'Harvestable Rights' in NSW, rural landholders are permitted to capture 10% of the average regional rain water run-off in the Eastern and Central division (covering approximately 60% of the state) and all the run-off in the semi-arid to arid Western Division (NSW Government Gazette, 2006). Run-off capture in small dams can have a significant impact, with estimates of annual stream flow losses typically 0.5-1.5 ML per 1 ML of dam, or up to 30% of annual flow downstream (Nathan and Lowe, 2012) with losses likely to increase as more dams are built (Chiew et al., 2008).

5.3.2. Perceptions of a watercourse

There are multiple perceptions of a watercourse that come from our individual experiences and knowledge. However, when it comes to disputes about a watercourse, how much of the rhetoric is based on an individual's experience or understanding, and how much of the argument comes from the desire to remove any negative impacts (financial or otherwise)? A property developer may internally acknowledge the existence of a watercourse, yet argue the contrary because of the financial gain that can be achieved in doing so. Alternately, an objector may seek to inflate the merits of a drainage line to block a development. Expert witnesses may also provide conflicting interpretations depending on the evidence and their own experiences and motivations (Burgman, 2005). For example, with limited historical evidence the expert geomorphologists in *Silva v Ku-ring-gai Council* [2009] NSWLEC 1060 s41 conflicted as to whether a watercourse was natural or artificial, each providing evidence in favour of whom they appeared.

There is an ecological connection to every part of the landscape within a catchment. Our understanding, and division of the landscape, may result from the scale (magnitude or temporal) of the connection, or consequence that may result from those connections. For example, the slow movement of soil or organic material from a hillside during thousands of rainfall events does not necessarily engender the same sense of connection as water flowing through a river. In the same manner, a series of apparently isolated ponds may not evoke the same sense of connectivity, and consequence, as a flowing stream.

5.3.3. Protection of discontinuous watercourses

Headwater systems make up over 70% of the global channel network (Downing et al., 2012), yet this is not reflected in river research, which is weighted toward higher order perennial streams (Datry et al., 2014; Vaughan and Ormerod, 2010). To protect these vital parts of the catchment, science needs to provide a better understanding of the shifts in process that occur at the inception point of watercourses (Doyle and Bernhardt, 2011; Palmer, 2009), and also the interactions and scale of the connection between hillslopes and watercourses. There is also a need to understand how disturbances (both natural and anthropogenic) affect headwater streams and to be able to adequately characterise hydro-geomorphic diversity (Acuña et al., 2017; Wohl, 2017). An increased knowledge of the bio-physical processes that create and maintain these ecosystems is only one step toward protecting them. Communication of these findings and of the importance of the upper extent of the riverine network in terms of environmental services, including the social and economic value, will be vital to ensure that the community and policy makers encourage and provide the protections that are needed (Acuña et al., 2017; Wohl, 2017).

5.4. Conclusions

Fluvial environments that are discontinuous through channel or surface flow need more than the definition of a watercourse to ensure that they are protected. An understanding of their eco-hydro-geomorphic processes and functions need to be improved. This will enhance the case to acknowledge these systems as valuable in their own right (Acuña et al., 2017). Management policies and practices need to be flexible and able to be implemented at regional and local scales, with appropriate measurable monitoring outcomes for the type of river and individual sites. The competing interests, whether it be from land use, such as urban development and farming, or objections over jurisdiction, create additional pressures on an already complex process of managing a diverse array of dynamic environments.

Table 1. Definitions of a watercourse or waterway in Australian legislation

Commonwealth of Australia

Water Act 2007 (Cth) – applied to the Murray-Darling Basin

watercourse:

(a) means a river, creek or other natural watercourse (whether modified or not) in which water is contained or flows (whether permanently or from time to time); and

(b) includes:

(i) a dam or reservoir that collects water flowing in a watercourse; and

(ii) a lake or wetland through which water flows; and

(iii) a channel into which the water of a watercourse has been diverted; and

(iv) part of a watercourse; and

(v) an estuary through which water flows.

Australian Capital Territory

Water Resources Act 2007 (ACT)

waterway means—

(a) a river, creek, stream or other natural channel in which water flows (whether continuously or intermittently); or

(b) the stormwater system or any other channel formed (whether completely or partly) by altering or relocating a waterway mentioned in paragraph (a); or

(c) a lake, pond, lagoon or marsh (whether formed by geomorphic processes or by works) in which water collects (whether continuously or intermittently).

New South Wales

Water Management Act 2000 (NSW)

river includes:

(a) any watercourse, whether perennial or intermittent and whether comprising a natural channel or a natural channel artificially improved, and

(b) any tributary, branch or other watercourse into or from which a watercourse referred to in paragraph (a) flows, and

(c) anything declared by the regulations to be a river, whether or not it also forms part of a lake or estuary, but does not include anything declared by the regulations not to be a river.

Standard Instrument (Local Environmental Plans) Order 2006 (NSW)

watercourse means any river, creek, stream or chain of ponds, whether artificially modified or not, in which water usually flows, either continuously or intermittently, in a defined bed or channel, but does not include a waterbody (artificial).

Northern Territory

Water Act 1996 (NT)

waterway means:

(a) a river, creek, stream or watercourse;

(b) a natural channel in which water flows, whether or not the flow is continuous;

(c) a channel formed wholly or partly by the alteration or relocation of a waterway described in paragraph (a) or (b);

(d) a lake, lagoon, swamp or marsh, whether formed by geomorphic processes or modified by works:

(i) in which water collects, whether or not the collection is continuous; and

(ii) into, through or out of which a current (which forms the flow or part of the flow of a river, creek, stream or watercourse) passes, whether or not that passage is continuous;

(e) land on which, as a result of works constructed on a waterway described in paragraph (a), (b) or (c), water collects, whether or not the collection is continuous;

(f) land which is intermittently covered by water from a waterway described in paragraph (a), (b), (c), (d) or (e), but does not include any artificial channel or work which diverts water away from such a waterway;

(g) if any land described in paragraph (f) forms part of a slope rising from the waterway to a definite lip, the land up to that lip; or

(h) land declared under section 5(1) to be a waterway

Queensland

Water Act 2000 (Qld)

(1) A watercourse is a river, creek or other stream, including a stream in the form of an anabranch or a tributary, in which water flows permanently or intermittently, regardless of the frequency of flow events—

(a) in a natural channel, whether artificially modified or not; or

(b) in an artificial channel that has changed the course of the stream. [s 5] Water Act 2000 Chapter 1 Preliminary Page 40 Current as at 6 December 2016 Authorised by the Parliamentary Counsel

(2) A watercourse includes any of the following located in it—

(a) in-stream islands;

(b) benches;

(c) bars.

(3) However, a watercourse does not include a drainage feature.

(4) Further—

(a) unless there is a contrary intention, a reference to a watercourse in this Act, other than in this part or in the definitions in schedule 4 to the extent they support the operation of this part, is a reference to anywhere that is—

(i) upstream of the downstream limit of the watercourse; and

(ii) between the lateral limits of the watercourse; and

(b) a reference in this Act to, or to a circumstance that involves, land adjoining a watercourse, is a reference to, or to a circumstance that involves, land effectively adjoining a watercourse. Note for paragraph (b)— Generally, the non-tidal boundary (watercourse) of land bounded by a watercourse, as provided for under the Survey and Mapping Infrastructure Act 2003, would not correspond precisely with the line of the outer bank of a watercourse under this Act.

(5) In this section—

adjoining includes being bounded by, being adjacent to, or abutting.

lateral limits, of a watercourse, are the outer bank on one side of the watercourse and the outer bank on the other side of the watercourse.

drainage feature means—

(a) if a feature is identified on the watercourse identification map as a drainage feature—the feature identified on the map; or

(b) otherwise—a natural landscape feature, including a gully, drain, drainage depression or other erosion feature that—

(i) is formed by the concentration of, or operates to confine or concentrate, overland flow water during and immediately after rainfall events; and

(ii) flows for only a short duration after a rainfall event, regardless of the frequency of flow events; and

(iii) commonly, does not have enough continuing flow to create a riverine environment.

Example for paragraph (b)(iii)— There is commonly an absence of water favouring riparian vegetation.

South Australia

Water Resources Act 1997 (SA)

watercourse means a river, creek or other natural watercourse (whether modified or not) in which water is contained or flows whether permanently or from time to time and includes—

(a) a dam or reservoir that collects water flowing in a watercourse;

(b) a lake through which water flows;

(c) a channel (but not a channel declared by regulation to be excluded from the ambit of this definition) into which the water of a watercourse has been diverted;

(d) part of a watercourse;

(e) an estuary through which water flows;

(f) any other natural resource, or class of natural resource, designated as a watercourse for the purposes of this Act by an NRM plan;

Tasmania

Water Management Act 1999 (Tas)

watercourse means a river, creek or other natural stream of water (whether modified or not) flowing in a defined channel, or between banks, notwithstanding that the flow may be intermittent or seasonal or the banks not clearly or sharply defined, and includes –

(a) a dam that collects water flowing in any such stream; and

(b) a lake through which water flows; and

(c) a channel into which the water of any such stream has been diverted; and

(d) part of any such stream; and

(da) the floodplain of any such stream –

but does not include –

(e) a channel declared by the regulations to be excluded from this definition; or

(f) a drain or drainage depression in the contours on the land which only serves to relieve upper land of excess water in times of major precipitation;

Victoria

Water Act 1989 (Vic)

waterway means

(a) a river, creek, stream or watercourse; or

(b) a natural channel in which water regularly flows, whether or not the flow is continuous; or

(c) a channel formed wholly or partly by the alteration or relocation of a waterway as described in paragraph (a) or (b); or

(d) a lake, lagoon, swamp or marsh, being—

(i) a natural collection of water (other than water collected and contained in a private dam or a natural depression on private land) into or through or out of which a current that forms the whole or part of the flow of a river, creek, stream or watercourse passes, whether or not the flow is continuous; or

(ii) a collection of water (other than water collected and contained in a private dam or a natural depression on private land) that the Governor in Council declares under section 4(1) to be a lake, lagoon, swamp or marsh; or

(e) land on which, as a result of works constructed on a waterway as described in paragraph (a), (b) or (c), water collects regularly, whether or not the collection is continuous; or

(f) land which is regularly covered by water from a waterway as described in paragraph (a), (b), (c), (d) or (e) but does not include any artificial channel or work which diverts water away from such a waterway; or (g) if any land described in paragraph (f) forms part of a slope rising from the waterway to a definite lip, the land up to that lip;

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Chapter 6

Discussion

6.1. Thesis synthesis relative to the aims

This chapter will synthesise the key findings from the four preceding chapters and highlight the significance of the contribution to the understanding of the hydro-geomorphic structure, function and evolution of chains-of-ponds, and discontinuous watercourses more generally.

This thesis provides the scientific foundation for the recognition, conservation and rehabilitation of chains-of-ponds. It is built on the understanding that hydro-geomorphic processes create a physical template upon which fluvial ecosystems function, and are therefore essential in the restoration and conservation of riverine ecosystems (Brierley et al., 1999; Cullum et al., 2008; Larned et al., 2010; Montgomery, 1999; Thorp et al., 2006).

To achieve this, the thesis focuses on five research aims that identify the hydro-geomorphic structure and processes that underpin the formation, evolution and impairment or loss of chains-of-ponds, and investigate their protection under legislative frameworks (Table 1).

An understanding of the intrinsic and extrinsic controls on the hydro-geomorphic structure, function and evolution of chains-of-ponds (Aims 1, 2 and 3: Figure 1, grey boxes) provides an explanation for the spectrum of channel continuity and diversity of reach morphologies (Figure 1, pink box). This precipitated the development of quantifiable metrics to assess geomorphic sensitivity (Aim 4: Figure 1, blue box) (after; Brunsden, 1993a; Brunsden, 1993b; Brunsden, 2001; Brunsden and Thornes, 1979; Crozier, 1999; Fryirs, 2017; Phillips, 2006; Reid and Brierley, 2015). Elucidating the geomorphic evolution of these systems (aim 2) provides an understanding of the antecedent controls (Brierley, 2010; Brunsden, 1993b) and facilitates forecasting of future trajectories (Figure 1, yellow box) (Brierley and Fryirs, 2016). A combination of the first four aims builds a process for assessing, prioritising and developing hydro-geomorphic based management strategies for chains-of-ponds. The final contribution, Aim 5, provides scientific, cultural and legal perspectives on discontinuous watercourses (Figure 1, green box) that can guide managers and legislators on approaches to recognise and protect these important river types in river management policy.

Table 1. Relationship between the thesis aims, research approaches and the associated thesis chapters

Thesis Aims	Research Approach	Associated chapters
1. Characterise the diverse hydro-geomorphic structure and function of chains-of-ponds	• Identify the diverse longitudinal and planform characteristics and stratigraphy of chains-of-ponds across a range of spatial scales (large-scale and headwater) and channel discontinuity (intact alluvial fill to channelised); and, • Identify the intrinsic and extrinsic controls on the formation and evolution (and loss) of chain-of-ponds systems.	Chapters 2, 3 and 4
2. Assess the nature and timing of the late Quaternary evolution of chains-of-ponds	• Characterise the stratigraphy and planform to identify broad geomorphic assemblages and controls on the formation of the present system; and, • Quantify the timing of the evolution through optically stimulated luminescence dating to link the assemblages to long term regional changes in fluvial activity and the onset of the current discontinuous system.	Chapters 2 and 4
3. Characterise the surface and subsurface hydrological processes and connectivity of chains-of-ponds	• Quantify the hydrological inputs and outputs, and the surface and sub-surface interactions using hydraulic gradients, radon and stable oxygen and hydrogen isotopes; and, • Model streamflow and quantify the unit stream power and shear stress exerted on varied planform reaches that lead to scour and incision.	Chapters 3 and 4
4. Develop quantitative metrics for assessing geomorphic sensitivity of chains-of-ponds	• Identify intrinsic and extrinsic controls that make chains-of-ponds vulnerable to loss of discontinuity, incision and declining geomorphic condition; • Assess sensitivity of varied reaches through historical and field analysis of geomorphic changes; and, • Quantify suitable measurable pond and planform characteristics associated with the range of geomorphic condition.	Chapter 4
5. Evaluate the recognition and integration of discontinuous watercourses in policy and law	• Identify legislation under which riverine ecosystems are protected and the hydro-geomorphic limitations of the policy; and • Analyse how this legislation is interpreted by the courts and the implications for managing chains-of-ponds.	Chapter 5

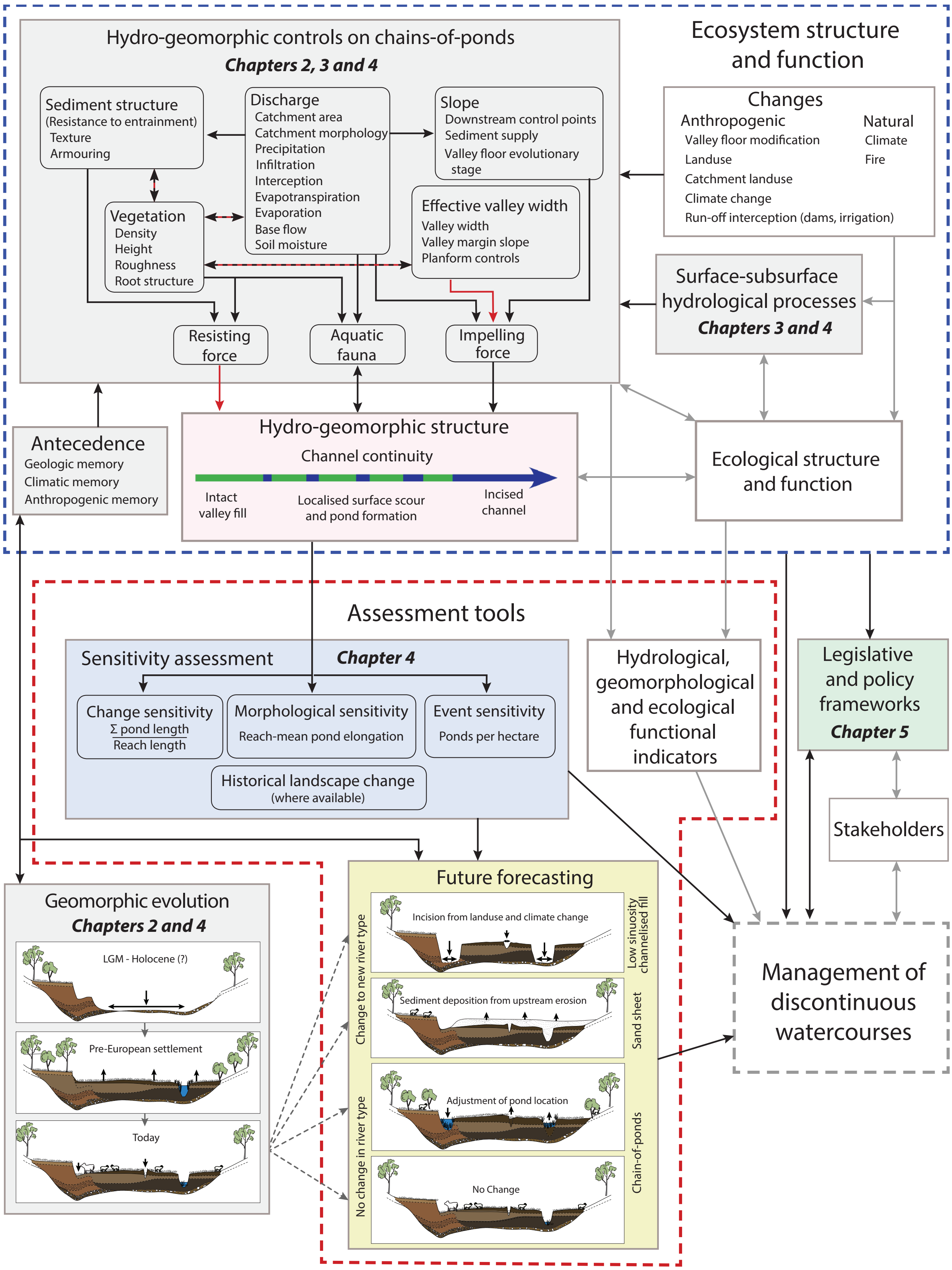

Figure 1. Conceptual diagram of the controls on discontinuous watercourse hydro-geomorphic structure and function for inputs into sensitivity assessment and river management. These incorporate antecedent and intrinsic and extrinsic changes as factors affecting the controls and morphology of discontinuous watercourses. Sensitivity assessment using change, morphological and event sensitivity metrics can be used as a prioritisation tool and with future forecasting to identify suitable management approaches. This must sit within, and inform, legislative and policy frameworks and incorporate the interrelated ecological structure and function of discontinuous watercourses.

Aim 1. Characterise the diverse hydro-geomorphic structure and function of chains-of-ponds, and Aim 2. Assess the nature and timing of the late Quaternary evolution of chains-of-ponds

These aims are achieved by describing and analysing the diverse longitudinal and planform characteristics and stratigraphy of chains-of-ponds in different catchment positions through a spectrum of channel discontinuity, from intact alluvial fill to channelised reaches. In addition, quantifying the age of the geomorphic assemblages using optically stimulated luminescence (OSL) highlights long term regional changes in fluvial activity and the timing of threshold changes in river types. This is vital for the identification of the intrinsic and extrinsic controls on the formation, evolution and loss of chains-of-ponds.

Background

Existing research describes chains-of-ponds as irregularly spaced, steep-sided ponds separated by densely vegetated alluvial valley-fill sediments (Eyles, 1977a; Hazell et al., 2003). Ponds form through scour of aggraded low-gradient drainage lines and are connected by shallow ephemeral channels or preferential flow paths across 'swampy meadows' (Mactaggart et al., 2008). This process is similar to small-scale chain-of-ponds on Mihi and Jacks Creeks in Chapter 4. A description of Deep Creek in central Victoria is of 'numerous 1–2 m deep and up to 15 m wide pools connected by narrower river sections, a form commonly referred to as chain-of-ponds or swampy meadows' (Cartwright and Morgenstern, 2016 p.10). However, the middle reach of this system, like the Mulwaree River (Chapter 2) and the lower Perry River (Zavadil and Ivezich, 2011), drains a relatively large catchment (>100 km^2) in a landscape position of laterally unconfined valleys with ponds that are up to 100 m in length with surface areas over 4000 m^2 (Figure 2). This presents two types of chains-of-ponds that have broadly similar planform characteristics, but occur at significantly different scales with different geomorphic structure and evolution and hydrological processes (Table 2).

