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The stratigraphy, mode of deposition and age of inset flood plains on the Barwon-Darling River, Australia

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Abstract Inset flood plains are a common feature of dryland river systems. These depositional landforms are attached to the bank between the riverbed and the main flood plain surface. Along the Barwon-Darling River in New South Wales, Australia, seven inset surfaces were identified. We used optical dating techniques and the presence of numerous European artefacts to show that these in-channel features range in age from ~10 to 2200 years. Three main stratigraphic sequences were recorded: a general fining upward sequence; a series of fine laminated sediments; and a distinct cut and fill sequence. The latter of which has not been previously reported for these deposits. Given their age and stratigraphy it is suggested that large quantities of sediment are exchanged between these temporary storage areas and the main channel over a period of 10–2000 years. The implication of these transfers on the ecology of this dryland river ecosystem is discussed.

Key words dryland rivers; Inset flood plains; sediment storage

INTRODUCTION

Inset flood plains are common features along the lowland sections of many Australian rivers. These relatively horizontal depositional landforms are bank attached sediment bodies that occur at intermediate elevations between the riverbed and the main flood plain surface. They have also been termed in-channel benches by Woodyer (1968) and have been recognized on many rivers worldwide (e.g. Kilpatrick & Barnes, 1964; Miller *et al.*, 1971). In-channel benches are important alluvial sediment storages, the character of which is dependent on a number of factors including catchment conditions, sediment supply, and prevailing hydraulic conditions during flood events (Thoms, 2003). Indeed, up to 87% of the sediment budget of some river systems can be in the form of temporary flood plain deposits like benches (Marron, 1992). The importance of in-channel benches for retaining organic material in lowland sections of dryland rivers has been demonstrated (Thoms & Sheldon, 1997). Large amounts of organic matter can accumulate on the surface of benches and the presence of these in-channel features increase the ability of these river systems to retain organic material.

Relatively few studies have detailed the sedimentology of in-channel bench deposits. Erskine & Livingstone (1999) organized the stratigraphy of channel deposits in the Hunter River, New South Wales, into three classes: stratic sediments, massive sediments and cumulic sediments, which together with a series of repeated channel cross sections suggest these benches are unstable. Catastrophic floods in the Hunter River—those with recurrence intervals greater than a 100 years and peak discharges 10 times the mean annual flood—cause the complete destruction of benches with their subsequent construction occurring over longer periods of time by smaller flood events. This cyclic formation contrasts to the long-term stability of benches described by Woodyer *et al.* (1979) along the Barwon-Darling River in western New South Wales, Australia. Benches in this low energy river system accrete both laterally and vertically at rates depending on their elevation and to a lesser extent their situation in the channel. Finely laminated accretionary sedimentary sequences up to 5 m in depth and a lack of erosional contact surfaces attest to the long-term stability of the various sedimentary sequences. However, Thoms & Sheldon (1997) reported significant changes to the cross sectional morphology of the Barwon-Darling over the last 100 years, with notable changes to the morphology of in-channel benches. Hence, the nature of in-channel benches differs between and within rivers. Different modes of bench formation will have implications for both the physical and ecological functioning of riverine ecosystems. Indeed, exchanges of sediment between various components of a river system and at different time scales, are an important ecosystem process and one that is recognized in various riverine ecosystem models such as the River Continuum Concept of Vannote *et al.* (1980), the Flood Pulse Model of Junk *et al.* (1989) and the Riverine Productivity Model of Thorp & Delong (1994).

The objectives of this paper are 3-fold: (a) to describe the stratigraphy of in-channel benches along the Barwon-Darling River; (b) to determine the age of the benches; and, (c) to comment on how they are formed.

STUDY AREA AND METHODS

The Barwon-Darling River drains 650 000 km^2 of the north-westerly portion of the Murray-Darling Basin in southeast Australia (Fig. 1(a)). Most of its tributaries (the Condamine-Balonne, Macintyre, Gwydir, Namoi, Castlereagh and Macquarie Rivers) drain the western margins of the Great Dividing Range in northern New South Wales and southern Queensland. Others, notably the Warrego and the Paroo Rivers, have their headwaters in the more arid west and are intermittent contributors, only providing significant runoff during periods of intense rainfall. The catchment is characterised by extreme climatic variability and runoff. Average annual rainfall and evaporation range from 200–1000 mm and 500–1800 mm, respectively (Thoms & Sheldon, 2000).

