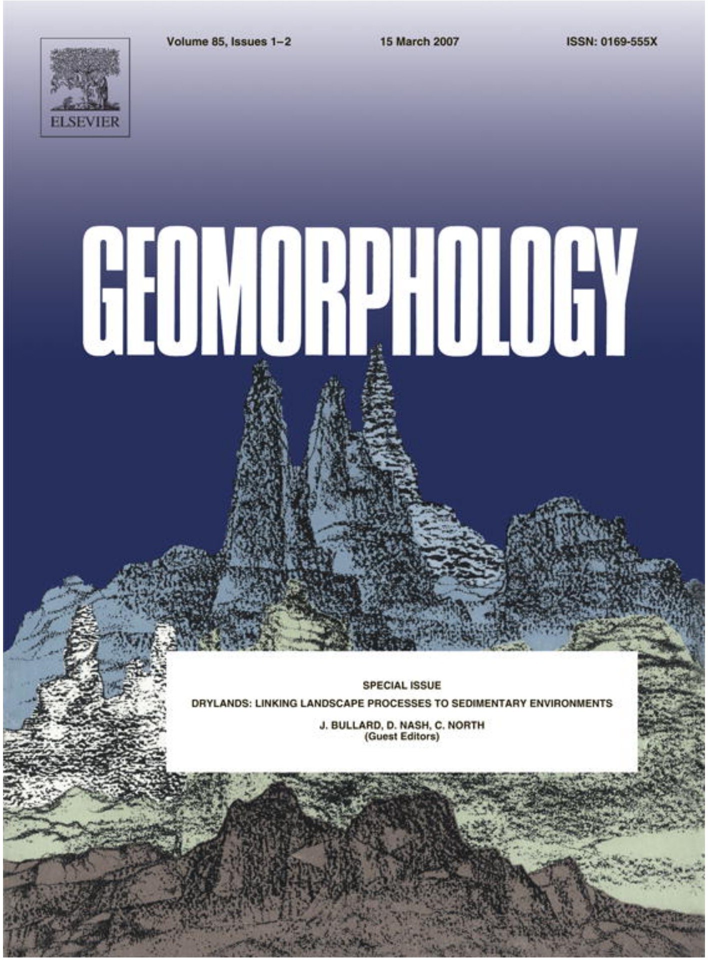
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Threshold-dominated fluvial styles in an arid-zone mud-aggregate river: The uplands of Fowlers Creek, Australia

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Abstract

Fowlers Creek is a mud-aggregate fluvial system. Floodplain muds dominate the river's deposits and consist of silt, fine to very fine quartzose sand, and clay. Up to ~80% of the silts and clays are bound into sand- and silt-sized aggregates and comprise a substantial component (>42%) of the floodplain muds. Mud-aggregate sediments behave like sands during transport, and as a result, muds can be deposited under conditions of greater flow velocity than would otherwise be the case. Newly deposited floodplain muds are loose and easily entrained, but older floodplain muds are cohesive, and the distribution of modern and older floodplain muds influences erosion patterns across Fowlers Creek.

In the lower order streams of the Fowlers Creek uplands, alternate reaches of shallow rectangular channels and unchannelled floodplains collectively form discontinuous ephemeral streams. These landform sequences consist of gullies, coalescing downstream to arroyos, which terminate in distributary intermediate floodouts. At Fowlers Creek, floodouts are preferentially located at tributary junctions, reflecting their origin during very large floods. At floodouts, low slope and high vegetation density promote sheetflow infiltration and landform stability. Their efficiency in retaining runoff make floodouts drought refugia; they are an important ecological element in this arid area.

The higher order channel of the mid-uplands is a mobile, low-sinuosity, single-thread arroyo, incised into wide muddy unstable floodplains. Fluvial processes are dominated by episodic flood-driven channel avulsion, and variability in stream energy and boundary resistance contributes to a non-equilibrium fluvial style. Frequent reach-scale channel relocation is accompanied by the burial of the abandoned channel in floodplain muds and both erosion and aggradation in downstream floodplains.

Keywords: Arid environment; Arroyos; Ephemeral streams; Floodplains; Fluvial sedimentation

1. Introduction

Braided channels and single-thread, wide and shallow channels have been regarded as characteristic of desert environments, but dryland rivers encompass a much wider range of river types (Tooth, 2000; Nanson et al., 2002). They may contain arroyos, or unchannelled reaches (floodouts), or both, and may transport a mud-aggregate sediment load. In this study, a mud-aggregate river with both arroyos and floodouts is described, and the relationships between its fluvial processes and its mud-aggregate sediment load are explored. Firstly, mud-aggregate rivers and rivers containing arroyos and floodouts are briefly reviewed.

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1.1. Mud-aggregate rivers

Although aggregated grains of silt and clay are a fundamental component of soils (Marshall et al., 1996), such particles usually disintegrate during fluvial transport. The silts and clays thus liberated are then deposited by settling out from slow or still waters. Interpretation of mudstones preserved in the rock record usually reflects this expectation of low-energy depositional environments (Nanson and Croke, 1992; Makaske, 2001).

However, some more robust mud aggregates are able to survive fluvial transportation (Nanson et al., 1986; Maroulis and Nanson, 1996); behaving like sands, they can be deposited in bedforms (Rust and Nanson, 1989; Gierlowski-Kordesch, 1998; Gierlowski-Kordesch and Gibling, 2002; Müller et al., 2004). Such aggregates originate in vertisols or other soils containing swelling clays (Nanson et al., 1986; Rust and Nanson, 1989, 1991; Maroulis and Nanson, 1996; Gibling et al., 1998; Müller et al., 2004). Vertisols form where aridity exceeds moisture for at least part of the year, contain > 30% clay, usually including some smectites, and are often associated with deep large cracks and gilgai (Blokhuis, 1996; Mermut et al., 1996). Many vertisols are self-mulching (generate a surface of loose soil aggregates) but others can be massive, and this is sometimes associated with a lower clay content (Blokhuis, 1996).

After mud aggregates are deposited, the aggregate structure is commonly destroyed (Nanson et al., 1986; Rust and Nanson, 1989; Maroulis and Nanson, 1996; Gibling et al., 1998; Gierlowski-Kordesch and Gibling, 2002). In the rock record, mud aggregates are usually preserved only under favourable circumstances, e.g., rapid burial rate, early carbonate cementation, or protection by non-compressible clasts (Rust and Nanson, 1989; Gierlowski-Kordesch and Gibling, 2002; Müller et al., 2004).

Mud aggregates are being increasingly recognised in modern and ancient fluvial systems. Cooper Creek is the most comprehensively documented (Nanson et al., 1986; Maroulis and Nanson, 1996; Tooth and Nanson, 2000) and is the modern analogue most commonly applied to ancient mud-aggregate rivers (Rust and Nanson, 1989; Marriott and Wright, 1996; Gierlowski-Kordesch, 1998).