Headwater chains-of-ponds are noted as a previously ubiquitous landform in many upland drainage lines, but landuse changes and direct modification has seen the loss of many of these systems (Eyles, 1977b; Prosser et al., 1994). Channel incision is the most common process in the shift from a discontinuous channel form and has been linked to land-clearing and over-grazing, and also direct modification to drain 'swampy' areas (Eyles, 1977a; Johnston and Brierley, 2006; Mould and Fryirs, 2017; Prosser, 1991).

Additional chain-of-ponds losses results from burial under sediment transferred from erosion (mainly gullies) that occurs upstream (Erskine and Melville, 2008). The chains-of-ponds that remain are of (geo)ecological significance as they provide habitat for species dependent on permanent (or longer-term), lentic water (Hazell et al., 2003) and are representative of pre-European small–medium sized rivers (Brierley et al., 2002; Eyles, 1977b; Rutherfurd et al., 2000).

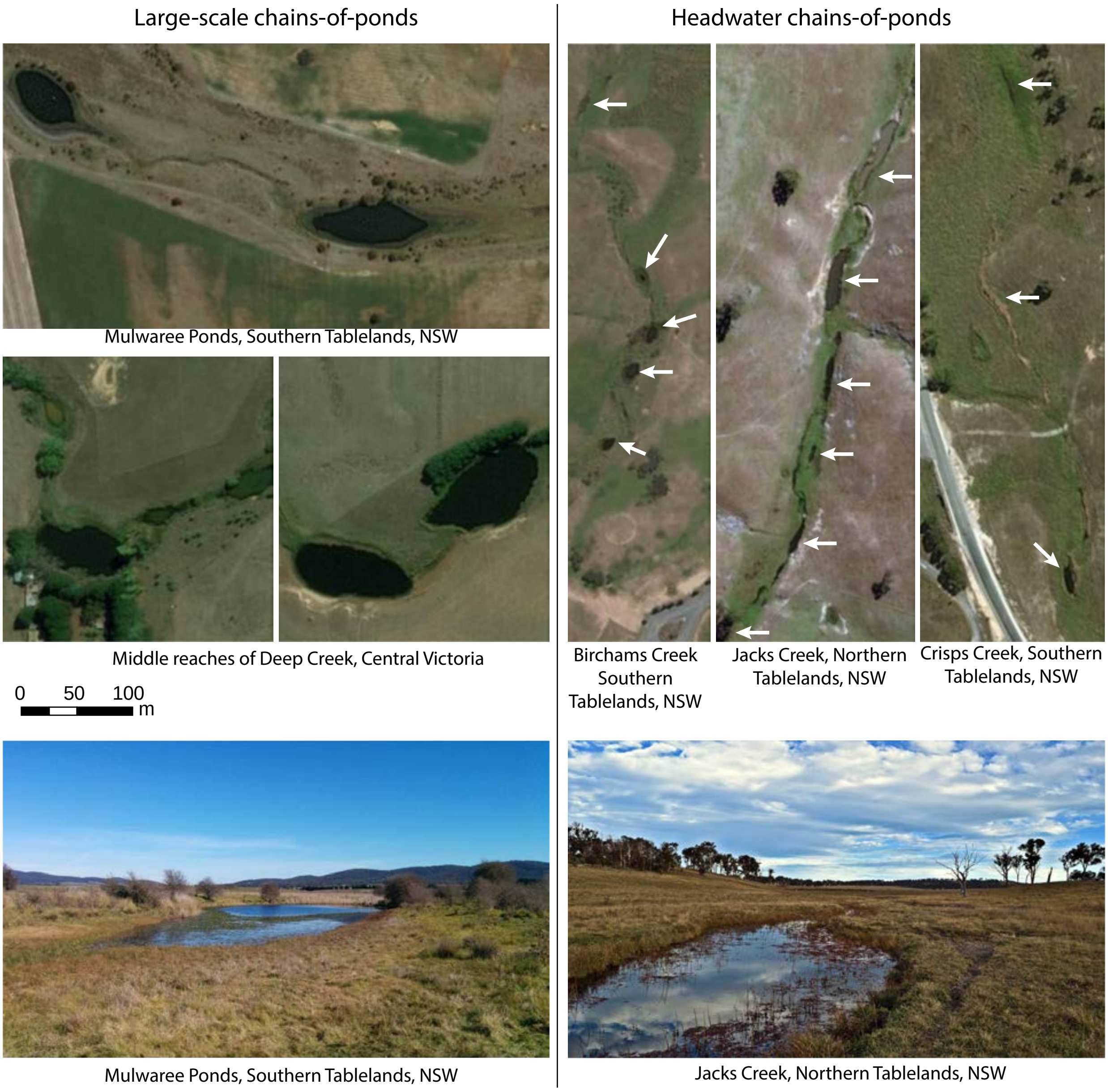

Figure 2. Pond size comparison of five chain-of-ponds in southeastern Australia. Images (all at the same scale) from ESRI Digital Globe-Vivid Australia 2015-2016. Images associated to previously studied locations of chain-of-ponds; Deep Creek (Cartwright and Morgenstern, 2016), Mulwaree Ponds (Chapter 2 and 3), Birchams Creek (Eyles, 1977a), Jacks Creek (Chapter 4) and Crisps Creek (Mould and Fryirs, 2017). Arrows show locations of the ponds in small-scale systems. Width of the pond on the lower left is ~50 m and on the lower right ~5 m.

Table 2. Ponds characteristics of small and large scale chains-of-ponds

	Large-scale	Small-scale
Example	Mulwaree River (Chapter 2)	Mihi Creek (Chapter 4)
Pond Size	500–13000 m^2	10–1000 m^2
Formation	Preservation of antecedent form after a threshold change in fluvial activity	Surface scour or in-channel deposition
Sensitivity (river type)*	Low	Low
Sensitivity (reach specific)*	Low–Moderate (I–II)	Low–High (I–III)
Timing of formation	Post-Last Glacial Maximum to Holocene	Holocene – possibly with multiple episodes of incision and aggradation

*Based on sensitivity analysis in Reid and Brierley (2015) for large-scale ponds and the assessment in chapter 4 for small-scale ponds

There is no research to date that describes the geomorphic structure and evolution of rarer large-scale chains-of-ponds, other than a mention by Eyles (1977b) that one of the ponds on the Mulwaree River was 11 m deep and may have form as a 'fixed bar' pond. Despite the conservation priority (e.g. Dunn, 2000), knowledge of their geographical extent, and hydro-geomorphic and ecological diversity remains limited. This reduces the capacity of land managers to conserve and rehabilitate these unique systems, and for their protection though inclusion in policy and legislation (see Aim 5).

The first aim of this thesis — to characterise the diverse geomorphic structure and function of chains-of-ponds — builds upon the existing literature that characterise the stratigraphy, morphology and controls on upland discontinuous rivers including upland swamps (Cowley et al., 2016; Fryirs et al., 2014a; Fryirs et al., 2014b; Fryirs et al., 2016), swampy meadows (Mactaggart et al., 2006; Prosser et al., 1994), cut-and-fill and valley fills (Erskine and Melville, 2008; Fryirs and Brierley, 1998; Johnston and Brierley, 2006; Wasson et al., 1998; Zierholz et al., 2001) and chains-of-ponds (Eyles, 1977a; Mould and Fryirs, 2017). The second aim — to assess the nature and timing of the late Quaternary evolution of chains-of-ponds — incorporates the existing evolutionary timing of fluvial systems across southeast Australia (e.g. Cohen and Nanson, 2007; Hesse et al., in review; Nanson et al., 2003; Page et al., 2009; Pietsch et al., 2013) to identify changes that are associated with the controls on chains-of-ponds and discontinuous systems more broadly.

Chapter 4 provided detailed stratigraphy and planform character of a diverse range of chain-of-ponds morphologies in varying stages of adjustment (or modification) since post-European landuse change. The small geographical extent of theses reaches means that they have very similar external forcing through the same climate and comparable catchment landuse. Thus it is possible to compare intrinsic controls on geomorphic change (e.g. alluvial valley-fill aggradation, pond formation and incision) relative to the only remaining, yet predictable, external variable of discharge that results from their differing catchment positions. Chapter 2 characterises the form and evolution of a large-scale chain-of-ponds system through analysis of the stratigraphy and OSL dating, identifying the form and timing of broad geomorphic assemblages and their controls on the formation of the present system.

Contribution of the research findings

This thesis provides four important contributions to the geomorphic understanding of discontinuous watercourses. Firstly, chapter 2 begins to fill the void of knowledge on these unique large scale chains-of-ponds by characterising their morphology and stratigraphy to elucidate the evolutionary and contemporary physical template upon which to build an understanding of the ecosystem function. This knowledge of the contemporary geomorphic structure is essential for both maintaining and restoring or repairing ecosystem function (Brierley and Fryirs, 2005; Corenblit et al., 2011; Hazell et al., 2003).

Secondly, rivers across the upland headwaters of southeastern Australia that are presently discontinuous have shown a general trend of declining fluvial activity and the vertical accretion of finer-grained sediments from the early–late Holocene. This has included a range of forms including swampy meadows (Prosser et al., 1994), valley fills (Eriksson et al., 2006; Fryirs and Brierley, 1998; Johnston and Brierley, 2006), peatlands (Nanson and Cohen, 2014), upland swamps (Fryirs et al., 2014a) and chains-of-ponds (Mould and Fryirs, 2017). Most show that sustained accretion has occurred over the past ~4 ka with others highlighting episodic gully incision followed by aggradation (Fryirs and Brierley, 1998; Prosser et al., 1994). This suggests that controls on form are due to long term climatic forcing combined with intrinsic thresholds, and do not necessarily preserve a fluvial archive of climatic change. The OSL ages at similar depths from two reaches on Mihi Creek (Chapter 4) show large differences in the timing since reworking and rates of deposition. The younger age (~1 ka) was from a high-energy planform-controlled downstream reach, while the older age (~18 ka) was from a low-energy upstream reach. This shows that while there has been a decline in energy since the Last Glacial Maximum, catchment position, intrinsic controls and threshold response play a more important role on the planform and stratigraphic architecture of headwater systems. This understanding of intrinsic controls on fluvial evolution will help assess recovery potential through forecasting future trajectories (Brierley and Fryirs, 2016; Fryirs and Brierley, 2016; Mould and Fryirs, 2017) and guide approaches to maintaining or restoring ecosystem function of discontinuous headwater systems in southeast Australia and similar systems internationally such as, dambos (Mäckel, 1973; von der Heyden, 2004) and arroyos (Bull, 1997; Cooke and Reeves, 1976) among other alluvial headwater streams (Wohl, 2017).

Thirdly, the long term evolution of the Mulwaree River shows that there have been large changes to the geomorphic structure, from a high-energy sand and gravel bed river to a fine-grained suspended-load discontinuous system, synchronous with climatic changes through the late Pleistocene and Holocene (Chapter 2). This response falls along a spectrum of hydro-geomorphic adjustments of rivers across southeastern Australia with the larger gaining rivers (those with increasing downstream discharge) typically maintaining channel continuity (Cohen and Nanson, 2008; Kermode et al., 2012) while some losing systems (those that receive little or no tributary input in their lower catchments) have undergone threshold changes resulting in anabranching or channel breakdown (Kemp, 2010; Pietsch et al., 2013; Ralph and Hesse, 2010). In all cases it is intrinsic controls that drive the responses, be it polycyclic terrace formation (Kermode et al., 2012) or floodplain expansion and losses to distributary channels (Pietsch and Nanson, 2011; Ralph and Hesse, 2010). The Mulwaree River has shown similar intrinsic controls that have exacerbated the late-Pleistocene and Holocene decline in fluvial activity, with the debouching of the river onto a broad and low-slope alluvial floodplain, dissipating energy and depositing sediment near the upstream extent (Rustomji and Pietsch, 2007). The antecedent control of pool location during the Mulwaree River's higher-energy phase has guided the establishment of exceptionally deep ponds that are beyond the capacity of the present river to create. This is seen through the preservation of geomorphic features from a higher-energy river, prior to decline in fluvial energy from both extrinsic and intrinsic factors (Chapter 2).This adds important insight to the range of non-linear responses (Phillips, 2006) through both intrinsic controls, such as well understood energy losses through an increase in effective valley width, but also more complex responses from the persistence of palaeo landforms (Brierley, 2010; Brunsden, 1993b). The contemporary geomorphic structure of this large-scale chain-of-ponds is a function of antecedent controls and geomorphic memory (Brierley, 2010; Brunsden, 1993b).

Lastly, the complexity of hydro-geomorphic response across different landscapes highlights the often unique and chaotic process (Phillips, 2003) of the evolution of the present fluvial form and reliant ecosystem. Unlike many smaller-scale discontinuous systems that have seen multiple phases of incision and aggregation through the Holocene, with some responding to post-European disturbance (Zierholz et al., 2001), the Mulwaree River and others like it (e.g. Deep Creek (Cartwright and Morgenstern, 2016)) carry additional significance as their unexpected form, once degraded, cannot be replaced.

Aim 3. Characterise the surface and subsurface hydrological processes and connectivity of chains-of-ponds

This aim is achieved by assessing the hydrological throughputs and the surface–subsurface interactions, using hydraulic gradients, radon and stable isotopes (δ^2H and $\delta^{18}O$), and identifying the influence of subsurface flows in maintaining pond water-levels during periods of flow cessation, which dominate the hydrograph. In addition, two-dimensional hydraulic modelling of streamflow is used to quantify the unit stream power (Wm^{-2}) and shear stress (Nm^{-2}) of small-scale chains-of-ponds with different planform and stratigraphic morphologies. Analysis of the results identifies the controlling longitudinal and planform characteristics that increase the likelihood of scour and incision, which are incorporated into an analysis of geomorphic sensitivity (Aim 4).

Background

While large- and small-scale ponds both have dichotomous states of high-flow and no-flow, their capacity to recharge from, and interact with, subsurface water can vary (Cartwright and Gilfedder, 2015; Hazell et al., 2003; Mould and Fryirs, 2017). Eyles (1977a) suggested that small-scale headwater systems possess clay substrates rendering them impervious to seepage, ensuring permanent sources of surface water. However, the banks of the ponds are of the same sediment as the adjacent valley-fills (Mould and Fryirs, 2017) with water tables remaining elevated for extended periods after rainfall in many swampy meadows (Mactaggart, 2008), enabling the influx of subsurface water to maintain pond levels despite evaporation. This connection varies depending on the water table or subsurface aquifer level, which is influenced by the timing and frequency of rainfall events (Jasechko et al., 2014). Recent investigations have characterised the groundwater inputs into a large-scale chain-of-ponds between 14% (at high flow) and 100% (during low flow) of the total discharge, but there is spatial variability with more shallow groundwater input into ponds near the bedrock margins, where there are steeper hydraulic gradients, and lower inputs into those in middle of the floodplain (Cartwright and Gilfedder, 2015).

Chains-of-ponds are susceptible to changes in hydrology due to anthropogenic landuse changes and direct modification (Eyles, 1977b; Mould and Fryirs, 2017; Wasson et al., 1998). Climate change is also likely to affect streamflow and vegetation structures in chains-of-ponds due to changes in the amount, intensity and variability of precipitation and increases in temperature, evaporation and evapotranspiration across southeastern Australia (Dowdy et al., 2015; Grose et al., 2015; Reinfelds et al., 2014). To understand how chains-of-ponds will respond, there needs to be an understanding of how the hydrology of a system influences their characteristic form and function.

The third aim of this thesis links to the first two through the interdependence of geomorphic structure, hydrological processes and their role in ecosystems function (Bellmore and Baxter, 2014; Malard et al., 2002; Poole et al., 2006; Thorp et al., 2010). These feedbacks are critical in understanding the physical form of discontinuous watercourses and how sensitive or resilient they are to hydrological change (Bragg and Tallis, 2001; Brierley et al., 1999; Bull, 1997; Church, 2002; Fryirs et al., 2014b; Fryirs et al., 2016; Wohl, 2017). Chapter 4 uses 2-D hydraulic modelling to identify the influence of overland flow on small-scale chains-of-ponds planform and pond characteristics (Aim 1, Chapter 4) and to assist in developing sensitivity metrics (Aim 4, Chapter 4). It also investigates the possible interactions of localised subsurface flows in maintaining pond water levels during periods of flow cessation. Research on the hydrological processes of large-scale chains-of-ponds using hydraulic gradients, radon and stable isotopes (δ^2H and $\delta^{18}O$) (Chapter 3) is used to quantify the surface–subsurface water interactions, and their significance in fluvial environments (Sophocleous, 2002) and groundwater dependent ecosystems (GDEs) (Kløve et al., 2011). There is also the goal of elucidating the hydro-geomorphic evolution of the Mulwaree River to develop a process that explains the preservation of antecedent landforms that influence the position and form of the large ponds.

Contribution of the research findings

As a companion to Chapter 2, Chapter 3 contributes to a scientific foundation for the hydrological processes of rare large-scale chains-of-ponds and in combination with their geomorphic structure builds a template for their ecological function. Surface–subsurface hydrological connectivity on the Mulwaree Ponds was weak during the stable isotope and radon sampling times with the ponds showing no clear signal of shallow groundwater inputs, but some flow from the ponds through the coarser gravel layers (Chapter 3). These system may behave more like the mid reaches of Deep Creek (Cartwright and Gilfedder, 2015) where the ponds in the middle of the floodplain received relatively small groundwater inputs compared to those on the valley margins due to steeper hydraulic gradients flowing from the hillslopes (Freeze and Cherry, 1979). This is seen in the Mulwaree River with steeper lateral hydraulic gradients from the east where the bedrock margin is closer compared to the west (Chapter 3). Therefore, any decline in the floodplain aquifer level, either through climatic drivers or groundwater extraction, will likely lower the water level in the ponds.

Groundwater recharge is vulnerable to decreases in rainfall, especially in winter (Jasechko et al., 2014), and increases in evaporation and evapotranspiration reduce antecedent soil moisture decreasing runoff and through-flow into the alluvial aquifer (Wood et al., 1990). Winter rainfall is predicted to decline in southeast Australia over the 21st century due to climate change, along with higher evaporation and evapotranspiration due to increased temperatures (Dowdy et al., 2015; Grose et al., 2015). This puts the Mulwaree River floodplain aquifer at risk of lower inputs and reduced water levels, thereby impacting pond water levels, base-flow inputs to downstream discharge, and pond and floodplain aquifer ecosystem function.

In smaller-scale headwater systems, the hydrological function varies in both surface and subsurface flows depending on their planform characteristics and sedimentary structure, and condition (e.g. intact or degraded). Results showing that there was no groundwater input to the ponds during the measurement period confirms that there is variability in the surface–subsurface connection in small-scale headwater systems. This is similar to the process described by Eyles (1977a) where the base of the ponds creates an aquitard with losses through evaporation. However, the reach from which the samples were taken contains much deeper alluvial sediments (>7 m) resulting in a deeper water table, and it is likely that other reaches intersect shallower water tables seen in other valley-fills (Mactaggart, 2008; Mould and Fryirs, 2017).

Maintaining the hydrological function of chains-of-ponds and similar discontinuous systems plays an important role in local ecosystem function and downstream hydrology. Risks to and from altered hydrological function are numerous:

- Urban development of headwater streams increases sediment influx followed by increases in discharges from impervious surfaces (Chin, 2006), which results in the two biggest risks to chain-of-ponds morphology; blanket sedimentation and incision (Erskine and Melville, 2008; Eyles, 1977a).
- Rural landuse changes have previously resulted in the loss of many discontinuous headwater systems (Eyles, 1977b; Mactaggart et al., 2006; Mould and Fryirs, 2017) showing that further modification of the valley floors that reduce effective valley widths or concentrate flows in drainage channels will continue the impairment or loss of chains-of-ponds.
- Incised streams in wetlands show significant declines in water tables (Daniels et al., 2008; Holden et al., 2011; Luscombe et al., 2016; Schilling et al., 2004) with reduced carbon storage (Cowley et al., 2017; Grand-Clement et al., 2013) and greater erosion from banks due to changes in vegetation structure (Micheli and Kirchner, 2002) and increases in outflow (Holden et al., 2006; Webb et al., 2017).
- The highly variable flow pattern in chains-of-ponds create soil profiles that do not remain saturated unlike other temperate higher-rainfall valley-fills, such as upland swamps (Fryirs et al., 2014b), and may allow for the infiltration and retention of rainfall and reduce downstream flood peaks (cf. Acreman and Holden, 2013).
- There are generally distinct processes in headwater streams due to the highly variable discharge and close coupling with hillslope processes (Gomi et al., 2002). Changes to hydro-geomorphic form and processes will impact in situ biotic structure and function, as seen in chain-of-ponds (Hazell et al., 2003) and other upland discontinuous systems in southeast Australia (Hose et al., 2014; Pemberton, 2005). The connectivity of these headwaters to higher order streams will also result in downstream changes to ecological function (Finn et al., 2011; Freeman et al., 2007; U.S. EPA., 2015).