The Barwon-Darling is a suspended load river with characteristic high bankfull width to depth ratios (>32) and a highly sinuous channel (sinuosities >2). It also has "complex" bankfull cross-sections (see Woodyer 1968; Woodyer *et al.*, 1979; Thoms & Sheldon, 1997) because of the presence of inset flood plains or in-channel benches. Woodyer *et al.* (1979) identified and described the stratigraphy of four inset flood plain surfaces within the Barwon-Darling channel near Walgett (Fig. 1(b)). The two lower surfaces were considered to be formed by suspended-load deposition; either point, concave, convex and lateral benches and are composed of essentially horizontal laminations (ranging in thickness from 0.1 to 14 cm) of fine inorganic sediments and organic rich mud (Woodyer *et al.*, 1979). The upper surfaces, also termed benches, are relic surfaces and part of the present flood plain being inundated about once in every 15 years (Woodyer, 1968). However, recent research by Thoms & Sheldon (1997) has shown there to be at least seven different bench levels along the Barwon-Darling (Fig. 1 (c)). Regardless of the number and type of feature, each surface in the channel reflects a response to a change in flow regime (Woodyer, 1968; Woodyer *et al.*, 1979; Thoms & Sheldon, 1997). Similar in-channel bench features have been reported along the lower River Murray in South Australia by Thoms & Sheldon (1997) and along the coastal rivers of New South Wales by Erskine & Livingstone (1999).

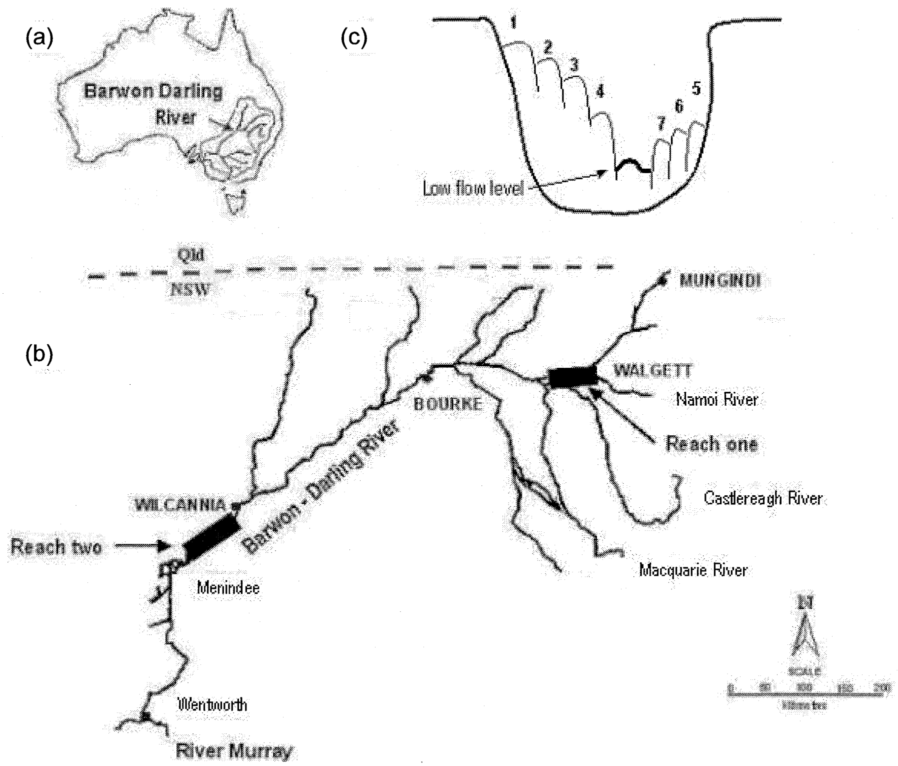

Fig. 1 (a) The Barwon-Darling catchment. (b) The Barwon-Darling River showing location of study reaches. (c) A schematic diagram of the river channel showing location of in-channel benches.