1.2. Discontinuous ephemeral streams, erosion cells, arroyos and floodouts

Described in a fluvial setting by Schumm (1977), scour-transport-fill (STF) landform sequences form *erosion cells* in non-fluvial as well as fluvial landscapes (Pickup, 1985; Tongway and Ludwig, 1990). In Australia, erosion cells are a common and an ecologically important landscape component (Pickup, 1985; Pickup, 1988; Bourke and Pickup, 1999). They consist of a sediment source (the scour zone), a transport zone, through which sediment is routed, and a fill zone, where sediment is deposited and plant growth is enhanced (Pickup, 1985). Erosion cells can form complex interlocking mosaics at different scales (Pickup, 1985; Pickup, 1988) (Fig. 1) and are likely where episodic short-lived rainfall promotes discrete transport events (Pickup, 1988). Scour-transport-fill events on a mega-flood scale can have long-lasting effects on fluvial geomorphology (Bourke and Pickup, 1999).

Alternating arroyos and unchannelled valley flats can be thought of as a linear series of erosion cells. Termed discontinuous ephemeral streams by Bull (1997), they represent STF sequences in which gullies and badlands

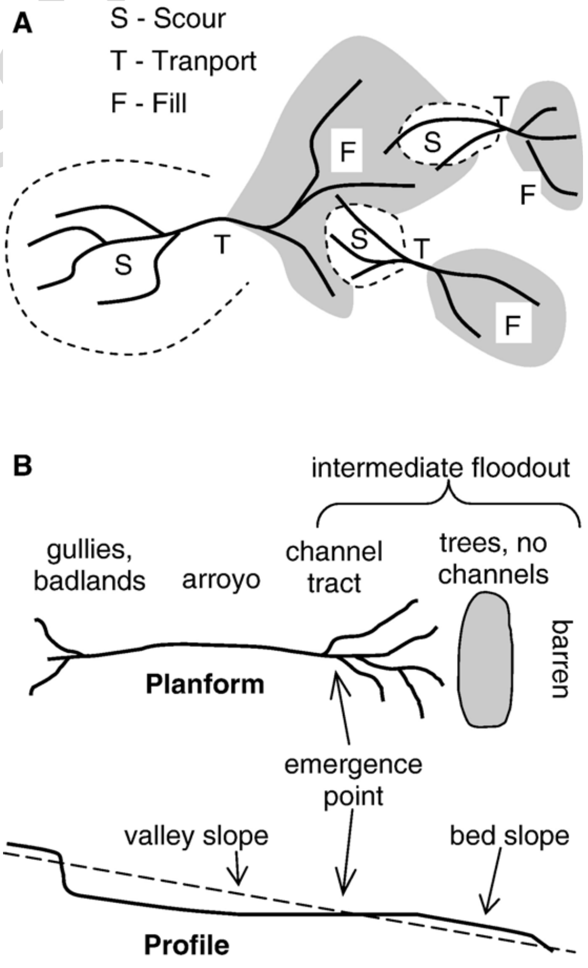

Fig. 1. (A) A mosaic of erosion cells (after Bourke and Pickup 1999). Flow is from left to right, grey areas indicate sediment deposition. (B) Planform and profile of a discontinuous ephemeral stream (after Bull, 1997).

form the scour zone, an arroyo is primarily a zone of transport, and sediment and water are deposited across the "channel fan". Differences in slope between channel and valley-floor govern the location of these elements (Fig. 1) (Schumm and Hadley, 1957; Bull, 1997). Channel slope decreases from the steep gully-head towards the central arroyo, where the channel floor has a similar slope to the valley floor. Downstream, the channel slope decreases further until it intersects the valley-floor slope. The channel vanishes and sheetflow spreads across the distributary "channel fan" (Bull, 1997). The increased slope at the toe of the "channel fan" promotes incision, initiating the next scour-transport-fill sequence downstream (Pickup, 1985; Bull, 1997).

The fluvial processes in discontinuous ephemeral streams fluctuate about the threshold between valley-floor aggradation and channel incision (Bull, 1997). Aggradation is promoted by factors which increase flow resistance or decrease flow strength (dense floodplain vegetation, shallow unchannellised flow, or a decreased slope). Incision is promoted by factors which increase flow strength above that which is required to entrain sediment, or which decrease valley-floor strength, making erosion more likely (decreased vegetation, increased slope, increased discharge during floods, or the prior deposition of a surface layer of erodible sediments) (Bull, 1997). Aggradational or erosional reaches are relatively stable, until something triggers a switch to the opposite state (Bull, 1997), as described below for the unchannellised "channel fan" or floodout.

"Channel fans" (Bull, 1997) and fill zones (Pickup, 1985; Pickup, 1988), both unchannellised areas downstream from which flows re-gather into new channels, are *intermediate floodouts* (cf. terminal floodouts, where flows dissipate) (Tooth, 1999). Where the central arroyo emerges from the transport zone (Fig. 1), the system becomes aggradational (Bull, 1997; Tooth, 1999). The channel widens and shallows in the floodout's most upstream zone (the *channel tract*, Fig. 1), then disappears downstream. Water spreads across the floodout surface as sheetflow, allowing infiltration and sediment deposition (including seeds and organic matter). Thus, the floodout is an ideal site for plant germination and survival.

Floodout stability is maintained by self-reinforcing processes, in which the low slope enhances infiltration which supports vegetation, and the vegetation's density promotes infiltration, inhibits erosion, and promotes sediment deposition, all of which maintain the low slope. Vegetation's critical role in maintaining floodout stability (Bull, 1997; Bourke and Pickup, 1999) requires a moderate level of aridity, such that vegetation flourishes in areas of extra moisture but has difficulty surviving elsewhere. If a channel is incised through the area, the balance of fluvial process swings towards erosion. Flows will bypass the floodout, and its vegetation will diminish or die (Pickup 1988; Bull, 1997). Thus, a floodout's downstream section, where re-establishing drainage captures runoff from the floodout's surface, may be barren (Fig. 1).

Scour-transport-fill processes create and maintain the gully–arroyo–floodout landform sequences which are collectively known as discontinuous ephemeral streams. The formation of discontinuous ephemeral streams is promoted by an over-abundant supply of poorly sorted but dominantly fine sediment which balances erodibility with cohesion (Cooke and Reeves, 1976; Bull, 1997). Fine sediments and swelling clays promote runoff from a bare surface (Campbell, 1997; Dunkerley and Brown, 1997), while also fostering water retention where other factors have allowed infiltration (Bull, 1997). A strongly alternating climatic pattern will predispose the soil to piping or gullying, as will the soil characteristics of dispersibility (swelling-clay and sodium content), loose texture, fine grain size, and the presence of macropores (Campbell, 1997; Bull and Kirkby, 2002).

1.3. Fowlers Creek

Fowlers Creek is a ~55-km-long endorheic river in far western New South Wales, Australia (Fig. 2). The climate is dry, with hot summers and mild winters, and an average annual potential evaporation (~2800 mm) which exceeds the median annual rainfall (200 mm) by an order of magnitude (Australian Bureau of Meteorology, 1988). Rainfall over Fowlers Creek is variable in timing, intensity and spatial distribution, ranging from short intense storms over a single tributary to widespread gentle rain.

