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The Holocene evolution and geomorphology of a chain of ponds, southeast Australia: Establishing a physical template for river management

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ABSTRACT

Chains of ponds are a discontinuous river type found in Australia. Their unusual morphology, important ecological functions and increasing rarity make them a priority for conservation, and yet very little research has investigated their physical structure, behaviour and evolution. This paper reconstructs the Holocene evolution and environmental history of Crisp's Creek, a headwater chain of ponds in the Southern Tablelands of NSW Australia. This history establishes baseline information on the physical template that can be used to assess a range of other biophysical processes and design appropriate river rehabilitation and management strategies for these rivers. Sedimentary aggradation began in the Late Holocene, at least 3.7–1.3 ka, broadly synchronous with aggradation phases at other sites in southeast Australia. Since European arrival in the Nineteenth Century, parts of the river incised, destroying intact ponds and smothering formerly swampy floodplains with post-incision alluvium. However, sections unaffected by incision provide a rare opportunity to examine the evolutionary trajectory of an intact variant of these rivers. This research deepens our understanding of the evolutionary context for contemporary river behaviour as relevant for designing appropriate and effective conservation and rehabilitation strategies for chains of ponds.

1. Introduction

Chains of ponds are part of a spectrum of rivers found in a laterally unconfined valley setting, that have discontinuous (or absent) channels (Brierley and Fryirs, 2005). In Australia, this range of discontinuous rivers includes intact valley fills and swamps (Fryirs et al., 2014a), swampy meadows (Johnston and Brierley, 2006; Prosser, 1991), chains of ponds (Eyles, 1977a, b; Hazell et al., 2003) and floodouts (Gore et al., 2000; Tooth, 2000). Outside Australia, similar systems have been termed arroyos (Bull, 1997) and dambos (Mäckel, 1974). Chains of ponds are typically set into broad, low-gradient valleys containing swampy, alluvial valley fill (Eyles, 1977a). They are characterised by irregularly spaced ponds that are separated by multiple preferential flow paths that do not carry flow under low-flow (baseline) conditions. In the Southern Tablelands and Southern Highlands of New South Wales (NSW), where the majority of chain of ponds research has been conducted, alluvial valley fills, which often contain chains of ponds, commenced accumulation in the Early Holocene, coinciding with transitions from a cold Late Pleistocene climate to a warmer and likely wetter Holocene climate (Johnston and Brierley, 2006; Prosser et al., 1994). However, within the Holocene, Prosser et al. (1994) and Fryirs et al. (2014a) argue that the influence of climate on swamp aggradation and erosion in these settings has been highly varied with more local, intrinsic factors such as bedrock valley morphology and establishment and disturbance of vegetation being the major factors driving the onset of swamp formation, and the subsequent structure of the valley fills. Valley fills in the Southern Tablelands and Highlands tend to follow a general pattern of decreasing sediment size with decreasing depth (fining upwards), from basal gravels to clays and silts, indicating a reduction in stream energy over time (Johnston and Brierley, 2006; Prosser et al., 1994; Rustomji and Pietsch, 2007).

Sedimentary evidence from other locations indicates that cut-and-fill (episodic incision of alluvial valley fills and refilling by aggradation) was common in the pre-European record (Fryirs and Brierley, 1998; Prosser, 1991; Prosser and Winchester, 1996; Zierholz et al., 2001). Phases of cutting (incision) have been attributed to localised vegetation and ground surface disturbance occurring in combination with proximity to a threshold of valley fill thickness, where increased upstream aggradation forms a sedimentary wedge that increases valley slope (Prosser, 1991; Prosser and Slade, 1994). Drivers of filling (aggradation) phases are less well understood, but appear to be closely related to colonisation of sediments by vegetation within the channel (Fryirs and Brierley, 1998; Prosser, 1991; Prosser and Slade, 1994).