A series of pits, trenches, exposures and auger holes were dug in 98 in-channel benches along two 10 km reaches of the Barwon-Darling River. Reach one is located near Walgett in a section of river studied by Woodyer (1968) and Taylor & Woodyer (1978). Reach two is located just downstream of Wilcannia (Fig. 1(b)). The position of each bench was located using data of Thoms & Sheldon (1997) with benches being numbered sequentially from higher (Bench 1) to lower (Bench 7) elevations within the main channel (Fig 1(c)). In this study, the seven different bench levels were sampled seven times along each reach. The stratigraphy of each bench was recorded; from the surface to the low flow level and sediment samples from seven different bench levels in reach two were collected for textural analysis and optical dating.

Optical dating of sediments

Optical dating can be used to estimate the time elapsed since buried sediment grains were last exposed to sunlight (Aitken, 1998). This method of sediment dating makes use of the fact that daylight releases charge from light-sensitive electron traps in crystal lattice defects in minerals such as quartz and feldspar. The release of trapped charge by light resets the optically stimulated luminescence (OSL) signal; this process is commonly referred to as bleaching. When grains of quartz are buried and hidden from light, they begin to accumulate a trapped-charge population due to the effects of ionising radiation, such as that arising from radionuclides naturally present in the deposit. This trapped-charge population increases with burial time in a measurable and predictable way. As a result, the time elapsed since sediment grains were buried can be determined by measuring the OSL signal (burial-dose) from a sample of sediment and estimating the ionising radiation to which it has been exposed since burial (the dose rate) such that: burial-time = burial-dose/dose rate. Optical dating has been successfully used to date aeolian, freshwater and marine sediments (e.g. Bailey *et al.*, 2001; Murray & Clemmenson, 2001; Radtke *et al.*, 2001; Hilgers *et al.*, 2001; Olley *et al.*, 1999, 2004; Murray & Olley, 2002).

Analytical methods

All OSL measurements were made on two Risø automated TL/OSL readers, each fitted with an EMI 9635QA photomultiplier tube and three U-340 transmission filters. The readers are also equipped with green-plus-blue light sources (420–550 nm), giving an illumination intensity of about 25 mW cm^{-2} on the sample (H. Christiansen, personal communication). Small aliquots (40–60 grains) of quartz were analysed using the regenerative-dose protocol described by Roberts *et al.* (1998), which was modified from those presented by Murray & Roberts (1998). The dose (D_e) for each aliquot was calculated as:

$$D_e = (L_n/L_r) \times (T_2/T_1) \times \text{regenerative dose} \qquad (1)$$

where L_n, L_r, T_1 and T_2 are the OSL signals produced by the natural, regenerative, test 1, and test 2 doses. The test dose signals are used to correct for any changes in OSL sensitivity between the natural and regenerative dose cycles. The samples were illuminated for 125 s at 125°C. In each case, the OSL signal was integrated over the first 20 s of illumination, and the OSL signal integrated over the final 20 s was subtracted as background. The reported uncertainties are based on the counting statistics, curve fitting errors and incorporate calibration uncertainties for the beta sources. A preheat temperature of 240°C for 10 s was used for L_n and L_r measurements, and a cut-heat to 160°C was given after each test dose.

To determine the field dose rate a sub-sample was taken from each of the OSL samples. These were analysed by high-resolution gamma spectrometry for ^{238}U, ^{226}Ra, ^{210}Pb, ^{228}Th, ^{228}Ra, and ^{40}K concentrations. Sample masses of about 200 g were cast in resin and counted for 24 h. The intrinsic germanium detectors were calibrated using the Canadian Centre for Mineral and Energy Technology (CANMET) uranium ore BL-5, and thorium nitrate refined in 1906 (Amersham International). Independent checks on calibration were performed using various standards from the USA National Bureau of Standards, and IAEA inter-comparisons.

Textural analysis

Particle size analysis was done on a 5 g subsample which was ultrasonically dispersed in a 5% sodium hexametaphosphate solution before being sized by a Malvern Autosizer, with a 63 mm lens. Results were expressed in phi (ϕ) units, where $\phi = -\log_2$ (mm). Each sediment sample was analysed three times to check instrument precision and to calibrate the instrument. National Bureau Standards of known sphere size were run after every 25 samples.