Chapter 4 contributes to the understanding of hydrological processes and their influence on geomorphic form of small-scale chains-of-ponds. It does this by quantifying unit stream power thresholds for chain-of-ponds formation and identifying the longitudinal and planform characteristics that influence morphological change. The increase in discharge downstream overlaid the more important reach and localised planform factors that affected slope and effective valley width including: bedrock outcrops; elevated floodplains, terraces or incised channels that confine flows; and, low gradient hillslopes adjacent to the floodplain that allowed water, and therefore energy, from larger flows to dissipate over a greater effective valley width. The seven reaches cover the spectrum of discontinuity, from intact valley-fills through a range of pond densities to channel continuity. Hydraulic modelling produced a range of unit stream power values relative to flow annual exceedance probabilities (Chapter 4, Figure 23) that provide indicative limits within which chains-of-ponds can form and persist. This can help understand the likelihood of a reach enduring adjustments to any of the controls on unit stream power (discharge, slope and effective valley width) and can guide the protection and management of these ecosystems. These results are applicable to similar discontinuous systems in temperate climates that have variable flows and water tables, including swampy meadows (e.g. Mactaggart et al., 2006), dambos (e.g. Mäckel, 1973) and alluvial valley-fills (e.g. Fryirs and Brierley, 1998).

Aim 4. Develop quantitative metrics for assessing geomorphic sensitivity of chains-of-ponds

This is achieved by identifying the controls that lead to the hydro-geomorphic structure and function of chains-of-ponds along with changes that make them vulnerable to declining geomorphic condition and loss of discontinuity through incision. This includes; assessing the sensitivity of morphologically diverse reaches through historical analysis of geomorphic changes; and, quantifying suitable measurable pond and planform characteristics associated with geomorphic condition.

Background

Management of fluvial ecosystems requires an understanding of their hydro-geomorphic character and behaviour to be able to develop processes to protect, maintain or repair these important landscapes (Brierley and Fryirs, 2005). In this context, it is important to be able to predict the impacts on the character and behaviour of a river from landscape modification and climate change (DeFries and Eshleman, 2004; Fryirs and Brierley, 2016). A key geomorphic concept in understanding how a system behaves is sensitivity; i.e. the way in which it responds to a disturbance, relative to the magnitude of the disturbance (Downs and Gregory, 2004; Fryirs, 2017). Sensitivity assessments of geomorphic condition require quantifiable measures of adjustment and change (Reid and Brierley, 2015); however, unlike frequently studied fluvial forms (e.g. braided and meandering) there are no quantitative metrics of planform characteristics for discontinuous systems to meaningfully measure or indicate morphological change.

Chapter 4 uses the findings related to Aims 1 and 3 by incorporating the varied geomorphic character and hydrological processes of seven small-scale headwater chains-of-ponds with an assessment of their historical geomorphic changes. The analysis of measurable pond and reach characteristics, relative to unit stream power, which is made up of the individual controls of slope, effective valley width and discharge, highlights several useful metrics for assessing the geomorphic sensitivity of chains-of-ponds. The controls and measurable characteristics used were limited to those available from remotely sensed datasets (aerial imagery and LiDAR-derived digital elevation models) to enable its application and advancement across greater geographical extents.

Contribution of the research findings

Across the seven headwater reaches, there is a correlation between unit stream power and four measurable reach and pond morphological characteristics including; average pond depth, ponds per unit area, total pond surface area relative to reach valley floor area, and total pond length relative to valley length (Chapter 4). Of these, depth is difficult to measure and contains the greatest uncertainty, especially from remotely sensed datasets where water levels may impede accurate measurements. The other metrics are able to be identified from remotely sensed imagery. Outliers with high positive residuals for total pond lengths and areas relative to their valley floors, indicate reaches with greater incision relative to unit stream power; and, therefore are sensitive of change to a new river type (Brierley and Fryirs, 2016; Brunsden, 1993a). A high number of ponds per hectare indicates the reach's sensitivity to flow and disturbance events (Crozier, 1999; Fryirs, 2017; Phillips, 2006) due to preconditioning, resulting in localised scour and geomorphic change to a generally resilient landform. An increase in the number of ponds over time may highlight a reduction in resisting forces, such as changes to vegetation or surface sediment structure from landuse. The lack of correlation between unit stream power and the reach-mean elongation of ponds (length/$\sqrt{}$surface area) can be used to indicate morphological sensitivity (Brunsden, 1993b) or resilience. The utility of these metrics were then tested against an on ground and historical assessment of the geomorphic condition of the reaches confirming that the higher values corresponded to those in poorer condition or at risk of change.

These metrics provide a basis for the assessment of geomorphic sensitivity for small-scale chains-of-ponds (*sensu* Reid and Brierley, 2015) and a process for creating similar quantifiable metrics in other discontinuous watercourses, including the large-scale chains-of-ponds in Chapters 2 and 3.

Aim 5. Evaluate the recognition and integration of discontinuous watercourses in policy and law

This aim is achieved by examining legislation that defines and protects watercourses and by assessing the hydro-geomorphic limitations of the policy. Further investigation is undertaken to determine how this legislation is interpreted by the courts and elucidating the implications for managing chains-of-ponds and discontinuous watercourses more generally.

Background

There is an international call to protect small headwater streams, especially those displaying discontinuity of flow and channel form (Acuña et al., 2014; Acuña et al., 2017; Bauer et al., 2017; Creed et al., 2017; Davies et al., 2011; Meyer et al., 2007; Williams and Fryirs, 2016 – Appendix 4; Wohl, 2017), stemming from the uncertainty of their protection under policy and legislation (Doyle and Bernhardt, 2011; Kalen, 2007; Lamaro et al., 2007; Murphy, 2007; Taylor et al., 2011). Headwater streams comprise up to 70% of the global channel network (Downing et al., 2012) and, though they are discontinuous in flow and/or form, maintain hydrological and ecological connectivity to downstream rivers (Alexander et al., 2007; Bishop et al., 2008; Finn et al., 2011; Freeman et al., 2007; Gomi et al., 2002; Nadeau and Rains, 2007; U.S. EPA., 2015; Wohl, 2017).

The geomorphic processes of channel discontinuity have long been studied as part of the spectrum of fluvial processes (Bull, 1997; Cooke and Reeves, 1976; Eyles, 1977a; Fryirs and Brierley, 1998; Leopold and Miller, 1956; Mäckel, 1973; Prosser, 1991; Tooth, 2000; Young, 1986). This aim focusses on headwater streams that are at the thresholds of transforming from a undefined drainage line to an identifiably continuous channel with bed and banks, of which there are many examples from Australia (Eyles, 1977a; Fryirs and Brierley, 1998; Fryirs et al., 2014b; Nanson and Cohen, 2014; Prosser et al., 1994) and elsewhere (Bull, 1997; Cooke and Reeves, 1976; Mäckel, 1973).

The legal definitions of a watercourse (or similar terms) in Australia acknowledge, to some degree, flow variability as an accepted feature of fluvial environments; however, ecosystems with channel discontinuity are generally excluded. From a legal (and often binary) perspective that seeks to demarcate a clear boundary of watercourse inception, the identification of where a watercourse begins in rivers with temporal and spatial discontinuity can be difficult, as the form of the fluvial environment may not contain bed and banks or a clear high water mark (Mersel and Lichvar, 2014; Taylor et al., 2011; Wohl, 2017). This only becomes more complex when considering how the systems change over time.

Chapter 5 expands on existing studies that examine the definition of a watercourse and the implications for their legal protection in New South Wales (Davies et al., 2011; Lamaro et al., 2007; Taylor et al., 2011; Taylor and Stokes, 2005). This aims to clarify the social, cultural, scientific and legal understanding of a watercourse in Australia, with a focus on the perception and physical reality of discontinuity in fluvial ecosystems. Chapters 2–4 improve the scientific understating of the hydro-geomorphic structure function and evolution of chains-of-ponds to complement the growing body of knowledge on discontinuous and headwater systems that can inform legislation and be incorporated into policy frameworks.

Contribution of research findings

There has been significant loss or damage of many headwater streams in urban and rural environments through active valley-floor modification or changes to hydrological processes from landuse changes. This loss is due to a lack of understanding of the importance of these ecosystems, and the limitations and repercussions that the previous and current water management frameworks have had on discontinuous watercourses (Davies et al., 2011; Mactaggart et al., 2008; Taylor and Stokes, 2005). Better understanding of the hydro-geomorphological processes (Chapter 2, 3 and 4) and ecological functions of discontinuous systems, will facilitate ecosystem managers to develop workable strategies for protecting and managing systems that do not as yet receive the same legal status as other rivers (e.g. Calhoun et al., 2017). A scientific understanding of these systems needs to communicate the environmental, social and economic value of discontinuous watercourses to policy makers: this will be vital for obtaining recognition and protection of the full spectrum of fluvial environments, and having discontinuous systems incorporated into legislation and ecosystem management practices (Creed et al., 2017; Spierenburg, 2012).

6.2. Future research

There is a need for future research to incorporate the hydro-geomorphic processes and functions presented in this thesis as a physical template upon which to assess the much needed ecological structure and function of these unique ecosystems. This may include:

- Identifying and quantifying the surface and subsurface hydrological sources of the Mulwaree Ponds using radon through continuous sampling over multiple flow stages and tritium (*sensu* Cartwright and Gilfedder, 2015; Cartwright and Morgenstern, 2016). This will establish a more robust understanding hydrological function of large-scale chains-of-ponds and the impact on ecosystem function.
- Quantification of the geomorphic effectiveness of flows through small-scale chains-of-ponds by using total energy (integration of unit stream power through the duration of the flow) rather than isolated peaks (Costa and O'Connor, 1995; Lisenby et al., 2017). Similar to the mean and peak unit stream power results used in Chapter 4, total energy can be obtained through modelling. However, truly meaningful outputs will require a better understanding of stream discharge and variability from more measurements in headwater streams (Wohl, 2017).
- Development of functional indicators, to complement the geomorphic sensitivity analysis, for condition assessments of chains-of-ponds and similar discontinuous watercourses. For example, controls of geomorphic structure on water table fluctuations (Fryirs et al., 2014b) and carbon flux and storage (Cowley et al., 2017), or the use of bioindicators to measure ecological health (Leigh et al., 2013).
- There is a need for research on the ecological processes and functions within discontinuous fluvial ecosystems and their integration with the hydro-geomorphological processes to understand ecosystem process relationships and feedbacks (Costigan et al., 2017; Vaughan et al., 2009). Research must incorporate; the variability of vegetation structure and other biotic components, such as the habitat of aquatic fauna and their integrated food webs (Naiman et al., 2012); and, feedbacks that both the vegetation and fauna exert on geomorphic structure and hydrological processes of these systems (Corenblit et al., 2011; Gurnell et al., 2012). This knowledge will support the development of ecosystems function goals are achievable (Palmer, 2009; Poole, 2002).

6.3. Conclusions

This thesis has provided an understanding of the hydro-geomorphic structure, function and evolution of chains-of-ponds and demonstrated the need to protect, conserve and rehabilitate these unique ecosystems. It has shown the importance of the interrelationship between hydrological processes and geomorphic form, both in its present natural or modified state, and through time. The reach-specific sensitivity of these naturally resilient landforms provides a useful indicator for prioritisation, and in combination with the capacity to predict future trajectories, allows for appropriate management of chains-of-ponds. As highlighted in this thesis, fluvial ecosystems with discontinuous channels do not receive the same legal protection as other rivers and are therefore subject to a greater risk of impairment or loss. It is imperative that the scientific understanding of their importance, in their own right and as valuable contributors to the broader channel and riparian networks, is communicated to ensure their ongoing representation in the landscape.

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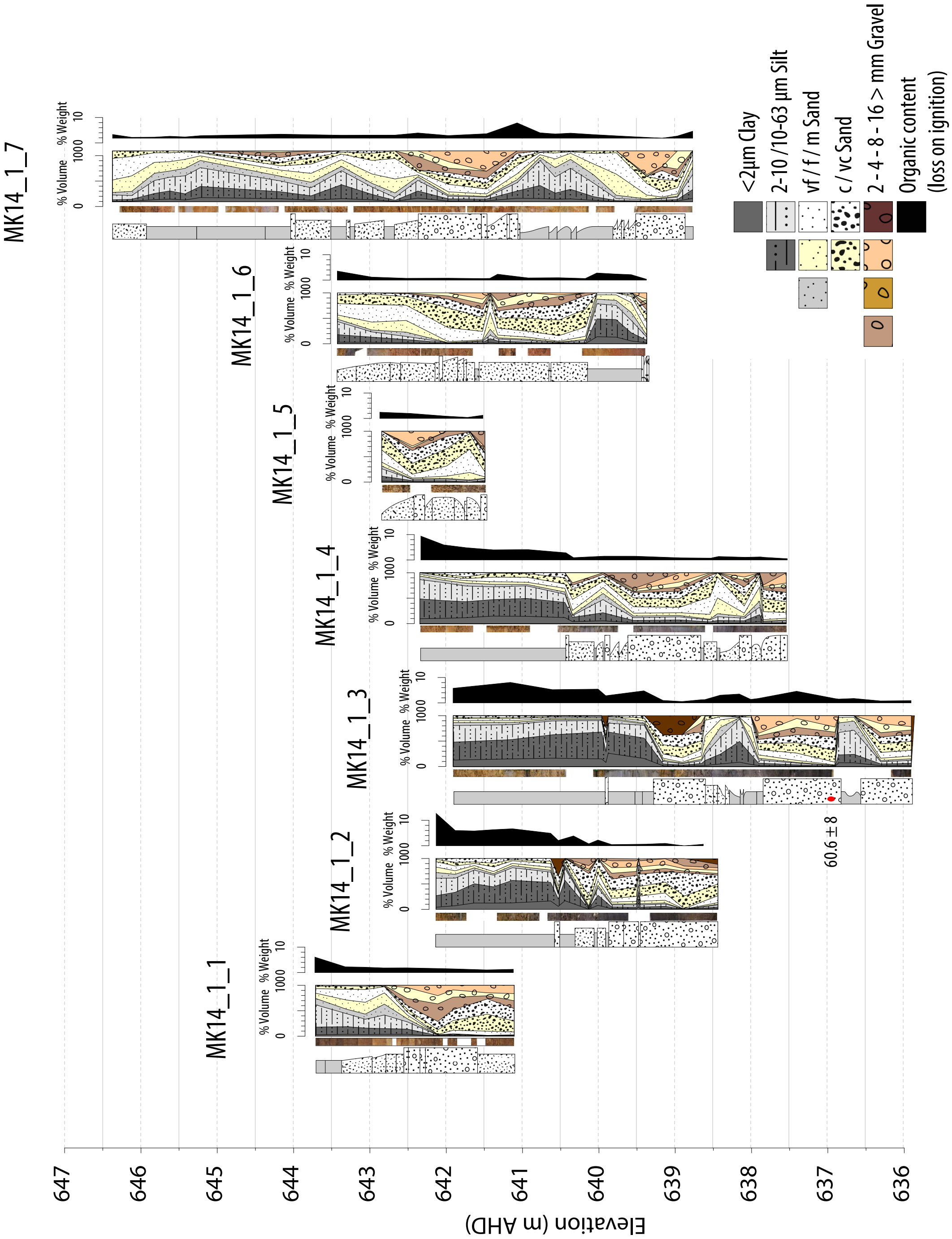
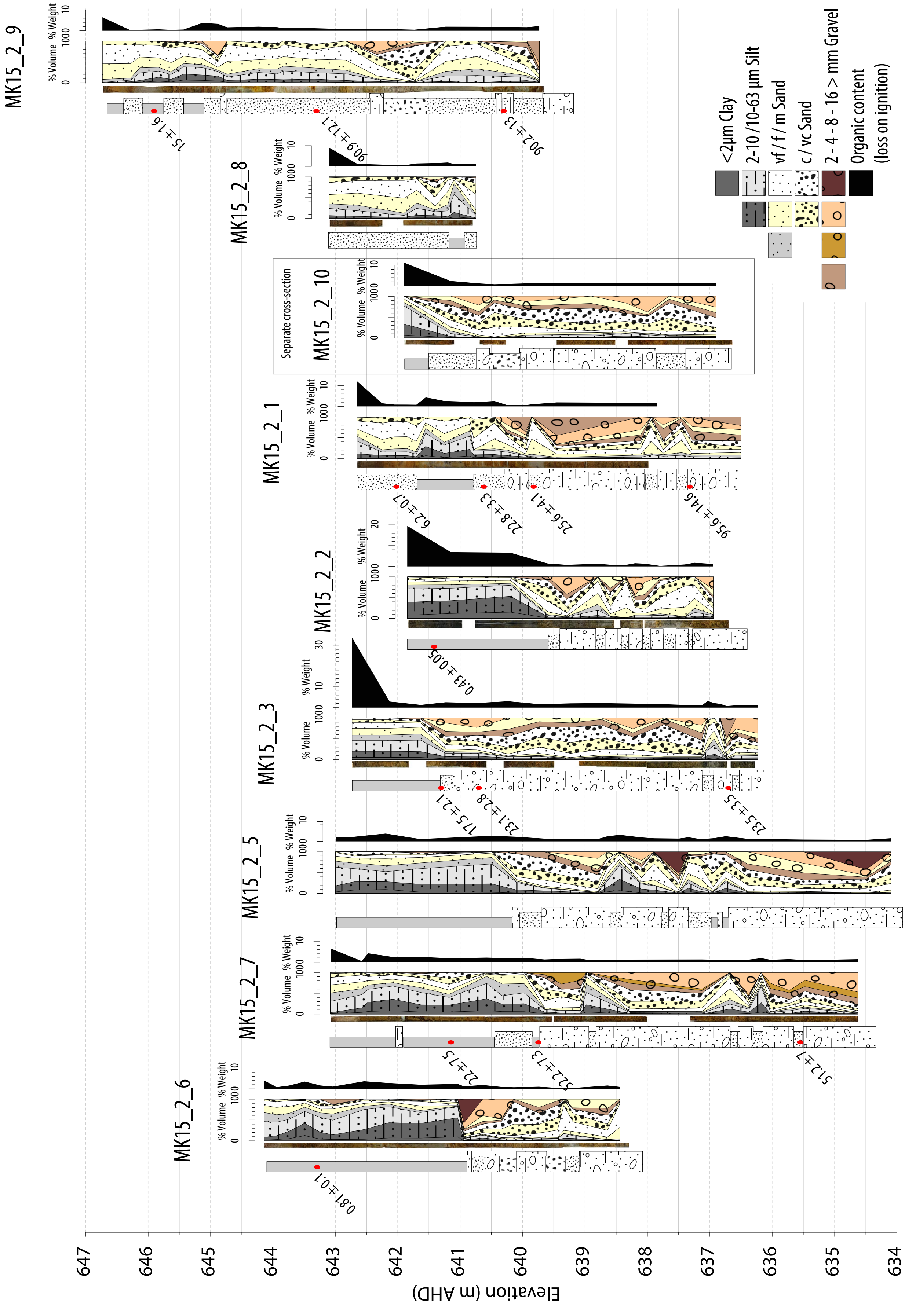
Appendices

Appendix 1. Supporting information for Chapter 2 – Sediment cores.