Fowlers Creek is usually dry, but may flow several times a year to sub-bankfull, bankfull or overbank levels. Most flows last only hours to days. According to how many and which tributaries receive rain, flows may start, peak, and finish almost anywhere in the drainage network. Tributary asynchronicity is common. In neighbouring Sandy Creek, extreme flow events have occurred on centennial and millennial timescales (Jansen, 2001), and Fowlers Creek is likely to have experienced a similar pattern. The limited available discharge data (five flows over an 8-month period) show that short flows have a flashy hydrograph, and longer flows are multi-peaked, reflecting the input of different tributaries.

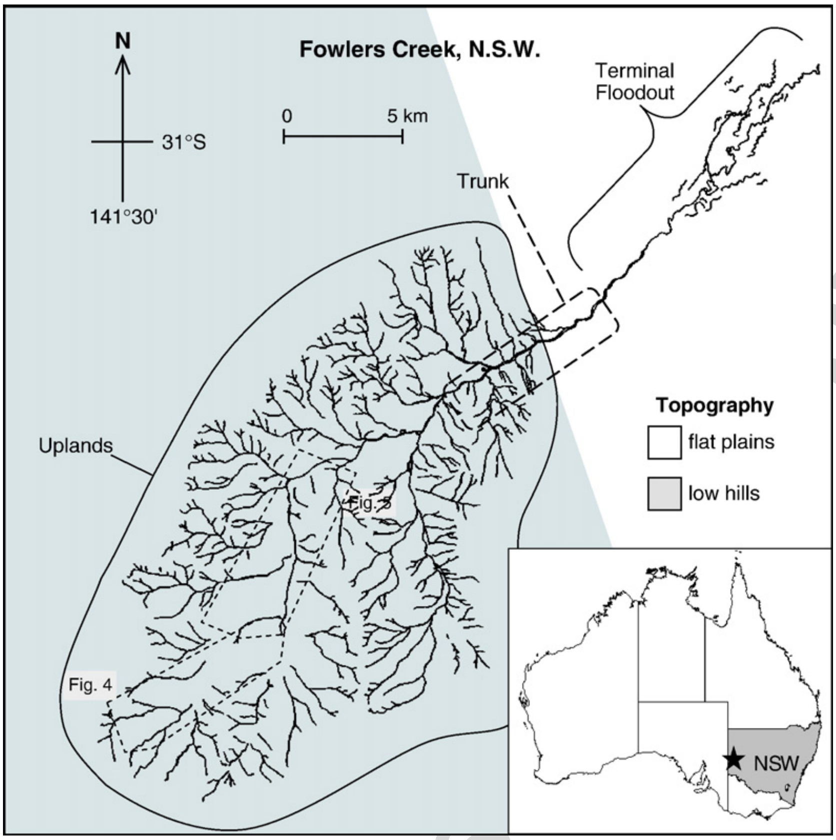

Fig. 2. The location of Fowlers Creek in New South Wales (Australia), and its three geomorphic subregions: uplands, trunk, and terminal floodout. Flow is from southwest to northeast. Dashed areas outlined are shown in Figs. 4 and 5.

Underlying geology, governing both down-valley slope (Table 1) and sediment supply, divides Fowlers Creek into three geomorphic sub-regions (uplands,

Table 1
Fowlers Creek down-valley and cross-valley slopes

Reach type	Down-valley slopes %		Cross-valley slopes %	
	Floodplain	channel	Towards channel	Away from channel
Fowlers Creek (entire)	0.27			
Fowlers Creek uplands	0.36			
Fowlers Creek trunk	0.23			
Fowlers Creek terminal floodout	0.17			
Proximal uplands	0.61–0.78	0.59–0.74	0.44–0.57	
Channel tracts	0.49–0.52	0.27–0.37	0.40–2.24	0.34–1.10
Central floodout	0.35–0.40	(no channel)	(no channel)	
Mid-uplands	0.21–0.30	0.04–0.61	0.14–0.27; *0.62	

* Cross-valley slope at Site12.

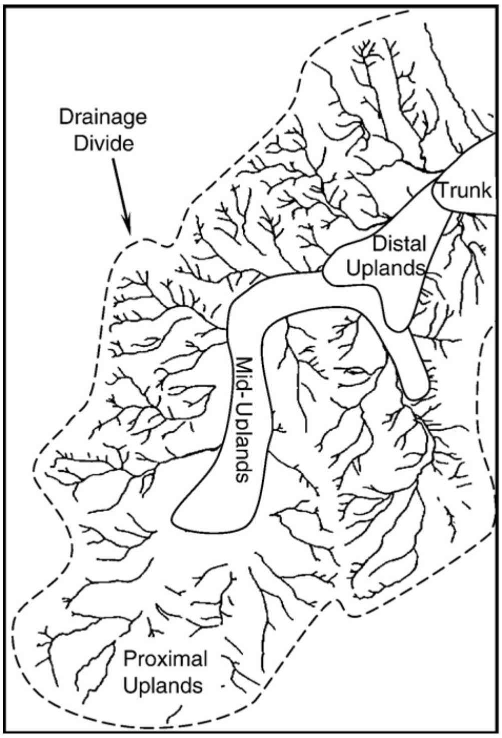

Fig. 3. The uplands are subdivided into proximal, mid-, and distal uplands.

trunk, and terminal floodout, Fig. 2), each possessing a characteristic fluvial style. In the trunk, the channels are anabranching, and in the terminal floodout the creek becomes meandering and diminishes to disappear amongst gilgai-covered plains.

The uplands cover >75% of Fowlers Creek's total area (Fig. 2), and are the source of most of the water and sediment which flows through the creek. A dendritic network of creek channels is incised into wide red-brown silty floodplains, which occupy shallow valleys between low hills. On the hillslopes, Adelaidean metasediments (Cooper et al., 1975) and a ≤1-m mantle of silty sediment combine to form contour-banded stony gilgai. Hillslope regolith includes massive to pedal loams and loamy sands, which contain smectite clays and abundant sand-sized mud aggregates (Corbett, 1973; Mabbutt et al., 1973; Ward and Sullivan, 1973; Chartres, 1982a,b).

The proximal uplands, occupying the upstream sector of the system, consist of a narrow zone of rocky hills at the drainage divide, surrounding an area of lower-order alluvial channels (up to third-order, Figs. 2, 3). The mid-uplands contain the highest order channels of the main drainage axis. The boundary between mid- and proximal uplands occurs where tributary channels join the main drainage axis and is characterised by a widening of the floodplain (from tens to hundreds of metres), a decrease in floodplain slope (Table 1), and often, the disappearance of the creek channel (Figs. 2 and 5 and e.g., the Enclosure Tank branch, Fig. 4). Unchannelled reaches also occur at some tributary confluences within the proximal uplands (e.g., the Little Acacia Tank branch, Fig. 4). (The distal uplands, which are transitional to the trunk, are not discussed here.)

In the proximal and mid-uplands, channel banks and floodplains are vegetated by sparse to closely spaced chenopod bushes and grasses. Riparian trees are uncommon, except in a few reaches (described below) which carry river red gum trees (*Eucalyptus camaldulensis*). In contrast, the channel banks in the trunk and terminal floodout carry a dense population of gum trees.