RESULTS

Particle size distribution and bench stratigraphy

Sediments contained in the various in-channel bench deposits were dominated by medium to fine sand and silt-clay mixtures. Median grain sizes ranged from 1.09 to 3.99 ϕ. Distinct variations in sediment colour and texture occur both between and within the different bench deposits. Lower level bench deposits (bench levels 5–7, Fig. 1(c)) are generally associated with coarser sediments (median grain sizes: 1.09–2.69 ϕ) in comparison to higher-level bench deposits (median grain sizes of bench level 1–4: 2.29–3.99 ϕ). Two distinct stratigraphic sequences were recorded in the higher-level benches (bench levels 1–4) (Fig. 2). The first consists of an intricate series of fine laminated deposits (Fig. 2(a)). Here, lenticular sand layers were common, some reaching a thickness of 35 cm although they did decrease in thickness up profile. In general, sand layers were separated by thin layers of a silt-clay mixture which, contained variable levels of organic matter (loss on ignition: 5.86–39.56%). Graded bedding was common and three different grading configurations were recorded; a simple grading from either sand to silt-clay or silt-clay to sand; a complex grading of sand to silt-clay to sand or silt-clay to sand to silt-clay; and, multiple grading in which there was several sequences of complex grading. The deposits contained flat and wavy parallel laminations as well as cross laminations and all contacts between the individual layers were generally depositional in nature. The second stratigraphic sequence recorded in the higher benches differs to that just described in that several erosional contacts were noted in some benches (Fig. 2(b)). Distinct cut and fill sequences were recorded in a number of level 2, 3 and 4 benches and these were traced along their length. In one level 4 bench, three cut and fill sequences were recorded. The silt-clay layers found in bench levels 2, 3 and 4 contained elevated levels of organic matter compared to that found within the bench level 1 deposits (loss on ignition of bench level 1: 3.24–12.45% and bench levels 2–4: 23.34–45.67%). A general fining upward sequence grading from a coarser basal layer of well-sorted medium sands through to a very fine sand coarse silt mixture at the surface was recorded in the lower level benches: bench levels 5–7 (Fig. 2(c)).

Optical dating

From Reach two, a sediment sample was collected at the boundary of the main channel–bench deposit boundary, thereby providing an age for the main channel of the Barwon-Darling. Further samples were collected from within the higher bench deposits, especially from those positions above and below notable erosional contacts. Dose rates were calculated using the conversion factors of Olley *et al.* (1996) and the computer program listed in Roberts *et al.* (1993). The water content measured in the samples ranged from 7.8 to 28.1 percent of their dry weight. These water concentrations are taken to be representative of the long-term average, and have been assigned relative uncertainties of ±50%. For all samples the dry dose rate, determined by gamma spectrometry, was corrected for these water concentrations, following Aitken (1998).

The cosmic-ray dose rates were calculated from Prescott & Stephan (1982) and Prescott & Hutton (1988). Beta-attenuation factors were taken from Mejdahl (1979) and the effective alpha dose rate contribution has been estimated using an alpha-efficiency “a” value for