Stratigraphic columns, images of sediment, particle size analysis, loss on ignition results and OSL sampling locations and ages from cross-sections MK14_1 and MK15_2. Elevations relative to AHD




MK15_2_9
MK15_2_8
Separate cross-section
MK15_2_10
MK15_2_1
MK15_2_2
MK15_2_3
MK15_2_5
MK15_2_7
MK15_2_6
% Volume
% Weight
Elevation (m AHD)
<2µm Clay
2-10 /10-63 µm Silt
vf / f / m Sand
c / vc Sand
2 - 4 - 8 - 16 > mm Gravel
Organic content
(loss on ignition)

Appendix 2. Supporting information for Chapter 3 – Mulwaree River stable isotope samples

Stable isotope (δ^2H and $\delta^{18}O$) values from the Mulwaree River over three sampling periods. NT = not nested

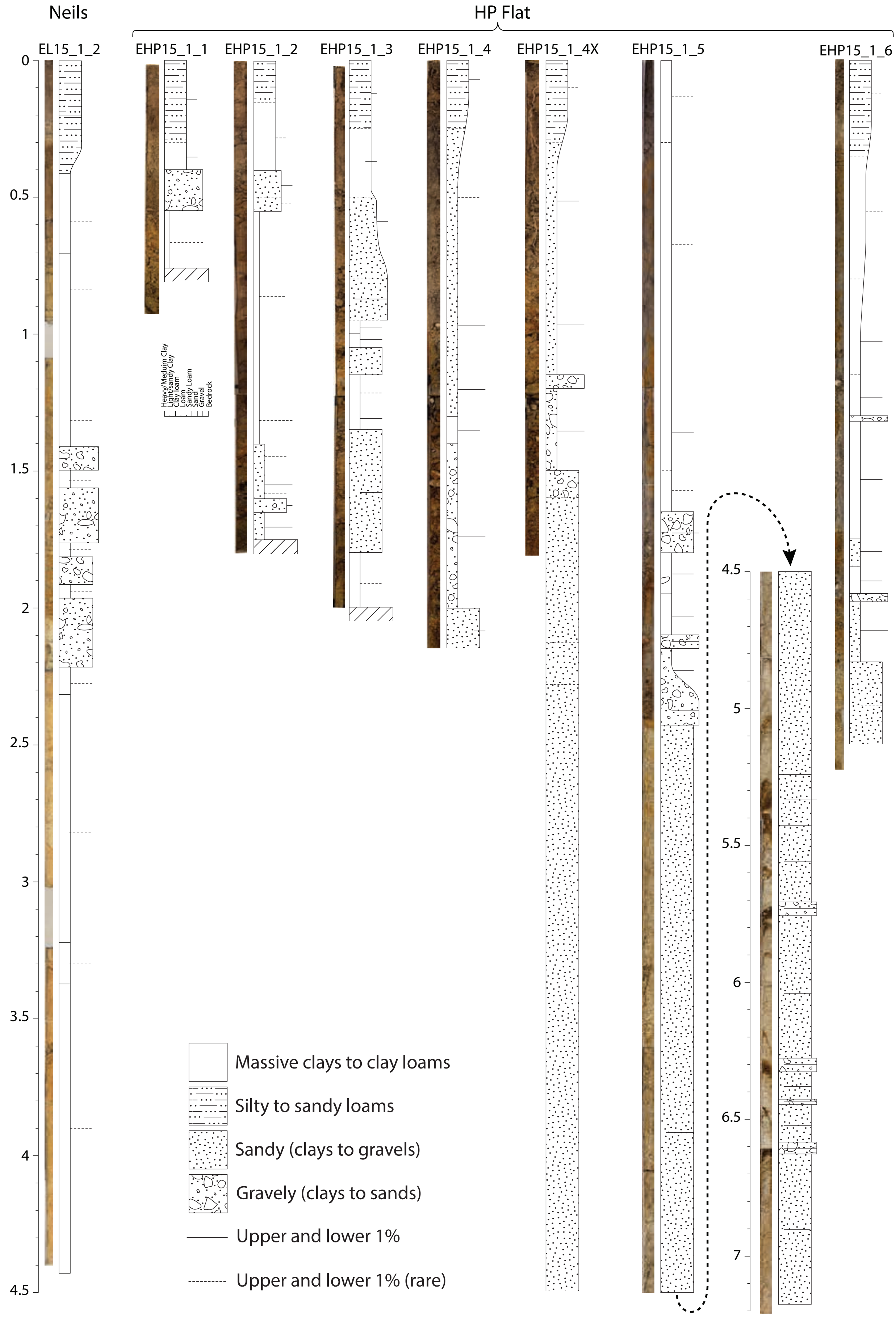
Sample ID	Sampling date	Sample type	(ANSTO) LIMS Number	δ^2H VSMOW (‰)		$\delta^{18}O$ VSMOW (‰)	
				Result	S.D.	Result	S.D.
August 2014							
MK14_1_0m	28/08/2014	Surface/pond	2014/0273I-1	-52.3		-8.23	
MK14_1_1m	28/08/2014	Surface/pond	2014/0273I-2	-51.6	0.52	-8.15	
MK14_1_1m	28/08/2014	Surface/pond	2014/0273I-2(2)	-52.4		NT	
MK14_1_2m	28/08/2014	Surface/pond	2014/0273I-3	-52.2		-8.20	
MK14_1_3m	28/08/2014	Surface/pond	2014/0273I-4	-52.6		-8.18	0.00
MK14_1_3m	28/08/2014	Surface/pond	2014/0273I-4(2)	NT		-8.18	
MK14_1_4m	28/08/2014	Surface/pond	2014/0273I-5	-52.8	0.87	-8.18	
MK14_1_4m	28/08/2014	Surface/pond	2014/0273I-5(2)	-51.6		NT	
MK14_1_5m	28/08/2014	Surface/pond	2014/0273I-6	-52.4		-8.16	
MK14_1_6m	28/08/2014	Surface/pond	2014/0273I-7	-52.7		-8.22	
MK14_1_7.2m	28/08/2014	Surface/pond	2014/0273I-8	-51.7		-8.19	0.03
MK14_1_7.2m	28/08/2014	Surface/pond	2014/0273I-8(2)	NT		-8.15	
MK14_1_2_50cm	28/08/2014	Groundwater	2014/0273I-9	-48.3	0.46	-7.49	
MK14_1_2_50cm	28/08/2014	Groundwater	2014/0273I-9(2)	-47.7		NT	
MK14_1_2_100cm	28/08/2014	Groundwater	2014/0273I-10	-46.4		-7.12	
MK14_1_2_150cm	28/08/2014	Groundwater	2014/0273I-11	-45.2		-6.91	
MK14_1_2_200cm	28/08/2014	Groundwater	2014/0273I-12	-37.2	0.49	-5.68	0.00
MK14_1_2_200cm	28/08/2014	Groundwater	2014/0273I-12(2)	-37.9		-5.67	
MK14_1_2_250cm	28/08/2014	Groundwater	2014/0273I-13	-35.1		-5.03	
April 2015							
MK14_1_2_80	16/04/2015	Groundwater	2015/0162O-1	-37.0	0.31	-5.24	0.03
MK14_1_2_100	16/04/2015	Groundwater	2015/0162O-2	-37.4	0.05	-5.33	0.02
MK14_1_2_150	16/04/2015	Groundwater	2015/0162O-3	-37.0	0.08	-5.25	0.02
MK14_1_2_200	16/04/2015	Groundwater	2015/0162O-4	-35.0	0.11	-4.99	0.02
MK14_1_2_250	16/04/2015	Groundwater	2015/0162O-5	-35.1	0.15	-5.01	0.02
MK14_1_4_90	16/04/2015	Groundwater	2015/0162O-6	-43.0	0.07	-6.82	0.03
MK14_1_4_120	16/04/2015	Groundwater	2015/0162O-7	-43.9	0.20	-7.02	0.03
MK14_1_4_150	16/04/2015	Groundwater	2015/0162O-8	-44.2	0.15	-7.05	0.03
MK14_1_4_200	16/04/2015	Groundwater	2015/0162O-9	-44.2	0.13	-7.07	0.01
MK15_2_1_200	16/04/2015	Groundwater	2015/0162O-10	-42.6	0.16	-6.59	0.04
MK15_2_1_200	16/04/2015	Groundwater	2015/0162O-10(2)	-42.6	0.18	-6.58	0.03
MK15_2_1_230	16/04/2015	Groundwater	2015/0162O-11	-43.5	0.07	-6.80	0.02
MK15_2_1_250	16/04/2015	Groundwater	2015/0162O-12	-43.7	0.10	-6.82	0.02
MK15_2_1_280	16/04/2015	Groundwater	2015/0162O-13	-44.4	0.04	-6.85	0.02
MK15_2_2_120	16/04/2015	Groundwater	2015/0162O-14	-37.0	0.24	-5.88	0.03
MK15_2_2_120	16/04/2015	Groundwater	2015/0162O-14(2)	-37.1	0.06	-5.88	0.04
MK15_2_2_150	16/04/2015	Groundwater	2015/0162O-15	-36.9	0.09	-5.79	0.02
MK15_2_2_180	16/04/2015	Groundwater	2015/0162O-16	-37.5	0.09	-5.98	0.02
MK15_2_2_210	16/04/2015	Groundwater	2015/0162O-17	-37.5	0.05	-5.95	0.02
MK15_2_2_240	16/04/2015	Groundwater	2015/0162O-18	-30.1	0.09	-4.49	0.01
MK15_2_3_245	16/04/2015	Groundwater	2015/0162O-19	-41.3	0.20	-6.58	0.03
MK15_2_3_300	16/04/2015	Groundwater	2015/0162O-20	-41.6	0.20	-6.60	0.02
MK15_2_3_350	16/04/2015	Groundwater	2015/0162O-21	-39.5	0.06	-6.20	0.02
MK15_2_3_400	16/04/2015	Groundwater	2015/0162O-22	-32.8	0.07	-4.91	0.01
MK15_2_7_250	16/04/2015	Groundwater	2015/0162O-23	-45.4	0.06	-7.31	0.02
MK15_2_7_300	16/04/2015	Groundwater	2015/0162O-24	-46.1	0.02	-7.44	0.02
MK15_2_7_350	16/04/2015	Groundwater	2015/0162O-25	-46.2	0.05	-7.45	0.01
MK14_1_P4-5_0	16/04/2015	Surface/pond	2015/0162O-26	-11.2	0.18	-0.80	0.02
MK14_1_P1_0	16/04/2015	Surface/pond	2015/0162O-27	-10.5	0.10	-1.12	0.02
MK14_1_P1_0	16/04/2015	Surface/pond	2015/0162O-27(2)	-10.4	0.16	-1.02	0.02
MK14_1_P1_50	16/04/2015	Surface/pond	2015/0162O-28	-10.5	0.06	-1.15	0.03
MK14_1_P1_100	16/04/2015	Surface/pond	2015/0162O-29	-10.3	0.02	-1.10	0.01
MK14_1_P1_200	16/04/2015	Surface/pond	2015/0162O-30	-10.3	0.07	-1.09	0.01
MK14_1_P1_300	16/04/2015	Surface/pond	2015/0162O-31	-10.9	0.25	-1.20	0.02
MK14_1_P1_400	16/04/2015	Surface/pond	2015/0162O-32	-11.1	0.08	-1.23	0.02
MK14_1_P1_500	16/04/2015	Surface/pond	2015/0162O-33	-11.1	0.05	-1.24	0.02

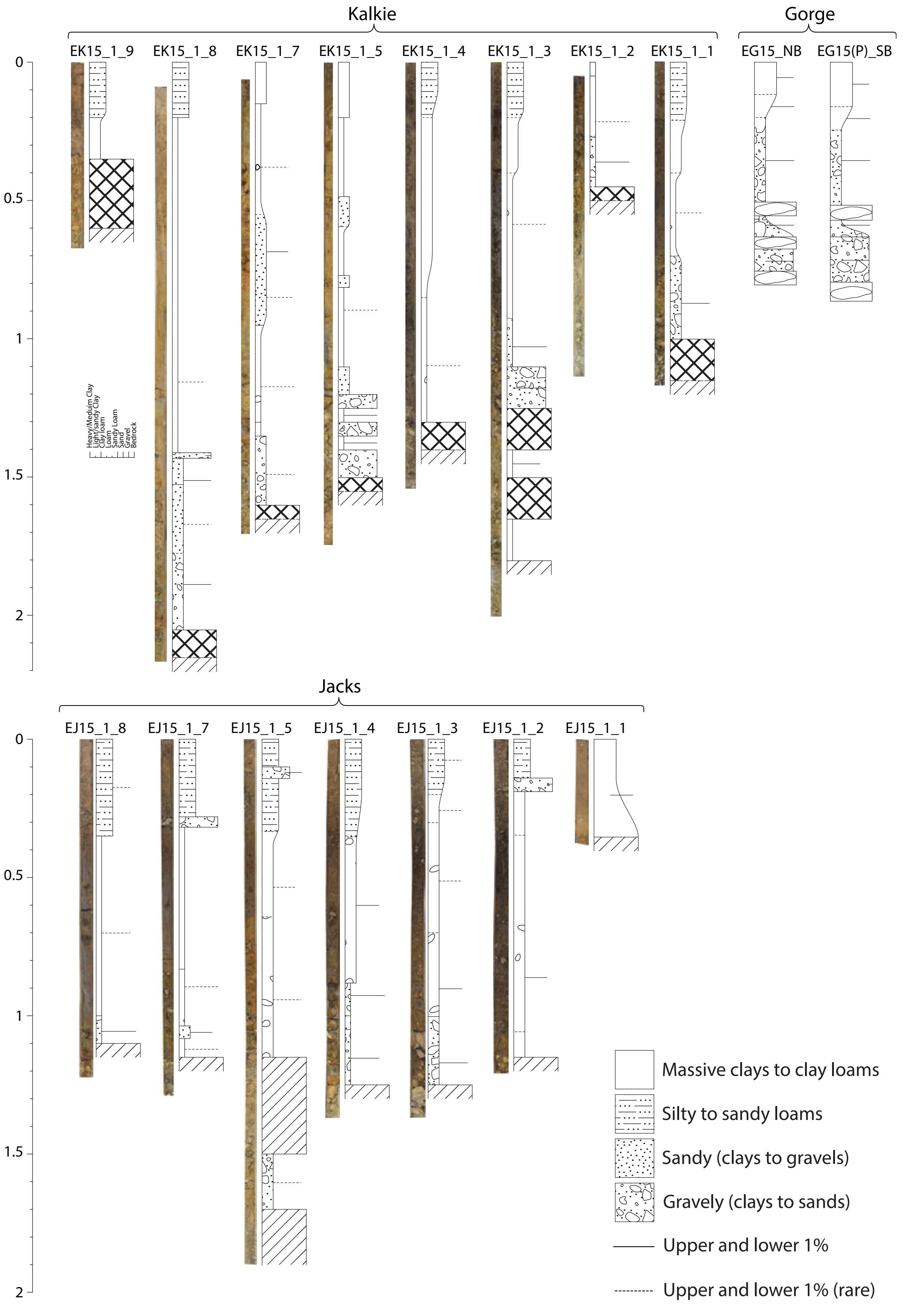
Sample ID	Sampling date	Sample type	(ANSTO) LIMS Number	δ^{2}H VSMOW (‰)		δ^{18}O VSMOW (‰)	
				Result	S.D.	Result	S.D.
April 2015 continued							
MK14_1_P2_0	16/04/2015	Surface/pond	2015/0162O-34	-11.6	0.05	-1.27	0.03
MK14_1_P2_50	16/04/2015	Surface/pond	2015/0162O-35	-11.6	0.03	-1.29	0.01
MK14_1_P2_100	16/04/2015	Surface/pond	2015/0162O-36	-11.7	0.03	-1.28	0.02
MK14_1_P2_200	16/04/2015	Surface/pond	2015/0162O-37	-12.1	0.06	-1.37	0.02
MK14_1_P2_300	16/04/2015	Surface/pond	2015/0162O-38	-12.4	0.16	-1.37	0.03
MK14_1_P2_400	16/04/2015	Surface/pond	2015/0162O-39	-12.2	0.08	-1.39	0.01
MK14_1_P2_400	16/04/2015	Surface/pond	2015/0162O-39(2)	-12.4	0.05	-1.38	0.02
MK14_1_P2_500	16/04/2015	Surface/pond	2015/0162O-40	-12.2	0.04	-1.38	0.01
MK14_1_P2_600	16/04/2015	Surface/pond	2015/0162O-41	-12.7	0.07	-1.47	0.01
MK14_1_P2_700	16/04/2015	Surface/pond	2015/0162O-42	-13.0	0.05	-1.50	0.02
MK14_1_P3_0	16/04/2015	Surface/pond	2015/0162O-43	-5.9	0.06	-0.31	0.01
MK14_1_P3_50	16/04/2015	Surface/pond	2015/0162O-44	-5.8	0.05	-0.30	0.03
MK14_1_P3_100	16/04/2015	Surface/pond	2015/0162O-45	-5.8	0.03	-0.31	0.01
MK14_1_P3_200	16/04/2015	Surface/pond	2015/0162O-46	-6.2	0.04	-0.38	0.01
MK14_1_P3_300	16/04/2015	Surface/pond	2015/0162O-47	-6.4	0.11	-0.40	0.03
MK14_1_P3_400	16/04/2015	Surface/pond	2015/0162O-48	-6.4	0.05	-0.41	0.02
MK14_1_P3_400	16/04/2015	Surface/pond	2015/0162O-48(2)	-6.7	0.16	-0.44	0.03
MK14_1_P3_500	16/04/2015	Surface/pond	2015/0162O-49	-6.7	0.05	-0.48	0.01
MK14_1_P4_0	16/04/2015	Surface/pond	2015/0162O-50	-15.5	0.03	-1.90	0.01
MK14_1_P4_50	16/04/2015	Surface/pond	2015/0162O-51	-15.5	0.21	-1.90	0.02
MK14_1_P4_100	16/04/2015	Surface/pond	2015/0162O-52	-15.6	0.08	-1.91	0.01
MK14_1_P4_200	16/04/2015	Surface/pond	2015/0162O-53	-16.2	0.12	-2.03	0.03
MK14_1_P4_300	16/04/2015	Surface/pond	2015/0162O-54	-16.0	0.10	-1.98	0.03
MK14_1_P4_400	16/04/2015	Surface/pond	2015/0162O-55	-16.0	0.04	-2.00	0.02
MK14_1_P4_500	16/04/2015	Surface/pond	2015/0162O-56	-16.6	0.10	-2.09	0.02
MK14_1_P4_600	16/04/2015	Surface/pond	2015/0162O-57	-18.4	0.22	-2.43	0.03
MK14_1_P4_700	16/04/2015	Surface/pond	2015/0162O-58	-35.3	0.11	-5.34	0.02
MK14_1_P4_730	16/04/2015	Surface/pond	2015/0162O-59	-37.1	0.09	-5.71	0.01
MK14_1_P4_730	16/04/2015	Surface/pond	2015/0162O-59(2)	-37.2	0.14	-5.70	0.01
MK14_1_P5_0	16/04/2015	Surface/pond	2015/0162O-60	-5.6	0.15	-0.15	0.01
MK14_1_P5_50	16/04/2015	Surface/pond	2015/0162O-61	-5.6	0.11	-0.15	0.01
MK14_1_P5_100	16/04/2015	Surface/pond	2015/0162O-62	-5.6	0.07	-0.14	0.02
MK14_1_P5_200	16/04/2015	Surface/pond	2015/0162O-63	-6.1	0.04	-0.22	0.01
MK14_1_P5_300	16/04/2015	Surface/pond	2015/0162O-64	-6.4	0.14	-0.30	0.03
MK14_1_P5_360	16/04/2015	Rainfall	2015/0162O-65	-22.4	0.08	-3.00	0.01
MK15_2_RAIN A	16/04/2015	Rainfall	2015/0162O-66	-14.2	0.06	-3.40	0.02
MK15_2_RAIN B	16/04/2015	Rainfall	2015/0162O-67	-14.4	0.08	-3.41	0.03
MK15_2_RAIN C	16/04/2015	Rainfall	2015/0162O-68	-13.3	0.12	-3.22	0.03
MK15_2_RAIN C	16/04/2015	Rainfall	2015/0162O-68(2)	-13.5	0.22	-3.24	0.02
MK14_1_P2_100A	16/04/2015	Surface/pond	2015/0162O-71	-11.6	0.11	-1.31	0.02
MK14_1_P2_500A	16/04/2015	Surface/pond	2015/0162O-72	-12.2	0.17	-1.38	0.07
MK14_1_2_80A	16/04/2015	Groundwater	2015/0162O-73	-36.9	0.17	-5.26	0.06
MK14_1_2_100A	16/04/2015	Groundwater	2015/0162O-74	-37.0	0.64	-5.33	0.06
MK14_1_2_100A	16/04/2015	Groundwater	2015/0162O-74(2)	-37.2	0.20	-5.26	0.03
MK14_1_2_200A	16/04/2015	Groundwater	2015/0162O-75	-34.5	0.11	-4.98	0.03
MK14_1_2_200A	16/04/2015	Groundwater	2015/0162O-75(2)	-34.6	0.09	-4.95	0.01
MK15_2_2_180A	16/04/2015	Groundwater	2015/0162O-76	-37.1	0.24	-5.83	0.07
MK15_2_7_300A	16/04/2015	Groundwater	2015/0162O-77	-46.0	0.06	-7.48	0.02
October 2015							
MK15_2_1_170/10	27/10/2015	Groundwater	2015/0368O-1	-42.9	0.20	-6.72	0.03
MK15_2_1_170/10	27/10/2015	Groundwater	2015/0368O-1(2)	-43.0	0.10	-6.84	0.03
MK15_2_1_220/10	27/10/2015	Groundwater	2015/0368O-2	-43.6	0.20	-6.78	0.03
MK15_2_1_270/10	27/10/2015	Groundwater	2015/0368O-3	-42.6	0.10	-6.72	0.02
MK15_2_2_100/10	27/10/2015	Groundwater	2015/0368O-4	-37.7	0.30	-6.06	0.05
MK15_2_2_150/10	27/10/2015	Groundwater	2015/0368O-5	-38.8	0.30	-6.19	0.05
MK15_2_2_200/10	27/10/2015	Groundwater	2015/0368O-6	-39.2	0.40	-6.27	0.07
MK15_2_2_250/10	27/10/2015	Groundwater	2015/0368O-7	-38.0	0.30	-6.07	0.04
MK15_2_2_100/10-2	28/10/2015	Groundwater	2015/0368O-8	-38.8	0.30	-6.17	0.02
MK15_2_2_150/10-2	28/10/2015	Groundwater	2015/0368O-9	-39.0	0.30	-6.25	0.06
MK15_2_2_200/10-2	28/10/2015	Groundwater	2015/0368O-10	-39.6	0.30	-6.34	0.04
MK15_2_3_250/10	27/10/2015	Groundwater	2015/0368O-11	-42.2	0.30	-6.75	0.03