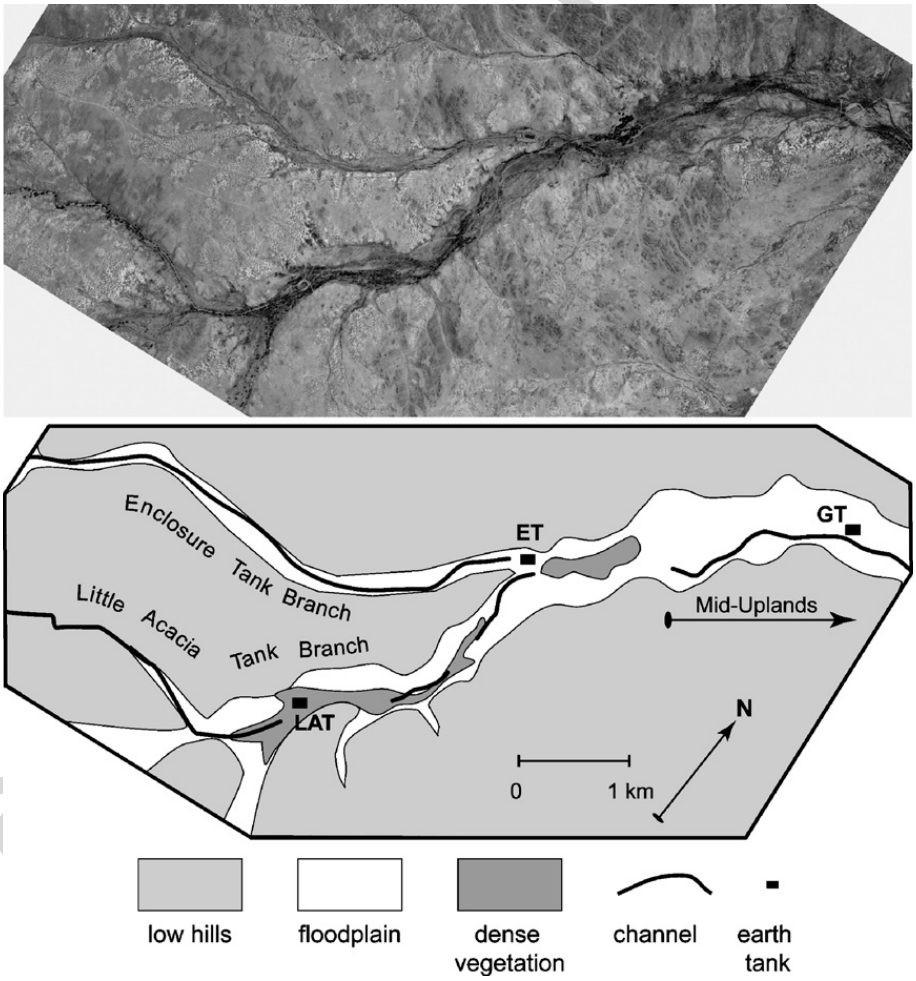

Fig. 4. Aerial photograph and sketch map of the proximal uplands; see Fig. 2 for location. Three earth dams are shown: Little Acacia Tank (LAT), Enclosure Tank (ET), and Gum Tank (GT). Gum Tank indicates the area of overlap with Fig. 5. Two lower-order streams of the proximal uplands are shown: the Enclosure Tank branch and the Little Acacia Tank branch. Flow is from left to right.

1.4. Methods

At 1–2-km intervals along the length of Fowlers Creek cross-sections were surveyed and the elevation established. From these measurements, floodplain slope and bankfull channel capacity were calculated. Flood capacity was calculated using flood debris elevations. The recurrence intervals represented by the floods so measured cannot be calculated with the available data, but since they were regarded as “normal” by local residents, they are estimated as having a recurrence interval of < 20 years.

At each site, thalweg and bank sediment samples were taken for grain size analysis, and the geomorphological and sedimentological features recorded. Bank stratigraphy was described with particular reference to the distribution of floodplain mud layers. The age of floodplain muds was assessed by stratigraphic position, burial of European artefacts, and dating by Optically Stimulated Luminescence.

The standard practice of cleaning and disaggregating fine sediments before grain size analysis destroys aggregates which may be a feature of sediment transport (Lewis and McConchie, 1994a,b). Bank sediment samples were therefore analysed in both the as-transported condition, without pretreatment, and in the fully disaggregated condition, with pretreatment (HCl, H_2O_2, and dispersal with sodium hexametaphosphate in an ultrasonic bath).

The grain sizes of thalweg sediments and the fully disaggregated bank samples were measured using dry sieves (gravel and sand fractions) and a Malvern