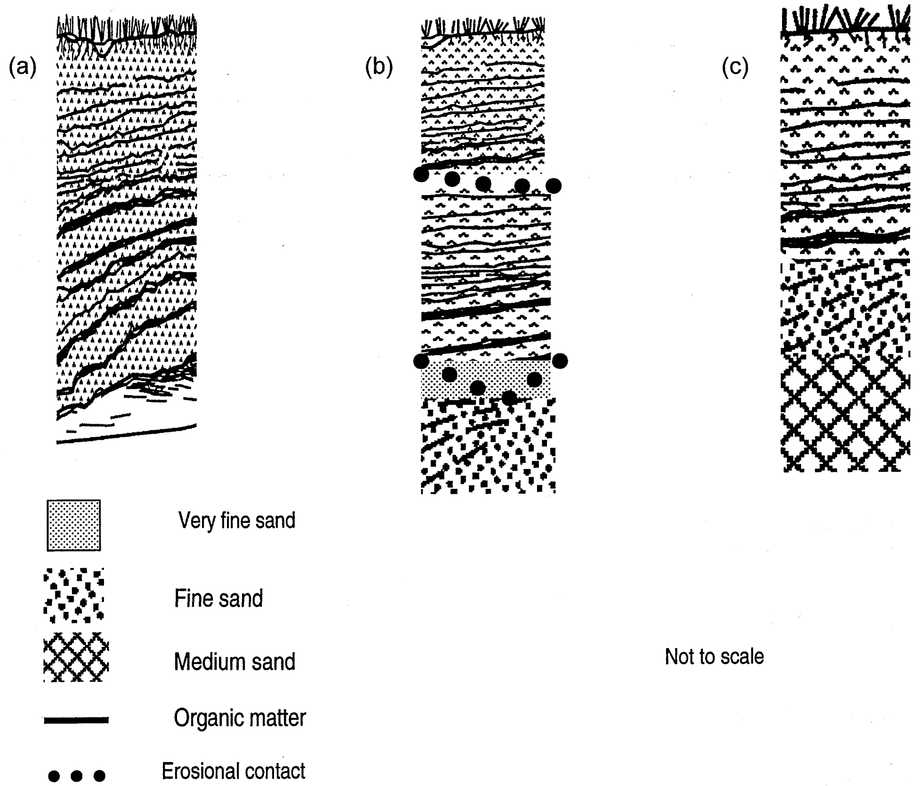

Fig. 2 Stratigraphy of in-channel benches. (a) Series of finely laminated sediments; (b) cut and fill sequence; and, (c) general fining upward sequence

quartz of 0.10 ± 0.02. The alpha dose rate contribution is about 5% of the total dose rate. The calculated total dose rates are presented in Table 1 and range from 1.64 ± 0.16 to 2.52 ± 0.22 mGy year^{-1}.

Doses measured on individual aliquots of each of the samples using the regenerative-dose, single-aliquot OSL protocol are presented in Table 1. There is clearly a wide spread of doses present in all of the samples, indicating that the sediments were not fully bleached at the time of deposition. For example, in sample CS–D3 the measured doses range from 0.00 ± 0.08 Gy to 22.6 ± 1.5 Gy. In such circumstances the best estimate of the burial dose

Table 1 Measured water contents (% dry weight), dose rates (D_r), dose range, burial dose estimates (D_b), and calculated burial ages for fluvial sediment samples CS–D1 to CS–D5.

	Water content %	D_r (mGy year^{-1})	Dose range (Gy)	D_b (Gy)	Age (years)
CS–D1	16.5	1.76 ± 0.17	0.41 ± 0.03 to 60 ± 2	0.43 ± 0.04	240 ± 50
CS–D1a	15.2	1.96 ± 0.18	0.754 ± 0.015 to 86 ± 4	0.76 ± 0.01	390 ± 60
CS–D2	7.8	2.18 ± 0.21	0.11 ± 0.05 to 60 ± 2	0.21 ± 0.01	95 ± 20
CS–D3	28.1	2.05 ± 0.25	0.00 ± 0.08 to 22.6 ± 1.5	0.06 ± 0.07	30 ± 20
CS–D4	17.9	1.64 ± 0.16	3.32 ± 0.17 to 54 ± 4	3.61 ± 0.16	2200 ± 250
CS–D5	8.4	2.52 ± 0.22	26 ± 3 to 140 ± 3	32.6 ± 2.1	13 000 ± 1500

will be provided by the aliquots containing the lowest doses (Olley *et al.*, 1998, 1999, 2004). Consequently, the burial dose for each sample has been calculated using the lowest dose population determined using the minimum age model (Galbraith *et al.*, 1999). The burial dose (D_b) and calculated ages are presented in Table 1.