Many valley fills in the Southern Tablelands and Highlands of NSW have experienced significant incision since the onset of European land

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use in the region (1820s onwards) such that intact chains of ponds, which were once widespread, are now largely lost (Eyles, 1977a; Johnston and Brierley, 2006; Wasson et al., 1998). Incision was more widespread and of a greater magnitude following European arrival than at any other time in the Holocene record (Fryirs and Brierley, 1998; Prosser, 1991; Prosser and Winchester, 1996; Zierholz et al., 2001). Channelisation and dewatering of ponds and swampy terrain has had secondary impacts on the hydrological function and aquatic ecology of these headwater systems (Fryirs et al., 2014b; Hazell et al., 2003; Krogh, 2007; Prosser, 1991). Removal of vegetation and drainage of these swampy valley fills have been cited as triggers for incision since the arrival of Europeans in Australia, specifically land clearing, grazing by sheep, cattle and rabbits, road building and drain construction (Brierley and Fryirs, 1999; Eyles, 1977b; Fryirs and Brierley, 1998; Mactaggart et al., 2008; Prosser, 1990, 1991). Some 150 years after disturbance in these settings, some of the channelised fills are showing signs of geomorphic river recovery. While these systems are unlikely to return to pre-disturbance conditions now that boundary conditions have been altered, recent formation of 'instream wetlands' and 'instream ponds' within previously incised channels indicate that the processes of channel recovery are underway and these landscapes are again trapping sediment (Fryirs and Brierley, 2016; Rustomji and Pietsch, 2007; Wasson et al., 1998; Zierholz et al., 2001).

Recognition of the value of chains of ponds and other discontinuous rivers has highlighted the need for baseline understanding of the character, behaviour and evolution of these systems (Freidman and Fryirs, 2014; Fryirs et al., 2016; Hazell et al., 2003; Mactaggart et al., 2006). With greater attention in environmental management being given to the physical integrity of riverine environments (not just the ecological integrity), it is critical that we have a physical template from which to work. This physical template then provides a basis for examining how associated ecosystems operate, and how physical, biological, hydrological and chemical interactions occur (Bellmore and Baxter, 2014; Brierley and Fryirs, 2008; Chessman et al., 2006; King and Hobbs, 2006; Maddock, 1999; Southwood, 1977). This is critically important where these systems remain geomorphologically intact, are showing signs of geomorphic recovery, or are under threat from land use or climate impacts. In this paper we use Crisp's Creek in the Southern Tablelands of NSW as our case study to establish the physical template of a headwater chain of ponds system. We draw on sedimentary and documentary evidence to reconstruct an environmental history and sequence of geomorphic evolution throughout the Holocene. This evolutionary history forms a basis for interpretation of the contemporary geomorphology and river behaviour as relevant for river management. We aim to characterise this chain of ponds in good geomorphc condition in a way that can serve as a baseline or reference condition to guide river rehabilitation planning and prioritisation in other catchments.

2. Regional setting and methods

2.1. Regional setting

Crisp's Creek is a headwater chain of ponds river and a tributary to the Mulwaree River (Fig. 1). This river is in the Hawkesbury-Nepean catchment and forms part of the Sydney water supply area that supports some 4.5 million people (HNCMA, 2007). Crisp's Creek joins with the Mulwaree River near the town of Tarago in the Southern Tablelands of NSW, southeast Australia. The Crisp's Creek subcatchment is approximately 30 km^2 in area and the creek is approximately 3 km long, starting from an elevation of 740 m above sea level. Crisp's Creek flows along an alluvial valley fill surrounded by bedrock ridges of Woodlawn Volcanics, consisting of Late Silurian rhyolite, ignimbrite, breccia and acid tuff (Felton and Huleatt, 1975), these ridges forming part of the Great Dividing Range. Mean annual rainfall measured at nearby Lake Bathurst (83-year record; Fig. 1d) is 683.4 mm with a slight spring and summer bias (October to February; Bureau of Meteorology, 2015a). Mean monthly maximum and minimum temperatures measured at Goulburn Airport (26-year record) are 19.6 °C and 6.0 °C respectively (Bureau of Meteorology, 2015b, c). Vegetation structure consists of grassland on valley floors (tussock grasses and exotic pasture grasses) and low open woodland (*Eucalyptus stellulata* and other *Eucalpytus* sp.) with grasses on ridges. Historical accounts suggest that the treeless state of valley floors was typical at the time of European arrival in the region in the early 1800s (Eyles, 1977b).