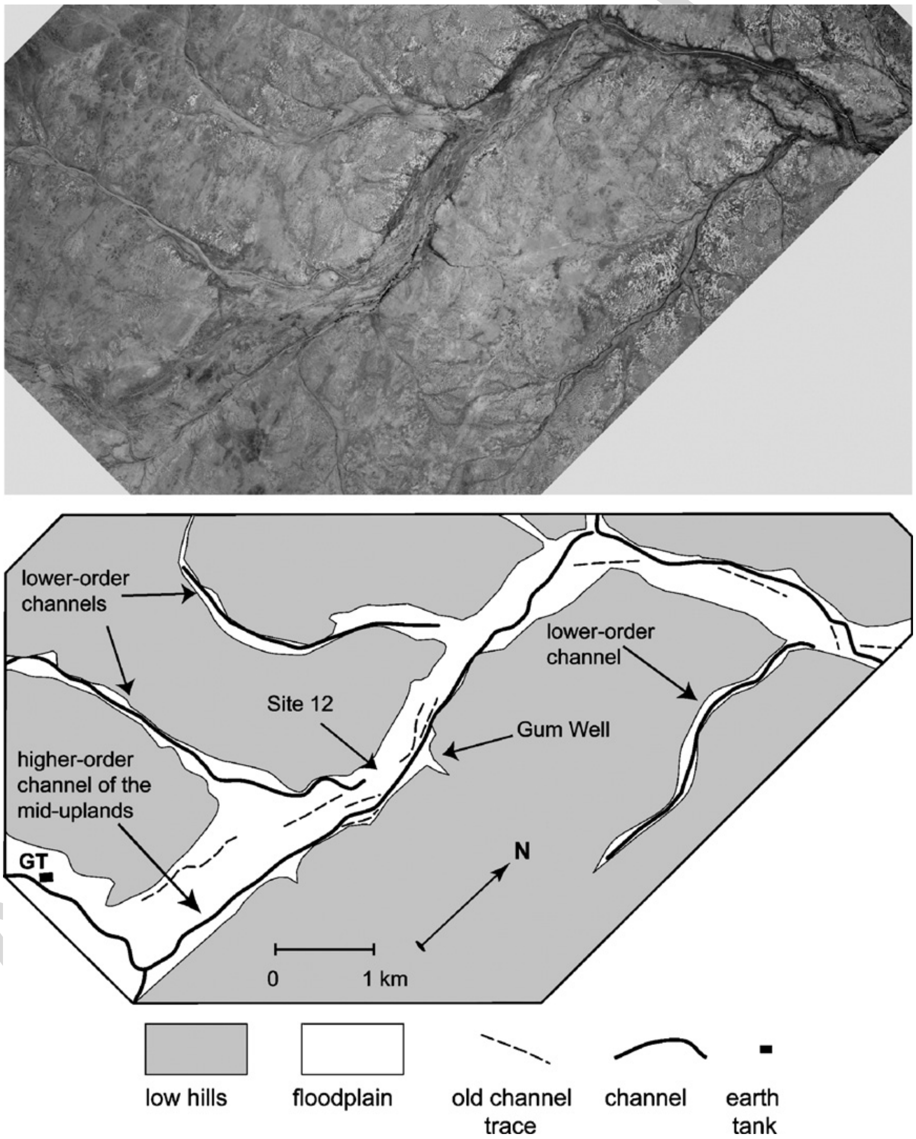

Fig. 5. Aerial photograph and sketch map of the mid-uplands; see Fig. 2 for location. Gum Tank (GT) indicates the area of overlap with Fig. 4. Flow is from left to right.

Mastersizer 2B.2 laser particle sizer (silt and clay fractions). The data were analysed using GRADISTAT (Blott and Pye, 2001). The as-transported bank samples could not be measured in the same way because cryptogam growth in the wet samples made laser particle-sizing inaccurate. Instead, they were moistened for 24 h, then made into a slurry and the relative proportions of (gravel + sand)/silt/clay measured using an ASTM soil hydrometer with a Beuyoucee scale. Comparison of fully disaggregated and as-transported grain size distributions revealed the proportion of sediment present as sand-sized mud aggregates. Fully disaggregated bank sediments are only discussed in that context. Elsewhere, sediments are described in their as-transported state.

2. Sediments

The channels of the Fowlers Creek uplands (Figs. 4, 5) carry a bedload of poorly sorted quartzose and lithic gravelly coarse sand (Fig. 6). The channels lack fine sediments, except for the occasional waning-flow deposit in which a few centimetres of laminated fine sediments overlie the clean coarse sands of the bedload. The floodplains are dominated by red-brown muds, divisible into pale red-brown modern muds (<150 years since deposition), distributed in patches across the floodplains, and two or three layers of underlying red-brown to dark-brown old muds, often exposed at the floodplain surface. Despite their textural differences, channel and floodplain sediments both originate from erosion of the regolith-covered hillslopes, and recycling of old fluvial sediments. Once entrained into the flowing creek, sediments are rapidly sorted into bedload, which travels only short distances during the brief flood peaks, and suspended load, which is either deposited across the floodplain or (when flows remain in-channel) flushed out of the uplands.

Modern muds are sandy, loose and non-cohesive, and rich in sedimentary structures (laminations, scours, current ripples, and intraclasts) indicating deposition under conditions of moderate to moderately high energy. Where they cover the floodplain, the surface is very soft. The older muds are stiff, dense, and cohesive, appear to be more clayey, and lack sedimentary structures, although they are sometimes faintly pedal or blocky. Where they are exposed at the surface, the floodplain is hard to very hard. The boundary between modern and older muds is generally erosional, but is occasionally gradational showing decreasing clarity of the sedimentary structures, and/or increasing pedality, with depth.

The modern and older floodplain muds differ substantially in appearance, but there is no real difference in their grain sizes (Fig. 7A, B); when wetted in the laboratory, old muds re-separate into their constituent aggregates, sands, and silts and clays. In their as-transported state, both muds are sands or silty sands (sand 66–95%, silt 2–31%, clay 1–8%), and in their fully disaggregated state, they are sandy silts or silty sands (fine to very fine quartzose sand 10–76%, silt 19–75%, clay 3–23%). This indicates that in their as-transported state, much (37–81%, median 72%) of the silt and clay is bound up as sand-sized aggregates, comprising nearly half (14–59%, median 42%) of floodplain muds as a whole (Fig. 7C). (Coarse silt-

Fig. 6. An arroyo in the mid-uplands has a floor of flat gravely sands and banks of floodplain muds. The riparian zone is vegetated by chenopod shrubs but has only a single small *Acacia* tree. Flow is away from the camera; 1 m scale.

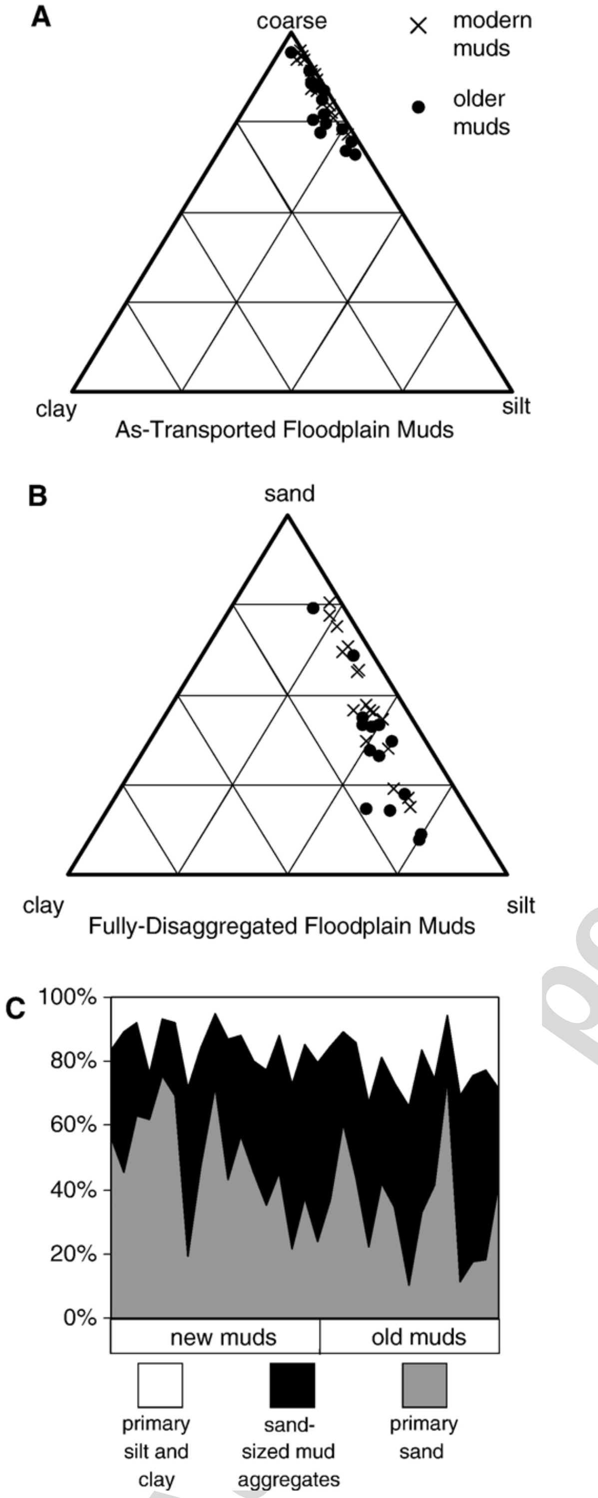

Fig. 7. Sand-silt-clay grain size distribution in (A) as-transported, and (B) fully disaggregated floodplain muds from all three of Fowlers Creek's geomorphic subregions. The triangles are subdivided at 25% intervals. (C) Comparison of the sand:(silt+clay) ratios in the as-transported and fully disaggregated floodplain muds indicates the proportion of sediments travelling as sand-sized aggregates.

sized aggregates are probably also present but could not be detected with the methods used here.)