Sample ID	Sampling date	Sample type	(ANSTO) LIMS Number	δ²H VSMOW (‰)		δ¹⁸O VSMOW (‰)	
				Result	S.D.	Result	S.D.
October 2015 continued							
MK15_2_3_300/10	27/10/2015	Groundwater	2015/0368O-12	-42.0	0.10	-6.71	0.03
MK15_2_7_250/10	27/10/2015	Groundwater	2015/0368O-13	-43.4	0.50	-7.19	0.09
MK15_2_7_300/10	27/10/2015	Groundwater	2015/0368O-14	-43.1	0.40	-7.23	0.06
MK15_2_7_300/10	27/10/2015	Groundwater	2015/0368O-14(2)	-43.2	0.20	-7.26	0.03
MK15_2_7_350/10	27/10/2015	Groundwater	2015/0368O-15	-43.2	0.50	-7.18	0.10
MK15_2_10_130/10	27/10/2015	Groundwater	2015/0368O-16	-37.2	0.50	-6.32	0.07
MK14_1_2_50/10	27/10/2015	Groundwater	2015/0368O-17	-18.9	0.50	-2.74	0.08
MK14_1_2_100/10	27/10/2015	Groundwater	2015/0368O-18	-16.6	0.10	-2.33	0.04
MK14_1_2_130/10	27/10/2015	Groundwater	2015/0368O-19	-16.2	0.01	-2.21	0.03
MK14_1_3_0/10	27/10/2015	Groundwater	2015/0368O-20	-20.7	0.30	-2.90	0.06
MK14_1_3_50/10	27/10/2015	Groundwater	2015/0368O-21	-22.4	0.20	-3.24	0.02
MK14_1_3_100/10	27/10/2015	Groundwater	2015/0368O-22	-23.8	0.30	-3.48	0.03
MK14_1_3_150/10	27/10/2015	Groundwater	2015/0368O-23	-24.4	0.40	-3.59	0.05
MK14_1_3_150/10	27/10/2015	Groundwater	2015/0368O-23(2)	-24.6	0.20	-3.62	0.07
MK14_1_5_140/10	27/10/2015	Groundwater	2015/0368O-24	-31.9	0.50	-5.80	0.03
MK14_P1_0/10	27/10/2015	Surface/pond	2015/0368O-25	-22.6	0.40	-3.20	0.04
MK14_P1_100/10	27/10/2015	Surface/pond	2015/0368O-26	-22.9	0.30	-3.31	0.05
MK14_P1_200/10	27/10/2015	Surface/pond	2015/0368O-27	-23.0	0.40	-3.28	0.05
MK14_P1_300/10	27/10/2015	Surface/pond	2015/0368O-28	-22.6	0.30	-3.24	0.05
MK14_P1_400/10	27/10/2015	Surface/pond	2015/0368O-29	-27.9	0.30	-4.16	0.05
MK14_P1_500/10	27/10/2015	Surface/pond	2015/0368O-30	-29.2	0.30	-4.41	0.04
MK14_P1_600/10	27/10/2015	Surface/pond	2015/0368O-31	-29.5	0.30	-4.52	0.04
MK14_P2_0/10	27/10/2015	Surface/pond	2015/0368O-32	-23.6	0.40	-3.42	0.02
MK14_P2_100/10	27/10/2015	Surface/pond	2015/0368O-33	-23.7	0.30	-3.42	0.03
MK14_P2_200/10	27/10/2015	Surface/pond	2015/0368O-34	-26.6	0.20	-4.01	0.04
MK14_P2_300/10	27/10/2015	Surface/pond	2015/0368O-35	-31.3	0.50	-4.86	0.07
MK14_P2_400/10	27/10/2015	Surface/pond	2015/0368O-36	-32.1	0.10	-5.02	0.03
MK14_P2_400/10	27/10/2015	Surface/pond	2015/0368O-36(2)	-32.1	0.10	-4.96	0.03
MK14_P2_500/10	27/10/2015	Surface/pond	2015/0368O-37	-32.1	0.40	-4.99	0.04
MK14_P2_600/10	27/10/2015	Surface/pond	2015/0368O-38	-32.4	0.40	-5.08	0.03
MK14_P2_700/10	27/10/2015	Surface/pond	2015/0368O-39	-32.5	0.30	-5.09	0.03
MK14_P3_0/10	27/10/2015	Surface/pond	2015/0368O-40	-23.7	0.20	-3.43	0.04
MK14_P3_0/10	27/10/2015	Surface/pond	2015/0368O-40(2)	-23.9	0.30	-3.46	0.05
MK14_P3_100/10	27/10/2015	Surface/pond	2015/0368O-41	-23.4	0.30	-3.37	0.03
MK14_P3_200/10	27/10/2015	Surface/pond	2015/0368O-42	-23.7	0.20	-3.44	0.01
MK14_P3_300/10	27/10/2015	Surface/pond	2015/0368O-43	-25.9	0.30	-3.90	0.05
MK14_P3_400/10	27/10/2015	Surface/pond	2015/0368O-44	-29.7	0.30	-4.52	0.04
MK14_P3_500/10	27/10/2015	Surface/pond	2015/0368O-45	-31.0	0.20	-4.77	0.03
MK14_P4_0/10	27/10/2015	Surface/pond	2015/0368O-46	-24.6	0.20	-3.58	0.03
MK14_P4_100/10	28/10/2015	Surface/pond	2015/0368O-47	-24.0	0.20	-3.44	0.02
MK14_P4_200/10	28/10/2015	Surface/pond	2015/0368O-48	-24.4	0.20	-3.56	0.03
MK14_P4_300/10	28/10/2015	Surface/pond	2015/0368O-49	-27.8	0.10	-4.15	0.04
MK14_P4_400/10	28/10/2015	Surface/pond	2015/0368O-50	-31.6	0.10	-4.91	0.02
MK14_P4_500/10	28/10/2015	Surface/pond	2015/0368O-51	-32.1	0.30	-4.98	0.03
MK14_P4_600/10	28/10/2015	Surface/pond	2015/0368O-52	-32.1	0.30	-4.97	0.03
MK14_P4_700/10	28/10/2015	Surface/pond	2015/0368O-53	-31.9	0.10	-4.84	0.03
MK14_P4_700/10	28/10/2015	Surface/pond	2015/0368O-53(2)	-31.9	0.10	-4.93	0.01
MK14_P4_730/10	28/10/2015	Surface/pond	2015/0368O-54	-31.5	0.30	-4.82	0.03
MK14_P4/5_0/10	27/10/2015	Surface/pond	2015/0368O-55	-22.1	0.10	-3.09	0.02

Appendix 3. Supporting information for Chapter 4 – Sediment cores

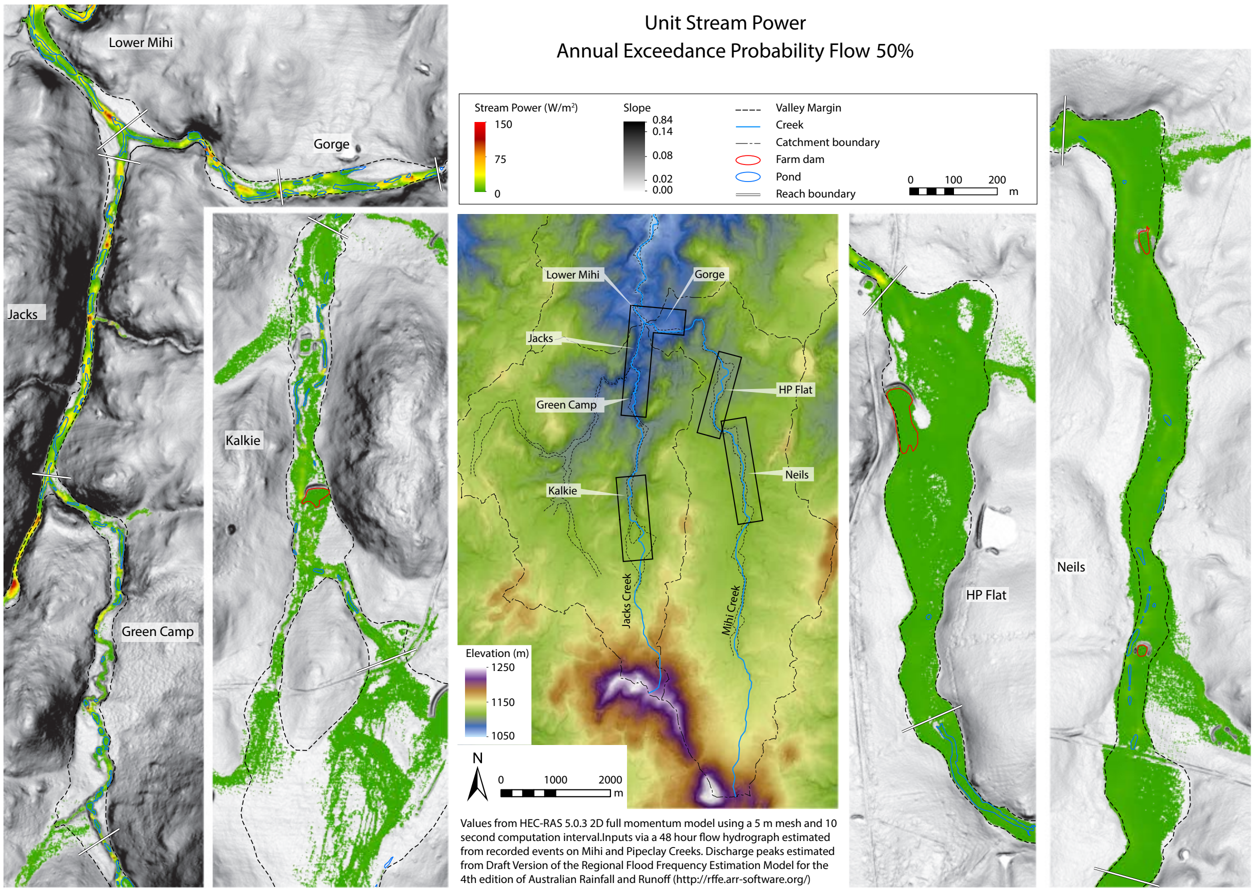
Stratigraphic columns and images of sediment cores from the Northern Tablelands field sites on Mihi and Jacks Creek

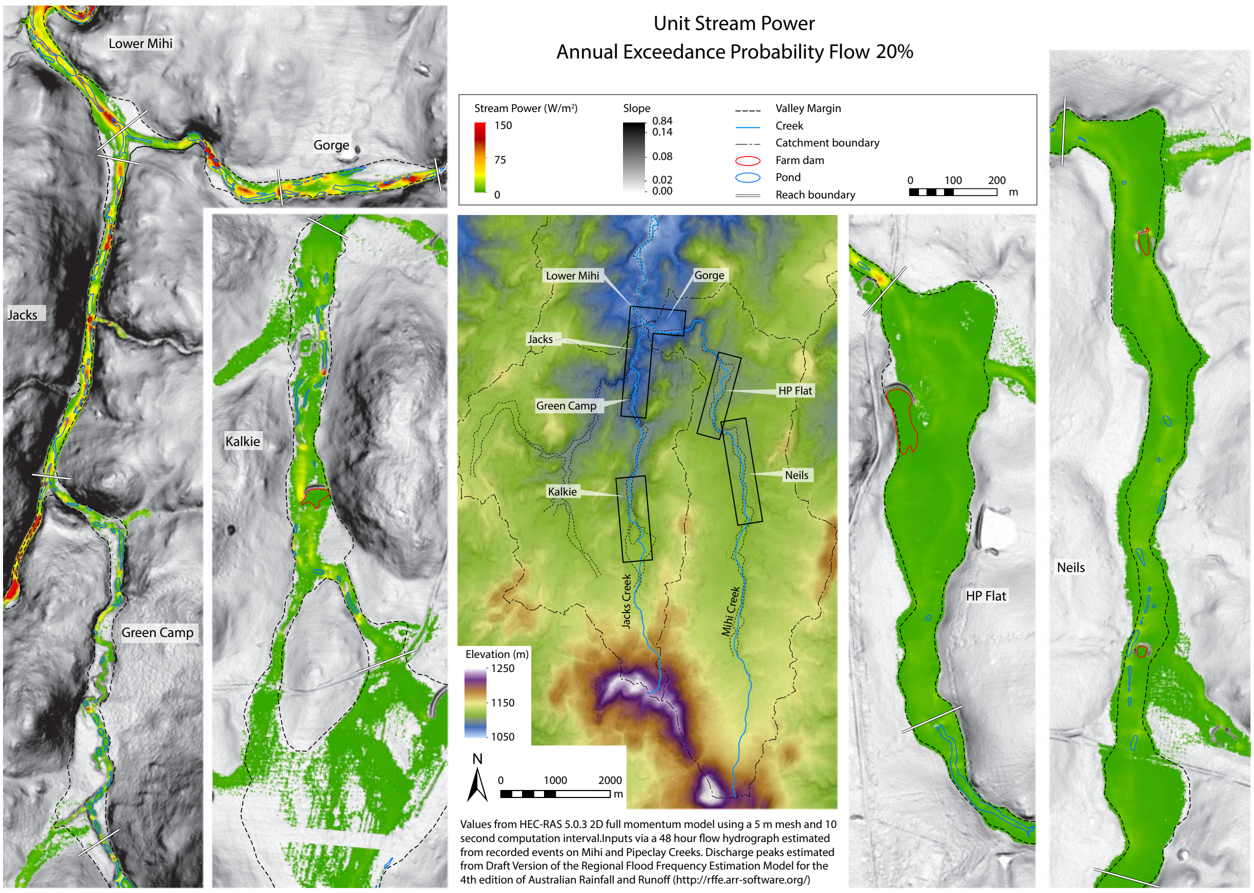




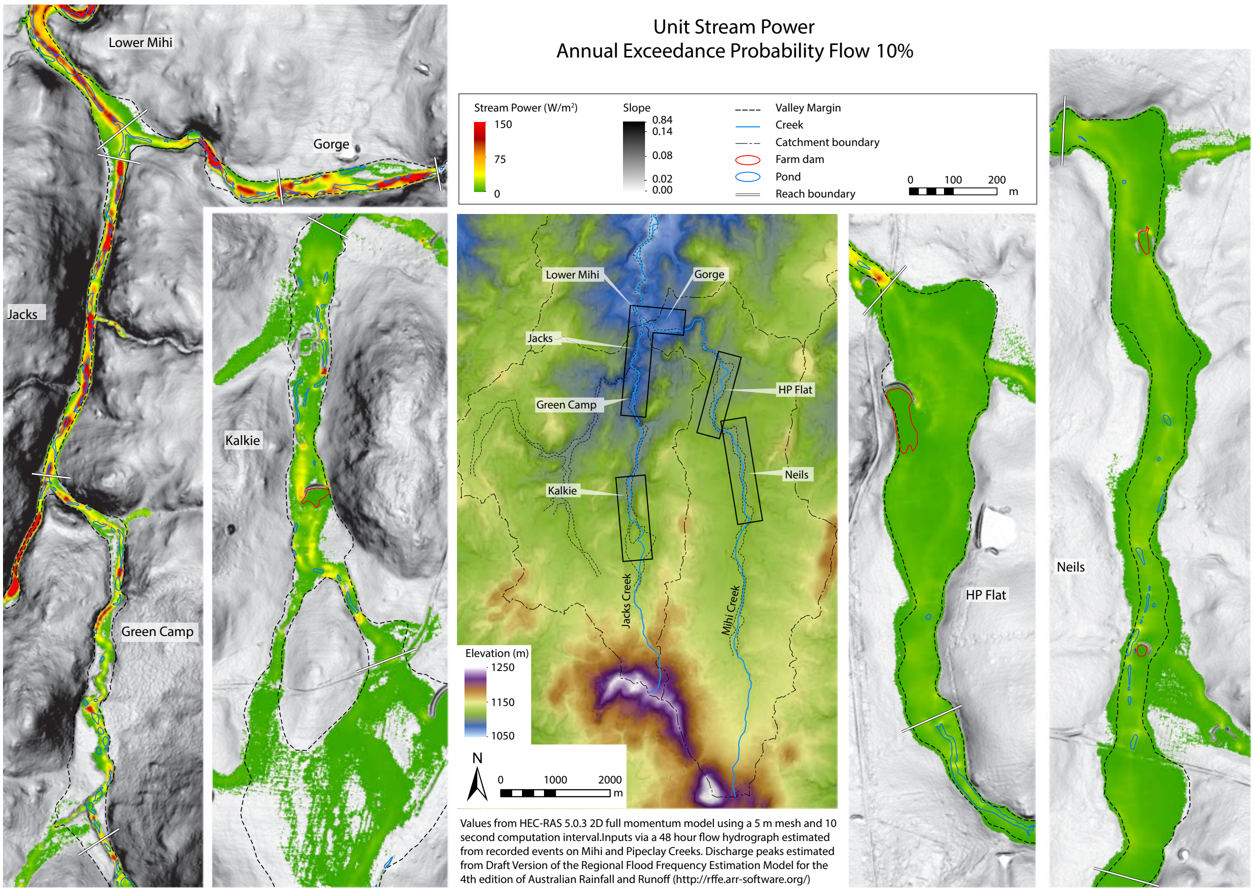
Kalkie
Gorge
EK15_1_9
EK15_1_8
EK15_1_7
EK15_1_5
EK15_1_4
EK15_1_3
EK15_1_2
EK15_1_1
EG15_NB
EG15(P)_SB
0
0.5
1
1.5
2
Heavy/Meduim Clay
Light/sandy Clay
Clay loam
Loam
Sandy Loam
Sand
Gravel
Bedrock
Jacks
EJ15_1_8
EJ15_1_7
EJ15_1_5
EJ15_1_4
EJ15_1_3
EJ15_1_2
EJ15_1_1
0
0.5
1
1.5
2
Massive clays to clay loams
Silty to sandy loams
Sandy (clays to gravels)
Gravely (clays to sands)
Upper and lower 1%
Upper and lower 1% (rare)

Appendix 4. Supporting information for Chapter 4 – Unit Stream Power and Shear Stress Modelling Results