DISCUSSION

Our understanding of many basic ecosystem processes in large dryland river systems is poor in comparison with those from more humid and temperate regions (Thoms, 2003). Current models of river system function cannot be easily applied to those in a dryland setting (Graf, 1988; Walker *et al.*, 1995) partly because these systems have highly variable and unpredictable flow and sediment regimes, with episodic connections between the main river channel and adjacent flood plain. The development of seven bank attached bench deposits along the Barwon-Darling River may be considered as a morphological adjustment in response to the highly variable flow and sediment regimes of the region (Thoms *et al.*, 2004). As a result of their presence, the Barwon-Darling River has a "nested compound" channel where lower flow channels are contained or "nested" within a series of higher flow channels, with each nested channel being marked by the horizontal surface of each bench. The nested channels are markedly younger than the main channel—the main channel had a buried date of 13 000 years compared to burial dates ranging from <20 to 2200 years for the in-channel deposits. The nested compound channel of the Barwon-Darling River differs from the compound channels in the Gila River, Arizona as described by Graf (1988). The Gila has a well-defined inner low flow channel that meanders within a much larger outer flood channel, which is often braided in planform. This reflects two modes of operation (Graf, 1988): a single low water channel and a wider high water channel represent an adjustment to a particular flow regime that is dominated by near continuous low flows coupled with a few rare high-discharge events. The multiple nested channels of the Barwon-Darling may then reflect multiple modes of operation. Hence, within-system morphological variability and its apparent relationship to hydrological and sediment regimes illustrate the complexity of dryland river systems.

Large quantities of sediment are stored within the main channel of the Barwon-Darling River as evidenced by the presence of seven distinct benches. Collectively, the morphogenesis of in-channel benches along the Barwon-Darling River is highly complex. Level 1 benches located at the highest elevations in the channel are relatively stable, displaying a stratigraphy characterized by sequences of thin interbedded sand and silt-clay layers (Fig. 2(a)). They are also the oldest in-channel deposits with a burial date of ~2200 years (Fig. 3). These benches are similar in nature to those described by Woodyer *et al.*, (1979). Level 2–4 benches, located at more intermediate elevations within the channel are not as stable and are younger than Level 1 benches. Whilst the overall stratigraphy of Level 2–4 benches was similar to Level 1 benches distinct cut and fill sequences were evident in the former and not the latter. Fill sediments were much younger with burial dates of 30–95 years compared to those immediately below erosional contacts—burial dates between 240 and 340 years (Fig. 3). Level 5–7 benches, at the lowest elevations in the channel, were the youngest deposits (all deposits <20 years) and all displayed a general fining upward sequence. These benches are probably formed in a similar manner to those described by Erskine & Livingstone (1999) where larger flood events completely rework these lower

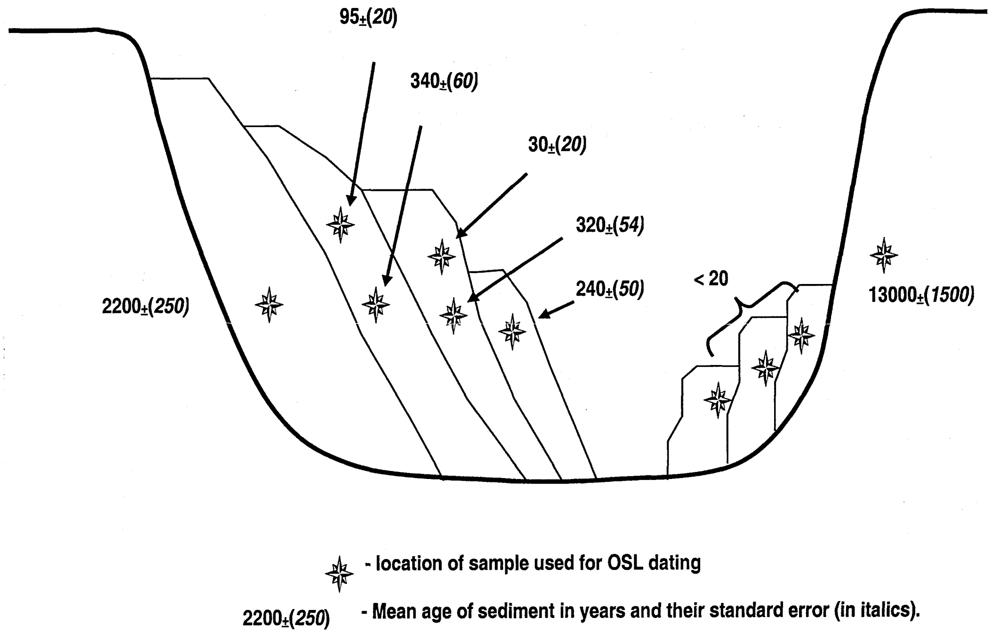

Fig. 3 A schematic diagram of a typical series of in-channel bench deposits and the age of the various in-channel benches.

elevation deposits and smaller floods are responsible for their construction. The variable sedimentology of the in-channel deposits of the Barwon-Darling reflects the variable discharge and sediment regimes and geomorphic scales of operation of this dryland river system.