The fine sediments in Fowlers Creek (dominantly fine to very fine to quartzose sand and sand- and silt-sized mud aggregates) are deposited across the floodplain, but not in the channel, indicating that they travel in the suspended load. At deposition, however, they are bedload, as shown by their sedimentary structures.

3. Geomorphology

3.1. Proximal uplands

3.1.1. Description

In the proximal uplands (Fig. 4), the creeks are small. The straight to low-sinuosity channels, 5–20 m in width, have wide rectangular cross-sections (arroyos) and are usually single. Channel widening and extension occurs through piping, sapping, and bank collapse. Scattered riparian gum trees are occasionally present. Flooding in excess of four times bankfull capacity covers the valley floor, lapping onto the rocky hills on either side, and this reflects the relatively narrow floodplain (20–200 m wide; the channel occupies 15–25% of the total fluvial width).

Relatively steep channel slopes occur in bedrock creeks of the drainage divide or in gullies incising into unchannelled valley floors. In the main arroyos, the channel slopes are more gentle and are similar to the down-valley slope of the floodplain (Table 1). The cross-valley slopes towards the channels are similar to or slightly less than the down-valley slopes (Table 1), assisting the efficiency of runoff delivery into the channel (or the return of floodwaters to the channel).

In most cases where arroyos approach tributary confluences, the channel becomes increasingly shallow and wide, and its slope becomes less than the floodplain slope (channel tract, Table 1). The floodplain becomes irregular, such that some sections slope away from the channel, and the number of channel multiplies. These conditions promote avulsion, especially under a variable flow regime, and channel instability is evident in channels' irregular thalwegs and low, embayed banks.

Channels become increasingly shallow and poorly defined with distance downstream. Near the upstream edge of the confluence, the down-valley slope decreases and the channels disappear entirely (central floodout, Table 1). Sheetflow spills out across the floodout, depositing thin sheets of bedload near the channel ends and suspended load (fine sands, mud aggregates, and organic detritus) over the entire reach. Earth dams or "tanks", installed by the graziers to collect runoff for stock use, are often situated in or near these floodouts (Fig. 4).

The central floodouts are often notable for dense stands of tall gum trees and thick understory growing tens to hundreds of metres downstream from the channels' ends (Fig. 4). These are the only places in the uplands where gum trees grow so thickly and the only places in all Fowlers Creek where gum trees are not confined to channel banks. The density of the vegetation and its good condition during drought indicates a relative abundance of water. The dense vegetation discourages erosion by root-binding of the soil, and by canopy- and leaf-litter protection of the soil surface from rain splash. Vegetation slows water by making sheet-flow paths highly tortuous, increasing the floodplain roughness, and forming leaf-litter mini-dams perpendicular to the direction of flow; this promotes the infiltration of water and the deposition of sediment.

Downstream from these densely vegetated areas, the unchannelled floodplain may be almost bare of vegetation for several hundred metres. In this barren downstream zone, drainage re-establishes in the form of gullies and badlands leading to the next downstream arroyo. Piping pits (usually small, but up to ~4 m long and 0.5 m deep) focus runoff and promote gullying in this zone.

3.1.2. Interpretation

In the proximal uplands, the gully–arroyo–floodout landform sequences and the channel and floodplain slope relationships indicate that these creeks are discontinuous ephemeral streams. Fowlers Creek is predisposed to the formation of these systems by the moderately arid climate, the variable flow pattern, and the abundant fine sediment, which is (because of its mud-aggregate nature) both erodible and cohesive, and which contains swelling clays. These features contribute to piping and gullying, arroyo incision during larger flow events, the shedding of water from bare surfaces but the retention of water once infiltration has been achieved, and the preferential growth of vegetation in well-watered areas, maintaining floodout stability.

The location of floodouts at tributary confluences indicates that in Fowlers Creek, the gully–arroyo–floodout landform sequences may originate in large-scale scour-transport-fill events during low recurrence-interval floods. In other landscapes, scour-transport-fill sequences may repeat along the drainage axis. The gullies of one cut into the floodout of the next one upstream, and they may migrate slowly upstream (Pickup, 1985, 1988; Bull, 1997). The location of the erosion/aggradation threshold is not (in those cases) linked to the position in the landscape. In Fowlers Creek, however, floodouts are consistently found at lower order tributary confluences; this has also been noted for the Todd River (Bourke and Pickup, 1999) and Cooper Creek (Gibling et al., 1998). It is likely that the floodouts originate as large-scale scour-transport-fill sequences during large flow events. As flows widen and shallow upon entering a larger valley, they deposit substantial sediments, choking the tributary confluences and decreasing the floodplain slope. With the growth of vegetation germinated in the flood-borne sediments, the floodout becomes self-sustaining.

3.2. Mid-uplands

3.2.1. Description

The mid-uplands contains the higher order channel of the Fowlers Creek main drainage axis. In its most upstream reach, it consists of gullies expanding headwards through the barren downstream edge of a floodout (Fig. 4). The headcut is influenced by piping pits which preferentially occur above buried channel sands, so new channels tend to re-occupy older channel locations. Downstream, the gullies coalesce into a single channel, an arroyo (Fig. 6) incised into a broad floodplain. The floodplain has an irregular surface, especially where small tributaries form heavily vegetated shallow interlinked swales. Riparian gum trees are rare, except at Site 12 (Fig. 5) which is unusual because many riparian gums are present, some of which are enormous and must therefore be very old (gum trees live for at least 400–500 years, Ogden, 1978). There are no floodouts, and the main channel is continuous downstream into the distal uplands.

The channel has straight to curvilinear planform. Flood capacity is up to 10 times higher than the bankfull channel capacity (Table 2). Unlike the proximal uplands, however, the whole valley width is not inundated even in large floods, due to the broader floodplain (~500 m wide). The channel occupies a much lower proportion (6–13%) of the total fluvial width. The down-valley slope is the lowest in the uplands (Table 1). The cross-valley slope may be less than half the down-valley slope, reducing the delivery of floodwaters back into the main channel. Only at Site 12 is cross-valley slope steep enough (Table 1) to force floodwaters back into the main arroyo.

The degree of floodplain inundation varies, as shown by the patchy distribution of modern muds. Where present, these sediments vary in thickness from a few centimetres to ≤2 m (in abandoned channels), and some floodplain reaches carry ≤1.2 m of vertically accreted modern muds in 5–20-cm beds.