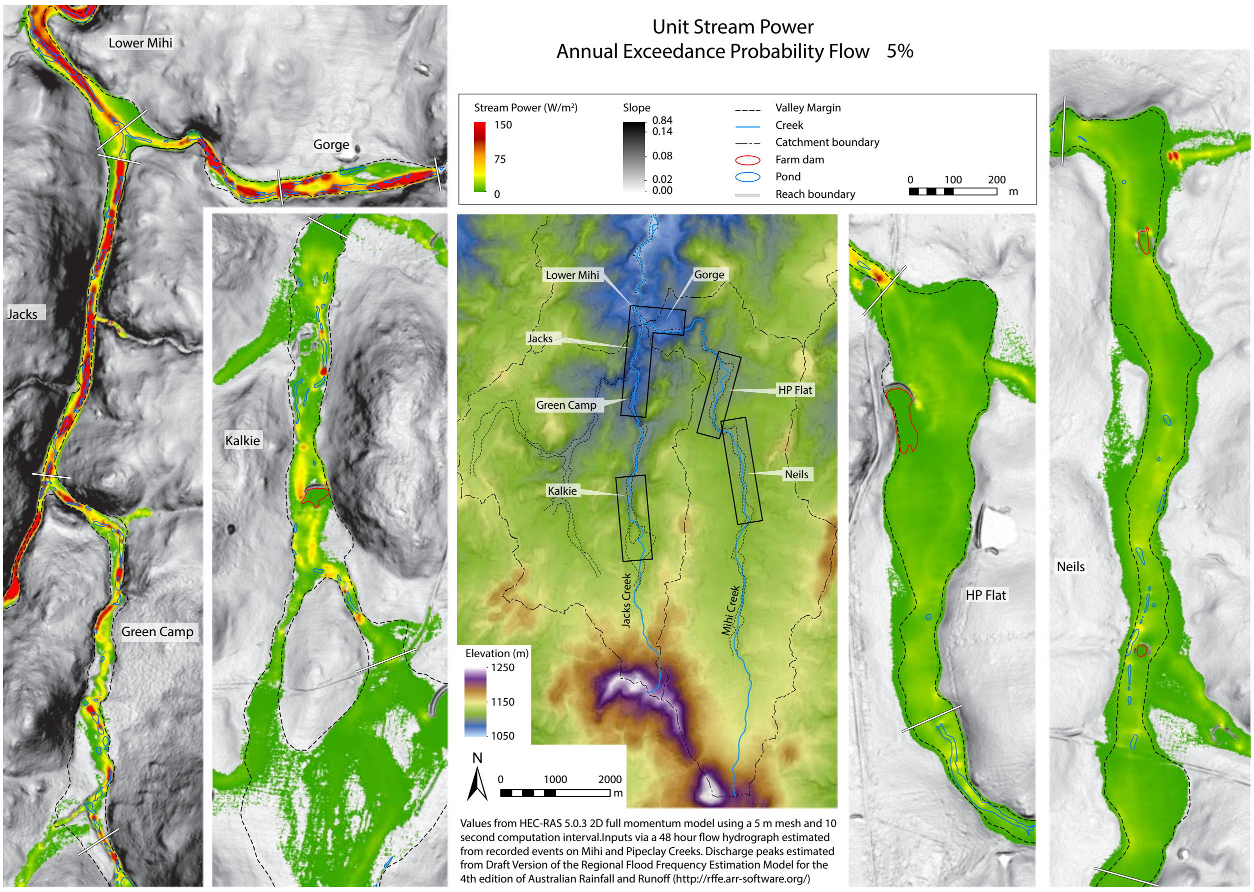


Unit Stream Power
Annual Exceedance Probability Flow 10%



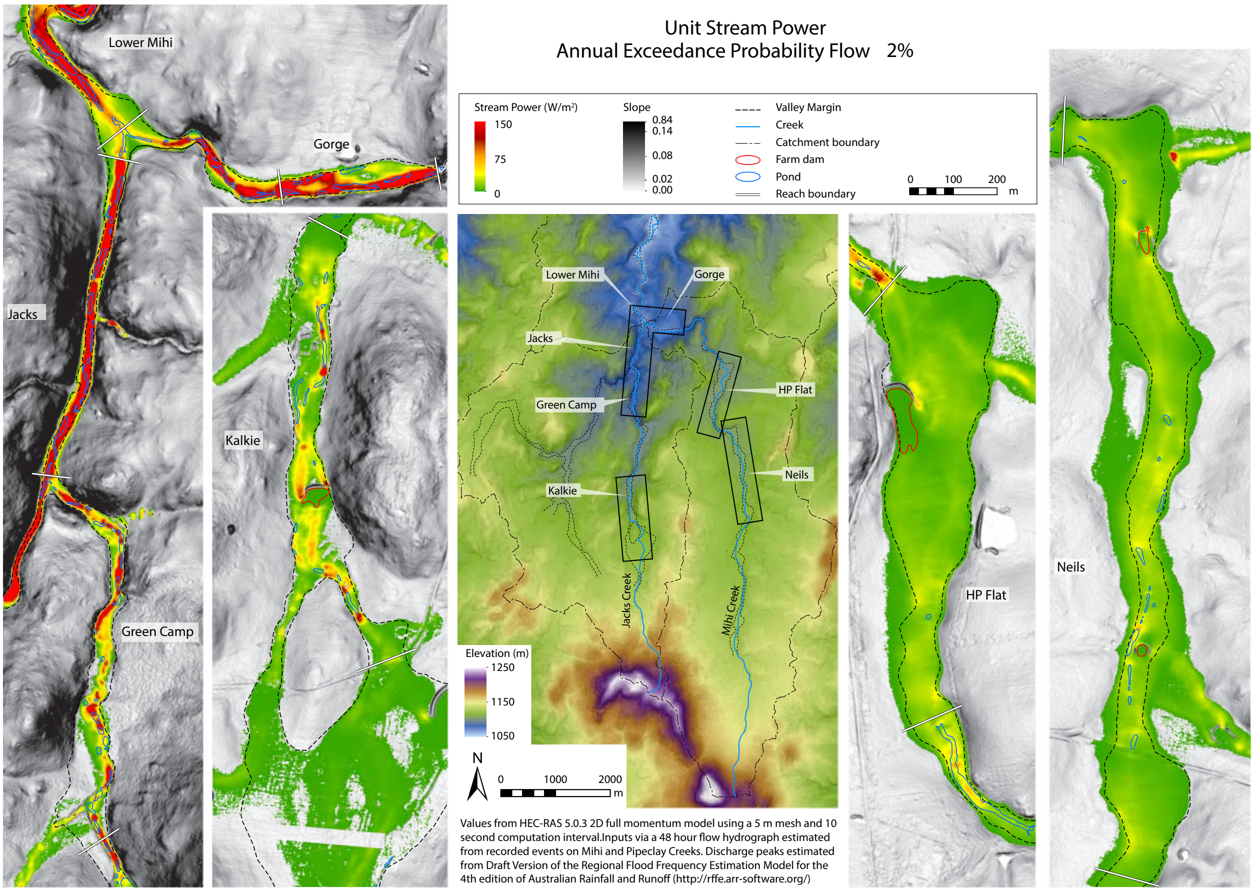
Values from HEC-RAS 5.0.3 2D full momentum model using a 5 m mesh and 10 second computation interval.Inputs via a 48 hour flow hydrograph estimated from recorded events on Mihi and Pipeclay Creeks. Discharge peaks estimated from Draft Version of the Regional Flood Frequency Estimation Model for the 4th edition of Australian Rainfall and Runoff (http://rffe.arr-software.org/)

Unit Stream Power
Annual Exceedance Probability Flow 5%



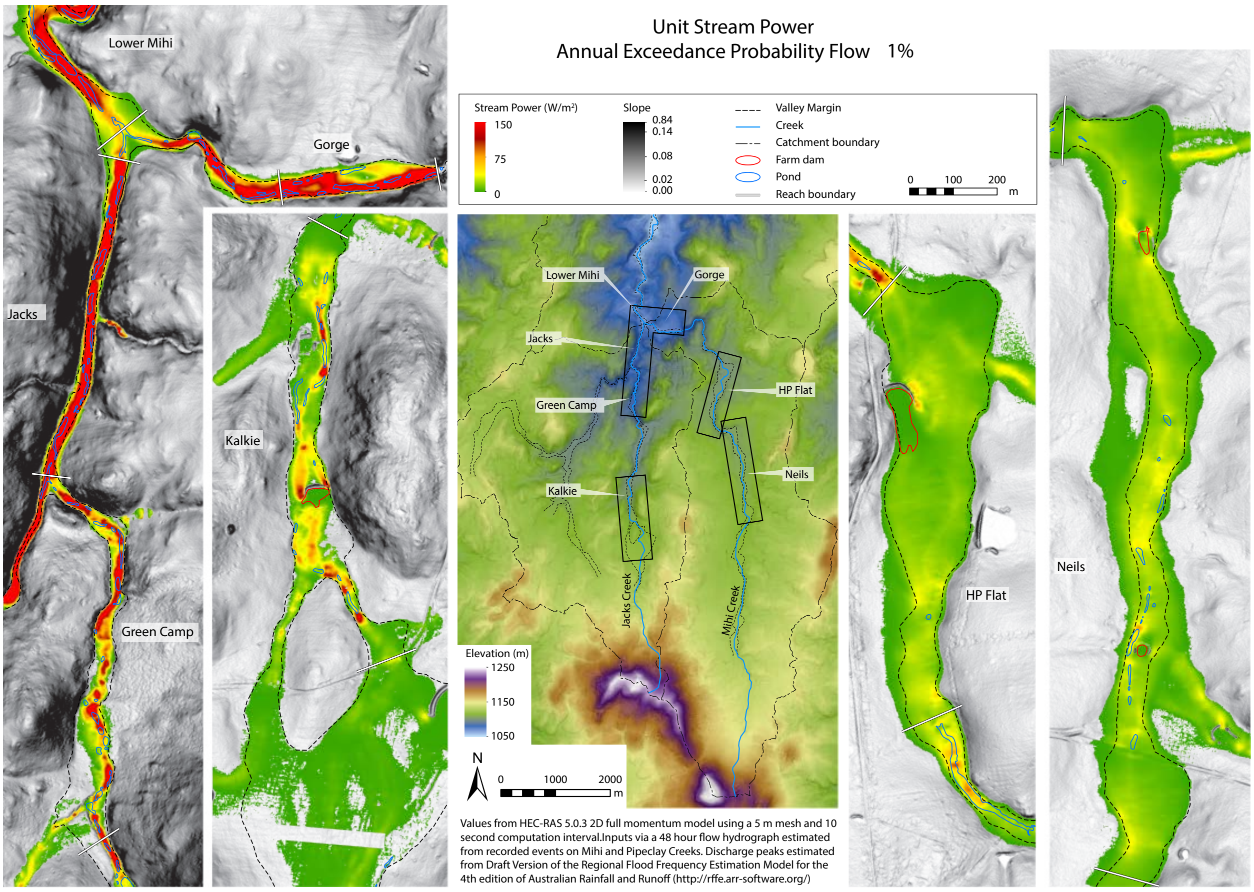
Values from HEC-RAS 5.0.3 2D full momentum model using a 5 m mesh and 10 second computation interval.Inputs via a 48 hour flow hydrograph estimated from recorded events on Mihi and Pipeclay Creeks. Discharge peaks estimated from Draft Version of the Regional Flood Frequency Estimation Model for the 4th edition of Australian Rainfall and Runoff (http://rffe.arr-software.org/)

Unit Stream Power
Annual Exceedance Probability Flow 2%



Values from HEC-RAS 5.0.3 2D full momentum model using a 5 m mesh and 10 second computation interval.Inputs via a 48 hour flow hydrograph estimated from recorded events on Mihi and Pipeclay Creeks. Discharge peaks estimated from Draft Version of the Regional Flood Frequency Estimation Model for the 4th edition of Australian Rainfall and Runoff (http://rffe.arr-software.org/)

Unit Stream Power
Annual Exceedance Probability Flow 1%



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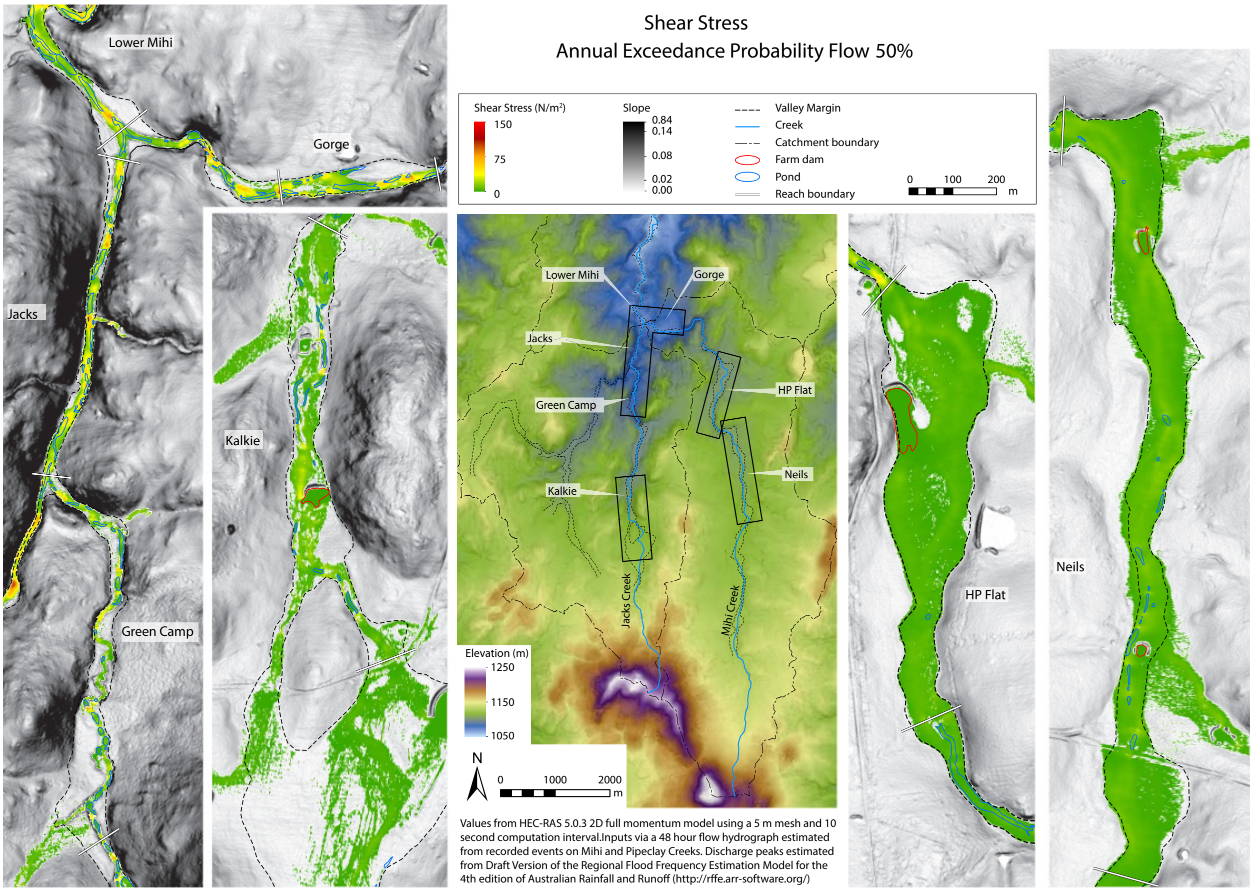
Shear Stress
Annual Exceedance Probability Flow 50%



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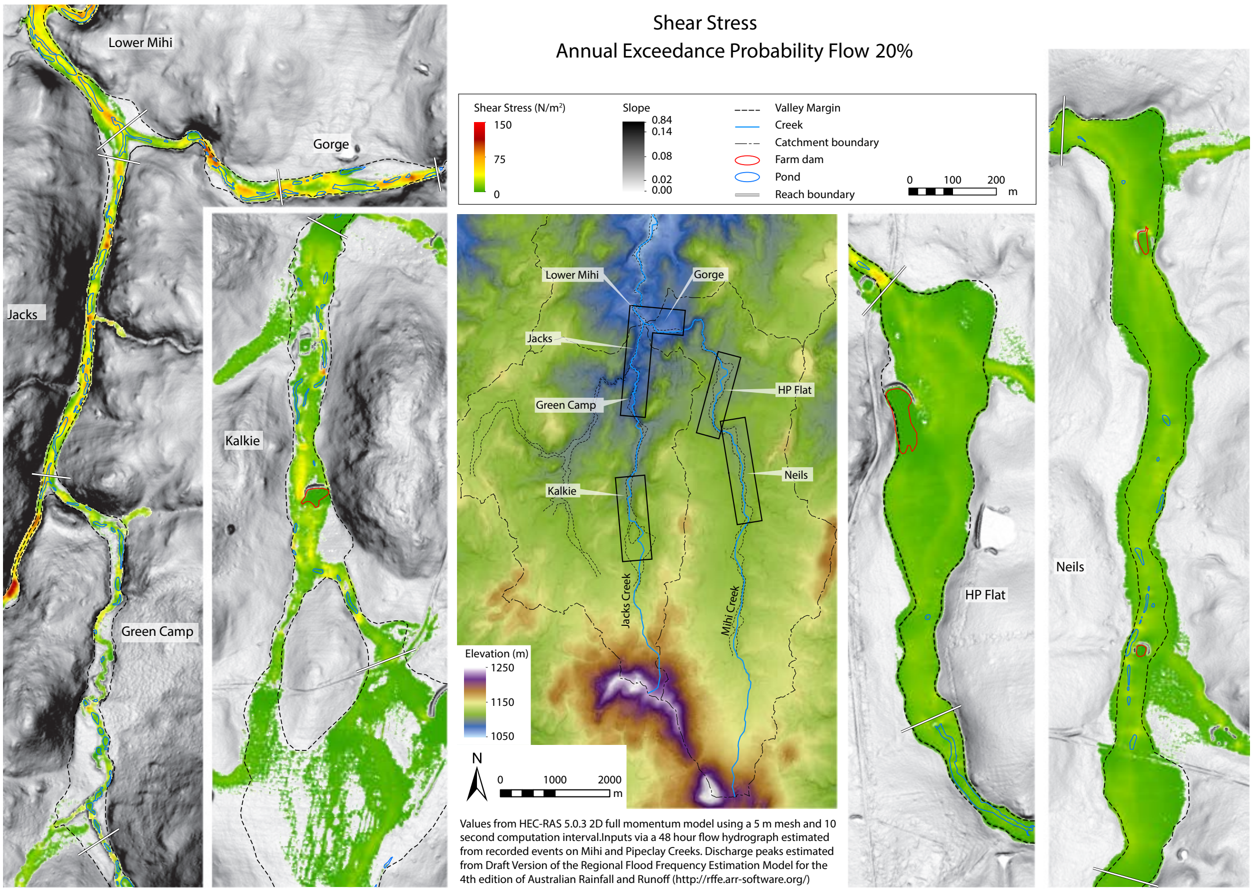
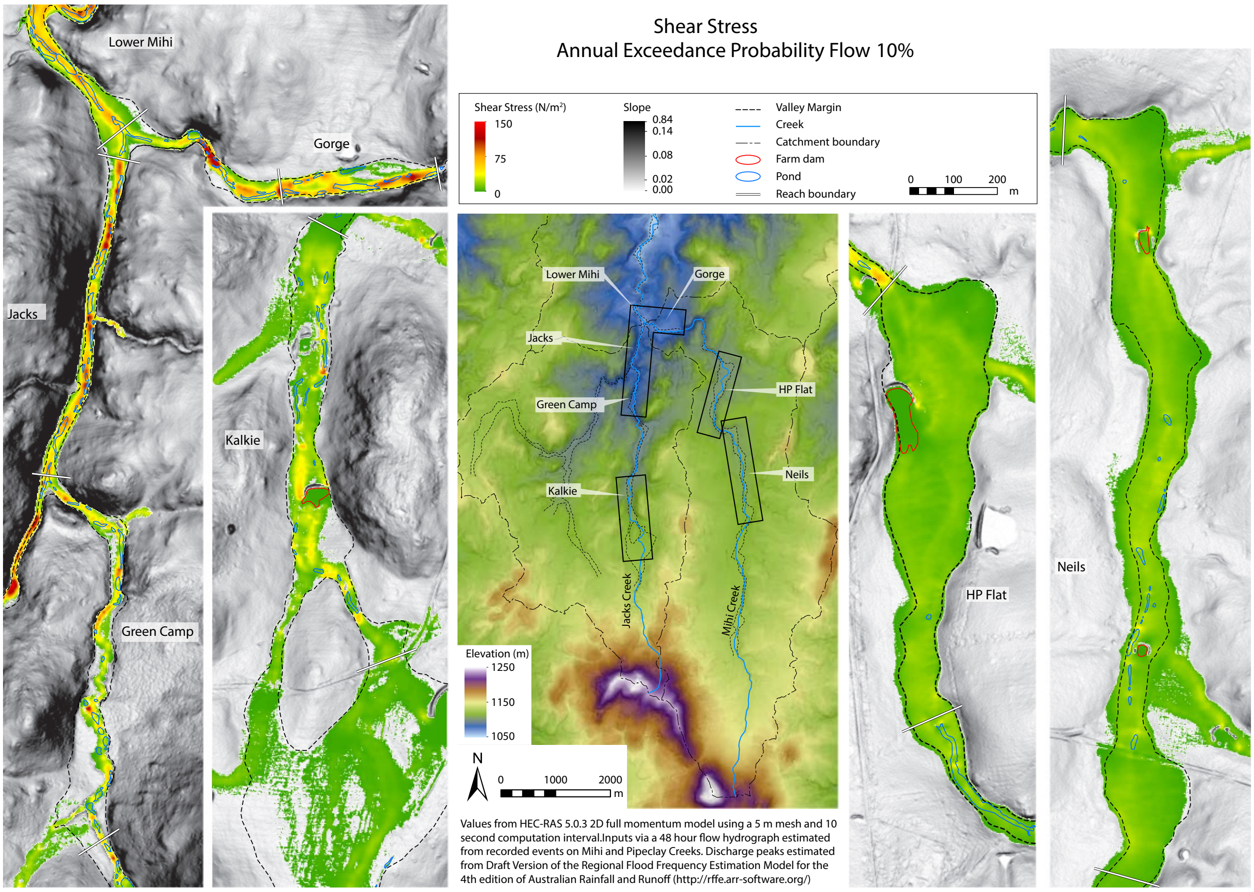
Shear Stress
Annual Exceedance Probability Flow 20%