Three modes of bench formation occur along the Barwon-Darling River:

(a) The long-term vertical and lateral accretion of benches located at higher channel elevations.
(b) Vertical and lateral accretion interrupted by the partial reworking of in-channel deposits at intermediate channel elevations.
(c) The complete reworking of lower level benches during flood events followed by their formation by smaller events.

Modes 1 and 3 have only been previously reported (i.e. Woodyer *et al.*, 1979; Erskine & Livingstone, 1999). Partial reworking and bench deconstruction followed by an accretionary stage similar to that recorded for benches located at higher elevations in the channel reflects the presence of regular cut and fill sequences within Level 2–4 benches of the Barwon-Darling. Olley & Caitcheon (2000) show that the sediment currently in transport in the Barwon-Darling does not originate from contemporary upland erosion, but is derived from lowland areas of the catchment that contain more weathered material. We propose that partial reworking of these in-channel bench deposits at time intervals up to 95 years is an important source of sediment to the river; a finding consistent with this previous observation. Moreover, large amounts of organic matter are present within these bench deposits and this material may represent an important albeit longer-term source of organic carbon to the food web of this dryland river.

Inset flood plains are temporary sediment storage areas. Combining data on the morphology of the different benches, their stratigraphy and age, approximately 1.186 m m^3 of sediment is stored within the in-channel benches of the two study reaches. The residence time of sediment differs between the various bench levels. It is estimated that 55 600 m^3 of sediment is reworked over a 20-year time span from the lower benches (benches 5–7)—5% of the total volume of sediment in the bench deposits. By comparison, 181 440 m^3 (15%) would be made available from the upper sections of the mid level benches (benches 2–4) every 20 to 100 years whilst 214 560 m^3 (18%) is reworked every 100 to 400 years from the lower sections of these benches. Larger volumes of sediment—735 000 m^3 (62%) are made available from the high level benches (bench level 1) over time periods up to 2000 years. Thus sediments contained within the in-channel benches constitute a large secondary and local sediment source in this dryland river system.

There has been a strong trend in recent years to view rivers as ecosystems. This requires a holistic framework that recognize:

(a) interconnections between the physical, chemical and biological components of riverine ecosystems and the different scales of operations of each;
(b) linkages between upstream–downstream and the river channel–flood plain; and;
(c) that different parts of the river system may operate over different time scales.

Large rivers are often considered less retentive than small streams for accumulating organic material, mostly the result of a decrease in retentive structures (Webster *et al.*, 1994). The apparent decrease in the availability of retentive structures in large dryland rivers ignores the role of in-channel benches. These variable geomorphic surfaces along river valleys are known to create complex physical patterns that are reflected in the development of riparian plant communities and the distributions of aquatic biota (Gregory *et al.*, 1991). In the Barwon-Darling River, in-channel benches not only retain large quantities of surface organic material (Thoms & Sheldon, 1997) but bench deposits are also a source and a sink of organic carbon that may be made available to aquatic food webs over time intervals of up to 100 years. Dryland rivers do experience relatively frequent within-channel floods that inundate in-channel "bench" features at one or more levels, depending on the magnitude of flow. Geomorphic in-channel complexity and its ability to retain organic material, therefore, means that although the dominant lateral movements of organic material from the flood plain and riparian zone into the channel will still occur during large overbank flows, smaller "pulse" inputs will also occur with each in-channel rise and fall in water level and during partial reworking of individual bench features. In dryland rivers, where large overbank flows only occur infrequently smaller "pulse" inputs of organic material from both the surface and during erosion events may also` be vital for the integrity of these ecosystems.

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