Table 2
Hydraulic parameters of the Fowlers Creek Uplands: cross-sectional area, wetted perimeter (P) and hydraulic radius (R)

Hydraulic Parameters						
Reach type	Bankfull			Flood		
	Area (m^2)	P (m)	R (m)	Area (m^2)	P (m)	R (m)
Proximal Uplands - ET	21.3	37.3	0.57	(no flood debris)		
Proximal Uplands - ET	10.0	55.5	0.18	59.0	198.8	0.30
Proximal Uplands - LAT	10.7	46.4	0.23	54.1	115.7	0.47
Proximal Uplands - LAT	6.3	19.9	0.32	26.8	77.3	0.35
Proximal Uplands - LAT	8.2	33.8	0.24	105.7	172.2	0.61
Channel Tract	39.5	196.6	0.20	39.5	196.6	0.20
Mid-Uplands	7.8	22.6	0.34	(no flood debris)		
Mid-Uplands (S12)	86.1	285.9	0.30	86.1	285.9	0.30
Mid-Uplands	55.0	49.0	1.12	233.0	357.9	0.65
Mid-Uplands	26.3	20.1	1.31	275.4	358.8	0.77
Mid-Uplands	33.1	60.7	0.54	61.9	137.0	0.45

Parameters are calculated for bankfull, and recent flood level (as indicated by the height of flood debris), and are listed in upstream-downstream order for each reach type. LAT, the Little Acacia Tank branch in the Proximal Uplands; ET, the Enclosure Tank branch in the Proximal Uplands; S12, Site 12 in the mid-uplands (see Figs. 4, 5 for locations).

There is no evidence of incremental changes in channel dimensions or location: no point bars in the curved reaches, and no accretionary benches. However, channel relocation is evident from the old channel traces visible on the aerial photographs (Fig. 5). The lack of riparian gum trees makes these old channels difficult to find in the field.

The Gum Well reach (Fig. 5) has been affected by recent catastrophic activity extending more than 5 km downstream. Gum Well's old (early 20th century?) stock trough has been buried by up to 2 m of modern muds and subsequently re-excavated, and the channel has been widened (3 m wide × 3 m deep to 12 m wide × 1.5 m deep) during a single 1-day rainfall event (1998). Downstream, channel incision has created a narrow, deep slot (~5 m wide × ~8 m deep), and sheet erosion has stripped the flanking floodplain (present in 1981 aerial photographs but still occurring). Further downstream, a wide shallow network of gullies is eroded into old floodplain muds, and further downstream, rapid channel incision has occurred. Overall, the space created by the Gum Well reach erosion event varies greatly in depth and width and has a very irregular bottom surface.

3.2.2. Interpretation

The mid-uplands gullies and arroyo represents the scour-transport zones of a discontinuous system, but instead of finishing in a floodout, the arroyo persists for the length of the uplands. This is because it is a higher order channel with greater stream power; longer arroyos are favoured in higher order streams (Bull, 1997).

The mid-uplands differ from the gully–arroyo–floodout systems of the proximal uplands in that the arroyo is very mobile and the floodplain is very unstable. Arroyo mobility is demonstrated by the old channel traces (Fig. 5) and by the general absence of riparian gum trees. This absence is not because the trees have been killed, buried, or cut down, since elsewhere along Fowlers Creek, tree skeletons, deeply buried but living trees, and axe-cut stumps are visible. Riparian gum trees in the trunk and terminal floodout rely on the channels to provide water necessary for survival; their germination and growth are strongly linked to the availability of moisture. The absence of trees in the mid-uplands indicates that rapid channel relocation is occurring, and channel banks are generally not stable for long enough to allow gum trees to grow. Movement of the channel by small distances (tens of metres) is not sufficient, elsewhere in Fowlers Creek, to eliminate riparian gum trees, and so this channel mobility must occur on a large scale.

This channel avulsion is promoted by the low down-valley slope, wide and topographically irregular floodplains, the great degree to which flood flows exceed bankfull channel capacity, and the absence of riparian trees. Site 12, where the steeper cross-valley slopes are more effective in returning floodwaters to the channel, is less prone to avulsion and is the only mid-uplands reach sufficiently stable to maintain gum trees.

Because only a small proportion of the flood flow is contained within the channel, bank cohesion can have little influence on maintaining channel stability. Nevertheless, areas of recent floodplain mud deposition with a loose, erodible floodplain surface probably have increased channel mobility. Channel avulsion results in thick deposits of fine sediments, both laterally, in the abandoned channel and its adjacent floodplain, and downstream, as pulses of floodplain muds are released by channel cutting and intense floodplain erosion flanking the new channel. Downstream reaches may also experience floodplain erosion or channel incision. Together, the newly incised channel and its eroded floodplain represent voids in the fluvial landscape which will be filled by a later generation of floodplain muds.

The width and depth of erosion are influenced by the nature of the floodplain surface as well as by flow strength. Flows of low to moderate strength over hard old muds result in shallow rill erosion, and strong flows over old muds lead to the incision of a narrow deep channel. Flows over thin to medium layers (≤1 m) of modern muds strip a wide area back to a hard bare surface of the underlying older floodplain muds. Thick (~2 m) modern muds in a channel's banks promote channel alteration, and in a floodplain, they lower the threshold of incision, making the reach vulnerable to avulsion.

4. Discussion

4.1. Fluvial processes in the Fowlers Creek uplands

4.1.1. Proximal uplands

In the proximal uplands, each gully–arroyo–floodout landform sequence is a single system (a discontinuous ephemeral stream). In each reach, stream power (channel incision) is balanced against valley-floor strength (floodplain stability or aggradation). Differences between reaches reflect their position with respect to the erosion/aggradation threshold: gullies occur in erosional reaches, floodouts in aggradational reaches, and arroyos exist where neither force is dominant.

The floodouts, located at tributary junctions, originate during large flow events. They subsequently become self-sustaining though positive feedback in which floodplain slope allows water infiltration, which supports dense vegetation; the vegetation prevents erosion and maintains the slope by retarding flow and promoting sediment deposition. The capacity of floodouts to retain water and to support vegetation, even during hard drought, makes them ecologically important. They are also important economically and culturally, since their efficiency in trapping runoff makes them a favoured location for the construction of the earth dams and wells which are used by the local grazing industry.

The fluvial processes of discontinuous ephemeral streams cross and re-cross the threshold between incision and aggradation (Bull, 1997). They are threshold-dominated and are therefore not equilibrium systems (Knighton, 1998). However, once the threshold is crossed in a reach, the system moves towards a new equilibrium. For example, a tributary-confluence reach which becomes aggradational is maintained by the slope-vegetation feedback. Such systems, which display incremental adjustments towards an equilibrium state, are disequilibrium reaches (Tooth and Nanson, 2000).

4.1.2. Mid-uplands

The mid-uplands are unusual in their geomorphic character. Although the floodplain has some areas of low-sinuosity interlinking swales, these are merely heavily vegetated overflow channels, so this is not a braided system. The creek is muddy, but not meandering: the channel is low sinuosity and shows no evidence of incremental lateral migration. The mid-uplands channel also differs from the low-sinuosity sand-bed channels of central Australia in its rectangular cross-section and its cohesive banks.