Crisp's Creek is situated adjacent to a former mine site, now a bioreactor plant operated by Veolia Environmental Services. A portion of Crisp's Creek is now under a management agreement designed to protect from degradation a relatively intact section of Crisp's Creek. The rehabilitation approach is largely passive, comprising new perimeter fencing to exclude livestock and the planting of approximately 3000 indigenous trees on hillslopes adjacent to the creek. The agreement was struck in 2014 with fencing and tree planting taking place early in 2015.

2.2. Field and laboratory methods

Nine transects were established to investigate the sedimentary structure of the alluvial valley fill, including sections containing ponds, preferential flow paths and incised channels. Transects were surveyed using a Leica TCR-705 Total Station. Along transects, sixteen cores and five bank exposures were used to analyse sedimentology. Coring was undertaken for detailed analyses ($n = 9$) using a GeoProbe® 54LT direct push mobile coring system and DT22 internal rod sampling system to minimise infill. Push cores were retrieved inside PVC liners with integrated core catchers. Hand-augered cores ($n = 7$) were then used to correlate sedimentary layers between GeoProbe cores. Bank exposures were used, where visible, to describe sediments in-situ. GeoProbe core samples were described and characterised in the laboratory. Grain size, sorting, rounding and mineralogy were determined using a hand lens, colour determined using a Munsell colour chart and facies descriptions completed according to Miall (1996). Augered cores were analysed in the field for grain size, field texture and colour. Bank exposures were described in the field and samples taken for organic matter content and dating analyses.

Loss on Ignition (LOI) to measure organic matter content was performed on 115 sediment subsamples using a Lindberg Blue furnace. Samples weighing between 8 and 20 g (wet) were dried, weighed and hand-milled prior to ignition in 50 mL porcelain crucibles. Samples were then heated from 25 °C to 550 °C over 2 h, held at 550 °C for 4 h and then cooled to 105 °C over 2 h. This approach has been used in peat forming swamp systems elsewhere in southeast Australia (e.g. Fryirs et al., 2014a) and although LOI may overestimate organic content in clay soils (Howard and Howard, 1990), it is a practical and indicative method for estimation of organic content (Beaudoin, 2003; Heiri et al., 2001). Samples were weighed immediately after removal from the furnace at 105 °C. Use of a desiccator was trialled; however, there was found to be no significant difference between weighing after removal at 105 °C and weighing after 1 h in a desiccator. One batch of 24 samples was subjected to a second cycle of LOI to determine if the temperature and duration were appropriate to achieve complete removal of organic material. The difference in weight between a single cycle and two cycles was insignificant, so a single ignition cycle was used for all samples.

Three charcoal and two bulk sediment samples were taken from a bank exposure on Transect H for AMS radiocarbon dating by Beta Analytic, USA (accredited under ISO/IEC 17025:2005). Bulk sediment dating was used to date two sedimentary units because charcoal recovery was very low. Samples were subjected to Acid/Alkali/Acid (AAA) and acid wash pre-treatments. Charcoal samples were extracted by floating and dispersing in deionised water. Samples were then washed with hot HCl acid to remove carbonates and then with NaOH to remove secondary organic acids. A final acid wash was used to neutralise samples before drying. Bulk sediment samples were dated using the bulk organic fraction. These samples were sieved to <180 μm to remove any roots or macrofossils and then neutralised using an HCl acid wash. Calibration