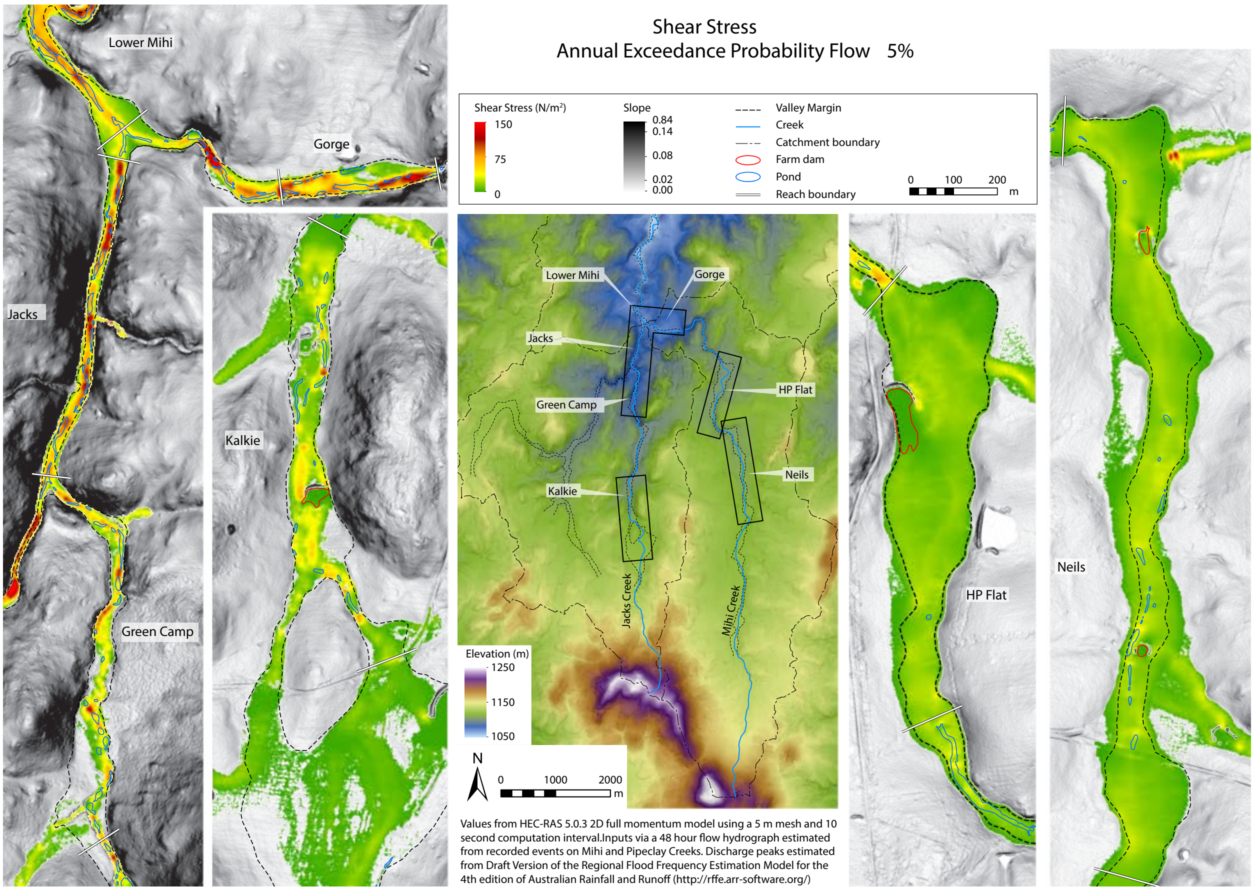


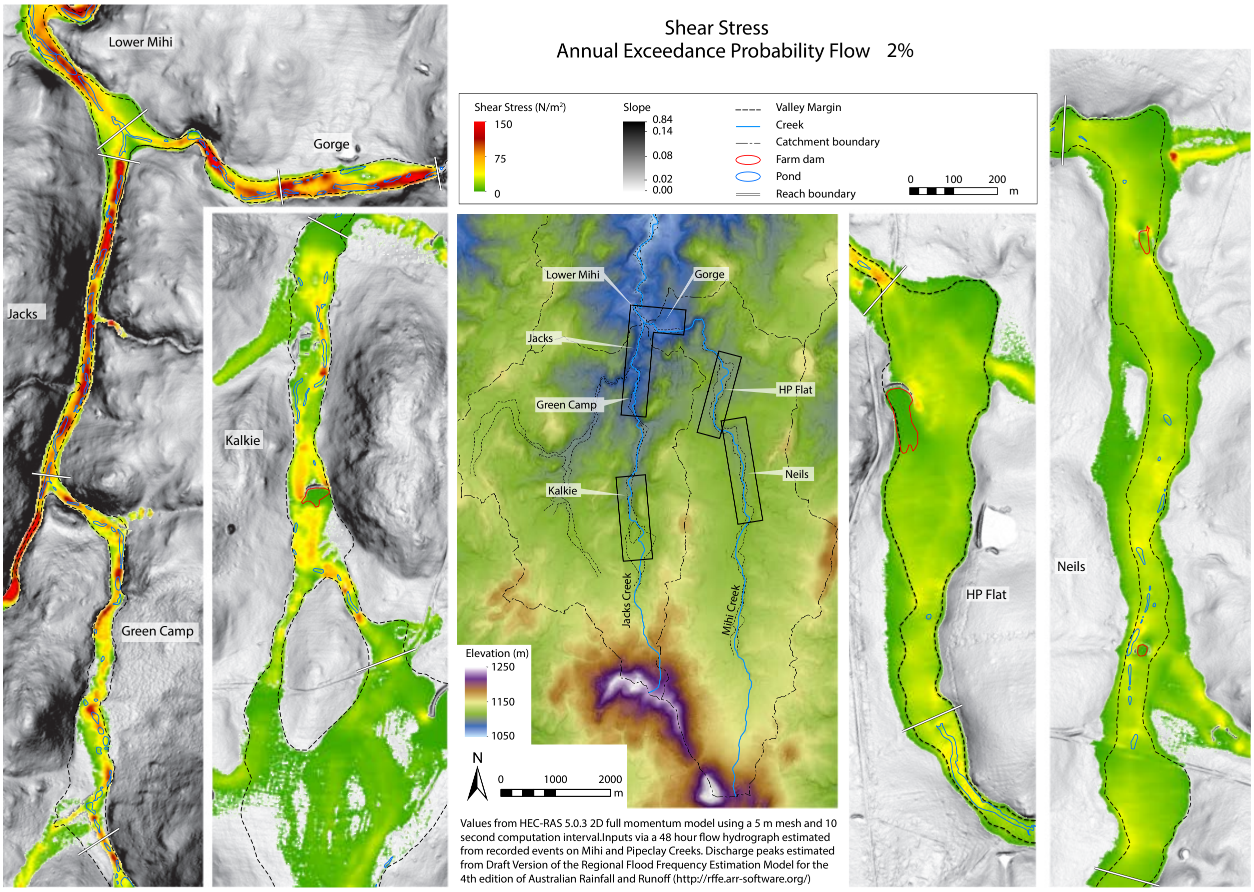
Values from HEC-RAS 5.0.3 2D full momentum model using a 5 m mesh and 10 second computation interval.Inputs via a 48 hour flow hydrograph estimated from recorded events on Mihi and Pipeclay Creeks. Discharge peaks estimated from Draft Version of the Regional Flood Frequency Estimation Model for the 4th edition of Australian Rainfall and Runoff (http://rffe.arr-software.org/)

Shear Stress
Annual Exceedance Probability Flow 10%



Shear Stress
Annual Exceedance Probability Flow 5%





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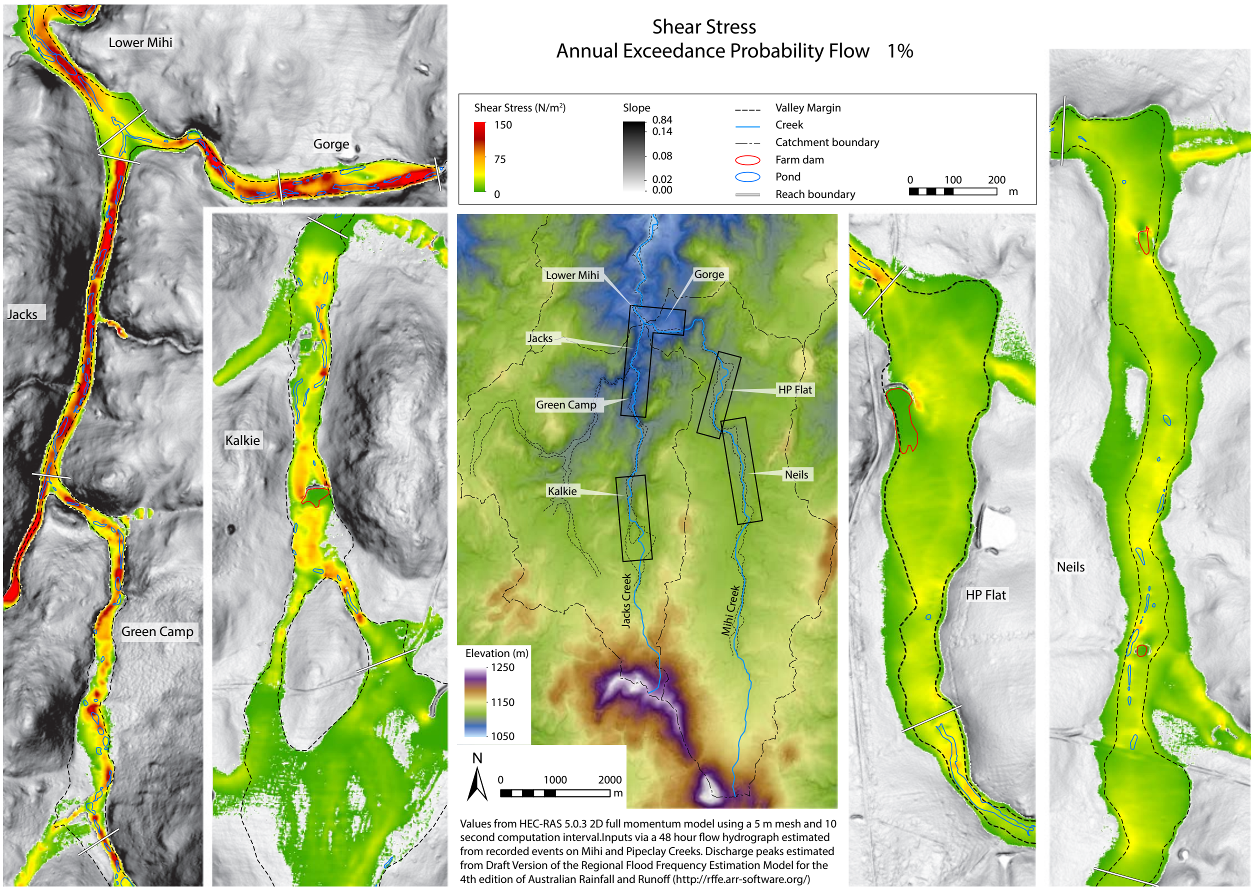

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Appendix 5. Initial concept for the work presented in Chapters 4 and 5

Published as:

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8ASM Full Paper

Williams and Fryirs - Management and conservation of chain-of-ponds

Management and conservation of a unique and diverse Australian river type: Chain-of-ponds

Rory Williams[1] and Kirstie Fryirs[1]

1 Macquarie University, North Ryde, NSW 2065. Email: rory.williams@mq.edu.au

Key Points
- Many chain-of-ponds have been lost through gullying and sedimentation, or artificially channelised to drain saturated floodplains.
- They are far more diverse in their evolution, structure and maintenance than early work recognised
- Under New South Wales legislation, chain-of-ponds are not recognised as rivers due to their lack of channel- and flow-continuity, nor are they protected under any other Acts
- Knowledge of their ecology and diverse hydro-geomorphic structure and function is required for conservation and rehabilitation
- Due to their lack of legal protection, landholder engagement is critical for conservation where these occur in agricultural settings.

Abstract
Many chain-of-ponds (steep-sided ponds separated by densely-vegetated valley-fill sediments or shallow ephemeral channels), once common in parts of the Australian landscape, have been modified or degraded since European settlement, resulting in gullies or continuous channels and leaving previously-saturated floodplains disconnected. This degradation resulted mainly from land-clearing and over-grazing, but the intentional drainage of these systems resulted in dewatering and the lowering of water tables across these alluvial floodplains. While there is a broad spectrum of upland discontinuous watercourses (swamps, mires, bogs, dells, etc.), chain-of-ponds have particular hydro-geomorphologic characteristics that may make them unique to Australia; yet unlike other discontinuous watercourse types, little attention has been brought to their conservation, nor are they afforded the legal protection of other 'continuous' rivers. This paper examines examples of chain-of-ponds from the Tablelands of New South Wales as a basis for discussing their hydro-geomorphic structure and function, and the need for better recognition, protection and rehabilitation of these unique Australian river types.

Keywords
Chain-of-ponds, policy, river management, discontinuous watercourses, legislation

Introduction
Chain-of-ponds consist of steep-sided ponds separated by densely-vegetated (mostly grasses) valley-fill sediments or shallow ephemeral channels (Eyles, 1977a, Hazell et al. 2001). They form in alluvial surfaces with gentle slopes, such as swampy meadows or broader valley-fills, through scour or deposition (Eyles, 1977a; Prosser, 1991). Land use changes and direct modification has seen the loss of many chain-of-ponds systems that were once common in parts of the Australian landscape (Eyles, 1977b; Prosser et al., 1994). This degradation has resulted mainly from land-clearing and over-grazing, but also from excavating channels along the valley-fill to make saturated floodplains accessible. This resulted in disconnecting the alluvial floodplains, lowering water tables and altering the ecosystems. This exploitation is not surprising as they provided well-watered productive grazing pastures for early graziers and continue to provide identifiable agricultural economic value. The economic values of the land are easier to comprehend, for most people, than the complicated and often intangible value of ecosystem services provided by chain-of-ponds. Chain-of-ponds have been noted as being of (geo)ecological significance because they are representative of pre-European small to medium-sized rivers (Eyles, 1977b; Rutherfurd et al., 2000) and provide habitat to species dependant

on permanent (or longer-term), lentic water (Hazell et al., 2003). There is some uncertainty of their pre-European distribution, as many early records describe the shape (at single point in time) of the water in the river as a 'chain-of-ponds', rather than a full account of the hydro-geomorphic character (Eyles, 1977b; Hazell et al. 2003; Mactaggart et al., 2007). Despite this, understanding of their hydro-geomorphic and ecological diversity remains limited, reducing the capacity of land managers to conserve and rehabilitate these unique systems. This papers seeks to further the scientific understanding of discontinuous rivers, highlighting the diverse structure and function of chain-of-ponds, to inform management practices and legislation to ensure their future protection.

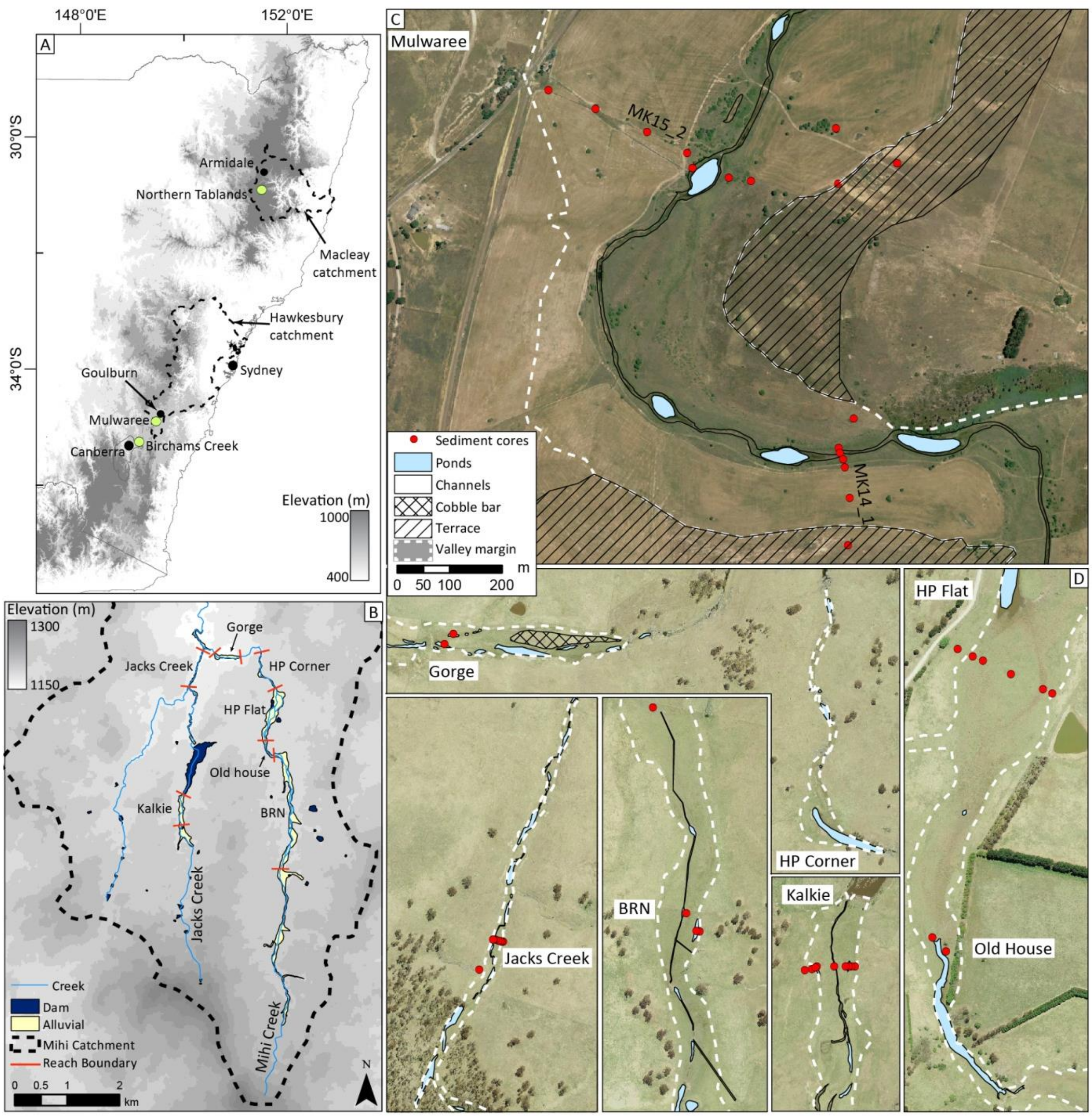

Figure 1. A) Location of study sites. (B) Mulwaree River at 'Kelburn' Mihi and Jacks Creeks on the. C) Location of the Northern Tablelands sites. D) Mihi and Jacks Creeks at 'Eastlake' (5 maps).

Field sites

The Mulwaree River, a tributary in the Hawkesbury-Nepean catchment, sits atop the Great Dividing Range and drains an area of 790 km^2 where it joins the Wollondilly River at Goulburn, NSW (Figure 1-A). The catchment consists of headwater tributaries in steeper, confined and partly-confined valleys, predominately cut-and-fill or chain-of-ponds, similar to those described by Eyles (1977a). At a catchment area of 73 km^2 the river debouches onto a broad (up to 2 km wide), low gradient (<0.001) partly- to un-confined alluvial valley. The study site, located on the property of 'Kelburn', is a 1.7 km reach consisting of five ponds of varying size, connected by a shallow, ephemeral channel (Figure 1-B).