Fowlers Creek's mid-uplands are in some ways similar to Cooper Creek, which transports a mud-aggregate sediment load and includes narrow channels with cohesive banks in its range of channel types (Nanson et al., 1986; Maroulis and Nanson, 1996; Gibling et al., 1998). However, Cooper Creek is much larger, has a lower gradient (Gibling et al., 1998), and its mud aggregates are much richer in clay (35–60% clay, Fagan and Nanson, 2004). The Cooper Creek floodplain has braid bars and active gilgai (Fagan and Nanson, 2004), neither of which is present in the mid-uplands, and its large channels are part of an anabranching system (Gibling et al., 1998), whereas the mid-uplands channel is not.

The mid-uplands arroyo differs from those of the proximal uplands in its frequent reach-scale relocation. This reflects the wider mid-upland floodplain, lower down-valley slope and more irregular topography, so that large floods have considerable freedom to find new down-valley directions. A new channel is created when the flood's stream power exceeds the strength of the floodplain alluvium.

The mid-uplands floodplain is dynamic in two ways. Firstly, floodwaters across the floodplain are not low energy, but rather are vigorous enough to create bedforms in sand-sized sediment, and to initiate channel incision. Secondly, the floodplain sediments are repeatedly eroded and redeposited during the frequent channel relocations. Cohesive old floodplain muds entering flowing waters re-separate into their component sands, sand-sized aggregates, and silts and clays, and are redeposited as cohesionless modern muds.

In fluvial systems, the opposing forces of stream energy (e.g., velocity) and boundary resistance (e.g., roughness) interact to create the river's geomorphology. Where the variability in these opposing forces is small, they can adjust to each other and the system reaches equilibrium. This is reflected in a relatively stable geomorphology in which consistent relationships exist between form and process, and there is temporal and spatial continuity of sediment transport (Richards, 1982; Tooth and Nanson, 2000). Where the variability in these opposing forces is great and they cannot adjust to each other, the system may be unable to develop equilibrium.

The mid-uplands has a high degree of variability. Stream energy is variable both because of flow fluctuation and because of variations in the size and direction of floodplain slope. Boundary resistance is highly variable because the mud-aggregate sediments may be either loose or cohesive. The mid-uplands are not equilibrium systems: they have unstable channels which are subject to rapid change, reach-scale differences in flow strength and net sediment transport, and chaotic sediment assemblages. Their fluvial processes are threshold-driven, crossing physical thresholds (overcoming barriers to cross-valley flow, exceeding the critical shear stress to cause entrenchment), and process thresholds (the transition between aggradation and erosion). Unlike the proximal uplands, the mid-uplands show no sign of adjustment towards an equilibrium, lacking any feedback processes which maintain a reach in its current condition. Such systems are non-equilibrium (Tooth and Nanson, 2000).

4.2. Mud aggregates and fluvial style

Fowlers Creek's fine sediments, dominated by mud aggregates and fine to very fine quartzose sand, are deposited across the floodplain, indicating transport in the suspended load. However, Fowlers Creek flow events are transient. As flow velocity decreases, the fine sediments behave like sands, and are deposited as bedload from flowing waters. This deposition of clays and silts would not occur if these fine sediments were travelling as independent primary particles.

In the proximal uplands, conditions which favour the formation of mud aggregates (aridity, fine sediments, swelling clays) are also those which promote discontinuous ephemeral streams, piping, gullying, arroyos and floodouts. The aggregates and the fluvial style arise coincidentally, rather than one being the cause of the other. However, it is likely that the mud-aggregate sediment load contributed to the development of floodouts at tributary confluences. Because the fine sediments behave like sands, they are more likely to be deposited at confluences, choking them with sediment. Had all the fine sediments been travelling in a fully disaggregated state, it is probable that they would have been washed downstream.

In the mid-uplands, mud-aggregate fine sediments have a more direct influence on fluvial style. In modern muds, the aggregates are still separate and are easy to entrain, whereas the older muds are hard, cohesive, and resistant to erosion. The distribution of modern and old muds will therefore affect the balance between channel incision and floodplain stability and influence the width and depth of floodplain erosion. The contrast in critical shear stress of the old and new muds adds another variable to an already variable system, contributing to its non-equilibrium nature.

River systems balance the river's power to erode and transport sediment with the cohesive resistance of the floodplain sediments (Nanson and Croke, 1992). The relationship between stream power and floodplain cohesion creates the different types of floodplain/channel, governing the resulting fluvial landforms. In Fowlers Creek, the same flow strength will have different geomorphic effects in different areas of the floodplain, depending on the age of the floodplain across which it has travelled.

5. Conclusions

This study describes the fluvial processes occurring in the uplands of Fowlers Creek, a mud-aggregate river in Australia's arid inland.

The uplands of Fowlers Creek consist of arroyos, floored with quartzose and lithic coarse sands and gravels. They are incised into muddy floodplain sediments consisting of silt, fine to very fine quartzose sand, and clay. Most (~72%) silts and clays are aggregated into sand- and silt-sized particles. Floodplain sediments are transported in the suspended load, but become bedload during deposition. Recently deposited floodplain muds have the appearance of loose sands, but older muds become compact and cohesive. Old muds re-separate into their component sands and aggregates after wetting and re-entry into fluvial transport.

Reaches in the lower order channels of the proximal uplands form landscape sequences of gullies, arroyos, and floodouts (collectively, discontinuous ephemeral streams) in which fluvial processes fluctuate between channel incision and floodplain aggradation. Floodouts originated when large floods dumped their sediment loads upon entering the wider valleys of tributary confluences. They are self-maintaining by feedback relationships between vegetation and valley-floor slope and are efficient at capturing and retaining water. They are characterised by dense vegetation and play an important ecological role as drought refugia.

The mid-uplands experience great variability in the elements governing river flow, contributing to a non-equilibrium fluvial style. The higher order channel of the mid-uplands is a mobile arroyo in which frequent reach-scale channel avulsion is promoted by flow variability, the wide and irregular floodplains, relatively low down-valley slope, variability in the floodplain's resistance to erosion, and the absence of riparian trees. Incision of a new channel releases a pulse of fine sediments, burying the abandoned channel and accreting vertically on some downstream floodplains. Channel incision is associated with floodplain erosion, flanking the new channel and in some downstream reaches. The erosion surface associated with channel relocation is irregular in its width and depth.

The formation of robust mud aggregates is favoured by aridity and soils containing abundant fine sediments including some swelling clays. These conditions also support the development of discontinuous ephemeral streams. In this respect, the mud-aggregate sediments do not necessarily have a causal relationship with the fluvial style, but rather arise from the same circumstances. Mud aggregates have a more direct influence on fluvial style in the floodouts and the mid-uplands floodplain, where the aggregated fine sediments can be deposited under flow conditions which would be too vigorous for the deposition of non-aggregated silts and clays. In addition, the contrast between the loose modern muds and the cohesive older muds governs the location, degree, and extent of floodplain erosion.

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