The Northern Tablelands sites, on the property 'Eastlake' (near Uralla NSW) in the upper Macleay catchment, are reaches on the adjacent Jacks and Mihi Creeks, each with catchment areas of 19 km^2 at their confluence (Figure 1-C, D). These reaches cover a range of chain-of-ponds morphologies with varying sedimentology, valley confinement, slope and geology. Both sites are located on tableland plateaus with temperature ranging from 12 to 27 °C in summer and 0 to 12 °C in winter. They receive highly variable rainfall with approximately 800 mm and 550 mm annually for the Northern Tablelands and Mulwaree, respectively.

Methods

A digital elevation model (DEM) was created by combining filtered surface scans (using a Leica C10 laser scanner) and bathymetric surveys (CeeScope 200 echo-sounder). The Mulwaree chain-of-ponds stratigraphy was revealed through examination of surface pits, bank exposures and 17 sediment cores across two valley-wide transects. Five cross-sections, each with 3-9 cores, along bank exposures, were used for Jacks and Mihi Creeks (Northern Tablelands). Site flood discharges and stream power values were calculated from a regional slope-area-discharge recurrence interval curves (see figure 2).

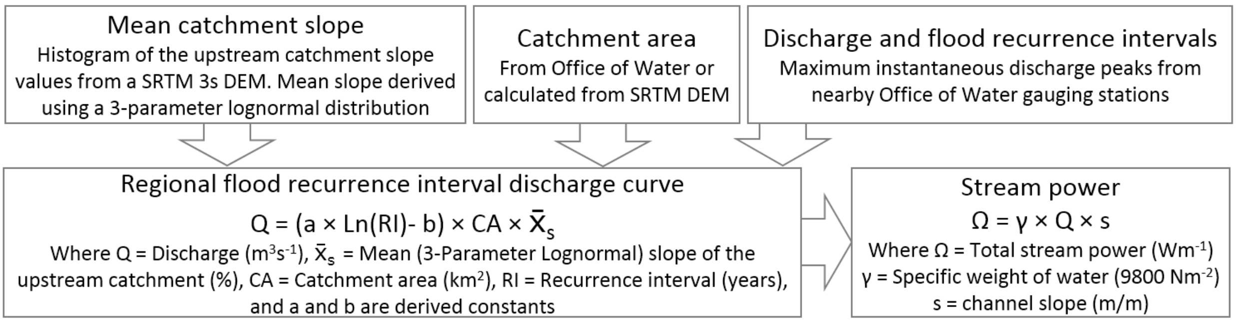

Figure 2. Flood discharge-recurrence interval and stream power calculation method.

Results and Discussion

Geomorphic variability

The lower Mulwaree River has layers of gravel and cobble clast-supported sediments (filled with a matrix of sands and silt) that dominates the stratigraphy from bedrock at a depth of ~18-30 m (Office of Water, 1981) (figure 3 and table 1). These coarse-grained layers are from 0.1 m to >1.5 m thick and separated by silt/sand deposits ranging from 0.02 m to 0.7 m. However, these fine-grained layers are rarely homogenous with distinct layers usually thinner than 0.1 m. Atop, finer sediments (mostly silt and fine sand) extend to a depth of 3 m in the centre of the existing channel and inset floodplain, and between 1 and 3 m on the more distal parts of the floodplain. The ponds, which sit into this valley-fill, are much larger (1000-4000 m^2 and up to 8 m deep) than those described by Eyles (1977b) and Prosser et al. (1994), and are relic forms from a much larger and more energetic gravel-bed river that have not infilled with the fine drape seen across the floodplain. A shallow ephemeral channel (~1 m deep) links the ponds and, with the exception of approximately 100 m where the banks are exposed and subject to erosion, is densely vegetated, impeding flows and encouraging sediment deposition.

The low slope of the Mulwaree River that persists from the point where is debouches near Tarago to its confluence with the Wollondilly at Goulburn plays a critical role in the maintenance of these very deep ponds. As documented by Rustomji et al. (2006) the large (>3x) increase in sediment yield since European settlement has not been transported through the system, but deposited in lobes near the point of unconfinement. Combined with the broad floodplain that creates a buffer (Fryirs et al., 2007) from tributaries and adjacent hillslopes, the transfer of anything other than suspended load is limited to extreme floods. Fine silts and clays that have settled in the ponds post-flood or during low-flow remain dispersible likely due to the constant pore pressure from subsurface flow through the coarse palaeochannel sediments. This lack of cohesion makes it easier for higher flows to re-mobilise finer sediments thereby limiting in-filling and maintaining the deep ponds. The Mulwaree River is unique due to its scale and stratigraphy, and while it is not scouring new ponds through the coarse substrate, it is still relies on the highly variable discharge, low slope and dense vegetation, typical to chain-of-ponds, to maintain them.

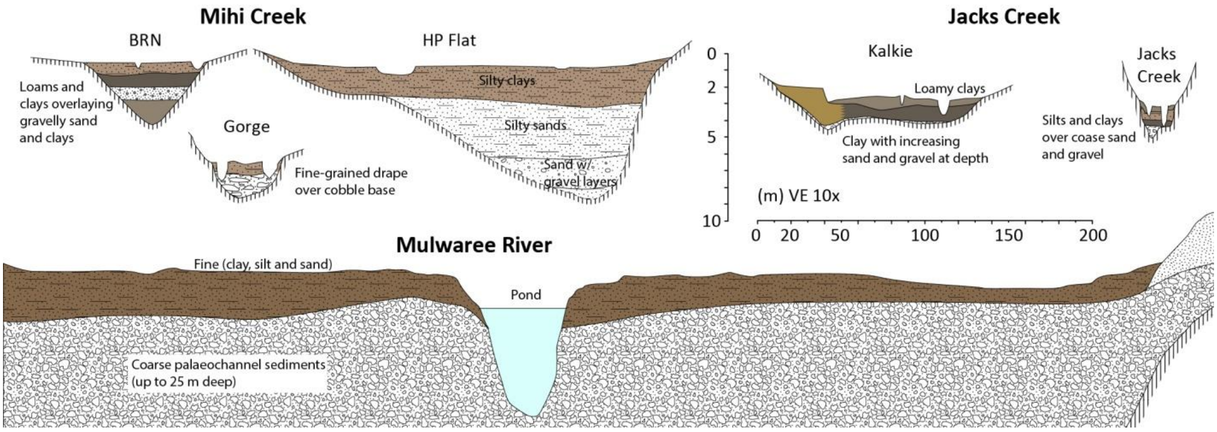

Figure 3. Cross-sections of 3 reaches on Mihi Creek at and 2 on Jacks Creek at 'Eastlake' on the Northern Tablelands and the Mulwaree River at 'Kelburn' on the Southern Tablelands. See figure 1 for locations.

Table 1. Chain-of-ponds study sites and metrics.

Site (River)	Location		Site					Discharge* (m^3s^{-1})			Stream power (Wm^{-1})		Ponds		
	Latitude	Longitude	Catchment area (km^2)	Mean catchment slope (%)	Valley width (m)	Alluvium depth (m)	Slope (m/m)	Q_5	Q_{20}	Q_{100}	Ω_5	Ω_{100}	Area (m^2)	Depth (m)	Bed material
Kalkie (Jacks)	-30.82	151.62	4.3	5.09	40-150	2	0.013	2.2	4.4	7.0	284	894	141	0.3	Fine-grained/ vegetated
Jacks Creek (Jacks)	-30.80	151.63	18.8	4.26	15	1-2	0.009	8.8	17.5	27.6	772	2431	120	0.7	Fine-grained
BRN (Mihi)	-30.82	151.64	12.5	3.67	40-100	2-4+	0.0043	5.2	10.4	16.4	219	691	171	0.3	Fine-grained/ vegetated
Old House (Mihi)	-30.81	151.64	14.6	3.56	23	0-2	0.0035	6.0	11.9	18.8	70	221	4589	1	Fine-grained drape on bedrock
HP Flat (Mihi)	-30.81	151.64	15.3	3.52	100-200	2-7+	0.002	6.2	12.3	19.5	200	629	40	0.3	Fine-grained/ vegetated
HP Corner (Mihi)	-30.80	151.64	17.7	3.51	25	?	0.005	7.1	14.3	22.5	385	1213	116	0.5	Fine-grained/ vegetated
Gorge (Mihi)	-30.80	151.63	19.2	3.59	50	0.5 to cobbles	0.01	7.9	15.7	24.8	772	2430	172	0.8	Armoured - flat cobbles
Kelburn‡ (Mulwaree)	-34.88	149.65	462.0	6.56	250-700	1-3 fine 18+ coarse	0.0007	58	187	292	399	2004	1816	3.5-8	Fine-grained drape over cobbles
Birchams Creek†	-35.26	149.31	4.4	4.26	25-50	1-2	0.02-0.07	2.3	4.5	7.1	454	1400-4800	179	0.5-2	Fine-grained

*Discharge (Q_x) and Stream power (Ω_x) subscript denotes flood recurrence interval

*Mihi and Jacks Creeks Q = (0.2305 × Ln(RI)-0.05) × Catchment Area × Mean Catchment slope

*Birchams Creek Q = 0.1909 × Ln(RI)-0.0272) × Catchment Area × Mean Catchment slope
‡Discharge estimates from flood discharge recurrence intervals values in Rustomji et al. (2006)
†Pond and alluvial depths, and sediment description from Eyles (1977a)

The Northern Tablelands sites are similar to those of Birchams Creek (Eyles, 1977a), but with a diverse range of stratigraphy and planforms. The two upper sites on each creek (BRN and Kalkie) have wide valley margins (~70-200 m), with little elevation change across the valley bottom. The stratigraphy of Kalkie (Jacks Creek) shows weathered bedrock at a maximum depth of 1-2 m, overlain with sandy clays with occasional small gravels (0.1-0.5 m) below silty clays and loams. The depth is controlled by outcrops of the steeply dipping meta-sedimentary bedrock as the valley margin narrows 0.15 km downstream, 1.5 m lower in elevation). The valley-fill sediments at the BRN site (Mihi Creek) are much deeper (>4.5 m at points) as the monzo-granite bedrock control-point is 5 m lower and 1.6 km downstream. Both sites have a dense covering of pasture grasses with tussocks dominating the lower (wetter) areas and a small (0.3 m deep) vegetated artificial channel. Many of the ponds are shallow and concave and only maintain water for a short time after heavy rain. Along the upper parts of Kalkie there are deeper ponds (1.5 m) that have eroded through headcuts and bank slumping from stock ingress. Downstream on Jacks Creek the valley narrows to 10-25 m with steep valley sides. Weathered bedrock is 0.5-1.5 m below gravelly sediments (only in the centre of the valley) and silty-clays, with tussocks covering the width of the flat valley bottom. These deeper ponds (~1 m) are steep sided and maintain water, except during extended dry periods, and many have narrow head cuts that are forming small channels between the ponds.

Below BRN on Mihi Creek there are four distinct pond and valley morphologies. The first pond (Old House) is steep-sided and bedrock (monzo-granite) confined as the creek moves between unconfined valleys. The pond has formed due to sediment deposition of levies and a floodout as the creek again debouches on to the broad valley where the next site is located. HP Flat is a broad (100-200 m) valley-fill, controlled by bedrock at the downstream point. Over the 1 km length of this reach, the elevation drops by 2 m (much less than the unconsolidated sediments that are over 7 m deep) and only holds two ponds; one small (50 m^2 and 0.5 m deep), and one large – estimated to be up to 2000 m^2 before it was extensively modified to hold water for stock. The stratigraphy is unlike any other reaches as the valley-fill is mostly silty-sands from >7 m to 2.5 m; the upper level being the same elevation as the bedrock outcrop downstream. Between 2.5 m and 1.8 m are loams with occasional gravelly flood deposits and then the more typical fine-sandy loams to the surface. The third reach (HP Corner) is a series densely-vegetated alluvial sediments built up behind bedrock control points. Unfortunately there are no cores to confirm the depth or stratigraphy. The last reach (Gorge) has ponds with an armoured base of cobbles that have been deposited after the creek exits a steep gorge. These cobbles also form a large (~4000 m^2) clast-supported bar with a fine-grained matrix, bordered by a near-flat valley floor 15-20 m either side. The ponds sit 0.5-0.8 m into the complex stratigraphy that moves from clast-supported to matrix-supported with a 0.2-0.5 m drape of fine-sands to clays. This surface is covered with large tussocks and pasture grass, and much like the nearby site of Jacks Creek maintains water except in extended dry periods and many of the ponds have head cuts. Notably, a ponds that is no longer active (but was less than 50 year ago) shows no evidence of incision. The steep sided ponds (all except the small pond in HP Flat) have bank slumping from livestock accessing water. All of the reaches have seen a modification to their flow variability with the construction of many small farm dams, but since the 1960s, the lower Jacks Creek reaches have seen a decline in the magnitude of high frequency discharges due a third of its catchment flowing into a ~500 ML dam. This has also reduced the sediment inputs, which are critical for balancing scouring from larger discharges.

Birchams Creek and other small chain-of-ponds in the Murrumbidgee catchment have been severely degraded by gullying or infilling (Eyles, 1977a; Prosser, 1991) but Mihi and Jacks Creeks (along with many small neighbouring catchments) remain relatively intact. Both regions have been extensively cleared for grazing during the late 19th and early 20th centuries and have similar topographic settings, rainfall variability, temperatures, catchment slopes and area-discharge relationships. The factor that puts Birchams Creek at greater risk is a channel slope from 2 to 5 times that of any of the study reaches (Table 1). This erosive power is also apparent when stream power values are compared (table 1), showing Birchams Creek up to 5 times greater, in a catchment of similar size. As Eyles (1977a p.151) comments, "In any chain of ponds where ponds are close together along a valley floor of appreciable slope… there is probably a very delicate equilibrium, with any disturbance triggering erosion and the development of active ponds or discontinuous gullies".

All small scale chain-of-ponds on the Northern Tablelands form through scour or deposition, similar to the processes described in Eyles (1977a). The ponds in upper reaches of Mihi and Jacks Creeks are scoured into fine-grained sediments, but the risk of gullying is reduced by the low slope and broad floodplains that are rapidly inundated because of the lack of channel. Downstream, floods are confined by narrower valley margins, however pond expansion is hampered by the very coarse (large gravel and cobble) substrate. Along the ponded reaches of Mihi and Jacks Creek, the low slope results from bedrock control points below, often deep, valley fill. On some reaches (e.g. HP Corner or Jacks Creek) this will limit the slope but also provide a 'break' in the event of gully initiation. These physical properties, of low slope, minimal or no channel, and a readily inundated floodplain combined with highly variable flows are critical for chain-of-ponds.

Management of chain-of-ponds

There is a well-developed process for prioritising reach scale projects and rehabilitation techniques that are suitable for most chain-of-ponds (e.g. Brierley and Fryirs, 2005; Rutherfurd et al., 2000). However, an increase in the understanding of the ecological and geomorphic diversity of this important Australian river type is required to inform these processes and manage the remaining chain-of-ponds. Conservation must be based on four key areas; intrinsic properties, extrinsic properties, value and landholder engagement. Intrinsic properties including the channel and pond morphology, slope, sedimentology, valley width, vegetation, and discharge are key in assessing a reaches resistance to degradation. As discussed, the morphology of chain-of-ponds can vary greatly between sites and therefore need to be interpreted to identify its risk of degradation or recovery potential. While the reach may appear resilient, upstream changes may push the ponds past thresholds. Extrinsic factors such as upstream catchment morphology, land use and vegetation impact discharge through a number of processes. Some chain-of-ponds may carry greater value than others, be it (geo)ecological, social, cultural, or economic. For example, the Mulwaree River chain-of-ponds are unique and therefore have high geomorphic and ecological value, but also have cultural significance to indigenous Australians and economic benefit as a permanent water source to farmers. Engagement of stakeholders is critical as most chain-of-ponds are located on agricultural land, therefore requiring the landholder to be invested in the process to achieve appreciable and long-term outcomes. Before these systems can be adequately conserved or managed it is required that they are recognised in legislation.

In NSW, the definition of a 'river' has been discussed in relation to rulings on development applications, while highlighting the inadequacy of the definition for Australian rivers (Lamaro et al., 2007; Taylor et al., 2011; Taylor and Stokes, 2005). The *Water Management Act 2000* (NSW) (WM Act) provides an update from the repealed Rivers and Foreshore Improvement Act 1948 (NSW), but remains an ambiguous definition;

> *river includes:*
> *(a) any watercourse, whether perennial or intermittent and whether comprising a natural channel or a natural channel artificially improved, and*
> *(b) any tributary, branch or other watercourse into or from which a watercourse referred to in paragraph (a) flows*

While this is an improvement, as it allows for greater flexibility in interpretation, there is still the omission of 'ephemeral' as a flow type. A decision in the NSW Land and Environment Court (Lloyd, 2010) concluded that intermittent and ephemeral are synonymous, expanding on the WM Act definition of a river. However, it is contended that this ruling is based on incomplete evidence as the terms are understood and used by geomorphologists to differentiate river types and function (Davies et.al, 2011). Further uncertainty remains as ‘watercourse’ is not defined in the WM Act, but, relies on the High Court ruling by Barwick (1968), which in turn relies on a definition from Anglo-American law from the mid-nineteenth century (Angell, 1854 p.2).

> *…the watercourse, in my opinion, must exhibit features of continuity, permanence and unity, best seen, of course, in the existence of a defined bed and banks with flowing water.’* (Barwick, 1968 18)

This High Court ruling has flowed down the legal channels and the question of whether chain-of-ponds are defined as a river, and therefore protected, was answered by Bannon (1996);

> *At best it can be classified as a drainage line with gullies to the East and West, together with intermittent ponds and flood plane* [sic] *where water flows are rare intervals, under the influence of rain.*

Who also noted an expert witness (Dr E.M. O'Loughlin, previous Chief Research Scientist with CSIRO)

> *…thinks of waterbodies in a scientific way, which includes waters such as Coopers Creek, but does not fit the definitions given by the Courts, taken as they are, from European conditions*

Considering the changes in understanding of (Australian) rivers since 1850, this definition is outdated. As Mactaggart et al. (2008) note, discontinuous systems, such as swampy meadows and chain-of-ponds, are not protected due to their lack of channel continuity; this is until (ironically) they become degraded by gullying and acquire the necessary geomorphic features of bed and banks. Some chain-of-ponds may have protection through the WM Act’s definition of a lake being ‘…any collection of still water, whether perennial or intermittent…’; however, like the definition of a river, it excludes the term ephemeral.

While they do not meet the conditions of permanence of flow, or continuity of (the legally defined) bed and banks of a channel, the process by which they form are evidently fluvial and result from Australia’s highly variable rainfall and streamflow conditions. Combined with their unique geomorphology, ecological value and documented decline in number (Eyles, 1977b; Prosser et al., 1994) this should be enough to ensure protection under a precautionary approach. Limited knowledge of the ecological communities may restrict their inclusion under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) or Threatened Species Conservation Act 1995 (NSW) (TSC Act). Unfortunately no chain-of-ponds are listed, nor are they afforded under any other protection (e.g. Directory of Important Wetlands in Australia) or acknowledged as groundwater dependent ecosystems (Bureau of Meteorology, 2016). Amendments to the definition of a *river* under the WM Act to include discontinuous and ephemerral rivers is unlikely. Therefore, to ensure their prolonged existence they may need to be included as endangered ecological comminuties, which will require greater ecological understanding to compliment the ongoing hydro-geomorphic research.

Conclusions

Once common across the Tableland headwaters, many chain-of-ponds have been lost due to land use changes since European settlement. Chain-of-ponds are a uniquely Australian river type, yet little is known of the diversity, or hydro-geomorphic processes, that are vital for developing management practices. To ensure the long-term conservation of these characteristically Australian rivers, they must be granted the legal protections that our current Anglo-American definition or a river withholds. As the last update to the statutory laws that govern their use took 52 years, with little change (or appreciation for the enormous increase in our understanding of Australian rivers), then other avenues of protection need to be pursued. This paper begins to inform on the hydro-geomorphic processes, but more is needed with additional ecological research. Until such time, those involved in river management will have to continue to engage land holders to conserve of the diversity of Australia’s chain-of-ponds systems.

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