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Geomorphology 60 (2004) 107–126

GEOMORPHOLOGY

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The morphology and formation of floodplain-surface channels, Cooper Creek, Australia

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Received 1 October 2002; received in revised form 1 July 2003; accepted 17 July 2003

Abstract

Floodplain-surface channels are prominent features of the floodplain of Cooper Creek, a low-energy, anastomosing river in semi-arid southwest Queensland. Three distinct floodplain-surface environments and corresponding pedological variations are identified. *Braided* patterns characterized by large-scale braid bars separating wide, shallow channels occupy 44% of floodplain area. Gilgai, undulations of the soil surface characteristic of many vertisol soils, are subdued or absent from the braided areas. The *reticulate* pattern occupies 39% of the floodplain surface and is characterized by densely developed networks of small channels with angular planforms. The prominently developed gilgai in these areas play a significant role in the formation of the reticulate pattern. High, rarely inundated areas of the floodplain are *unchannelled* and occupy the remaining 17% of the floodplain surface. Analysis of the distribution of the patterns over a 370-km-long reach of the river reveals that sensitive feedbacks between fluvial and pedogenic processes determine pattern expression. The energy of inundating flows is controlled by floodplain width, transmission losses and subtle floodplain topography variations. The patterns are distributed along an energy continuum. Braided patterns occur in higher energy areas in which fluvial erosion prevents gilgai expression. Reticulate patterns are confined to intermediate energy areas in which inundation frequencies are sufficient to provide wetting and drying frequencies necessary for gilgai formation and flow energy sufficiently low to allow gilgai expression. Unchannelled areas are neither inundated frequently enough to cause gilgai formation, nor with sufficient energy to cause channel formation.

Keywords: Alluvial channel pattern; Floodplain; Vertisol; Gilgai

1. Introduction

Floodplain-surface channels are important components of many alluvial floodplains and together with the floodplain surface and inset low water channels comprise the three levels of commonly found alluvial relief (Alabyan and Chalov, 1998). Floodplain-surface channels are only active during flood events (Mertes et al., 1996). While inset into the floodplain surface enough to enable their recognition as channels, they are not sufficiently deep to receive flow during bankfull or lower flows. Floodplain-surface channels form in two main ways. First, they may be abandoned sections of low-water channels. These are

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doi:10.1016/j.geomorph.2003.07.009

important components of many floodplain surfaces (e.g. Lewin, 1978, 1992; Alexander and Marriott, 1999), and the often slow pace of their removal by infilling or lateral migration can enable them to persist for extended periods after abandonment. Until their removal they function as channels during flood events. Second, floodplain-surface channels can form in-situ on the floodplain surface, for example crevasse channels and erosional swales (e.g. Thornbury, 1968). It is this latter type of floodplain-surface channel that is developed extensively across the Cooper Creek floodplain in semi-arid southwest Queensland.

Floodplain-surface channels will form where overbank flow is sufficiently energetic to incise them or to preferentially retard deposition, forming low areas which develop into channels. However, they are not confined to high energy floodplains, but occur on a range on floodplain types spanning the energy gradient (Nanson and Croke, 1992). Although low energy channels, anastomosing rivers experience large flood events as a consequence of high bank resistance constraining channel capacities and highly seasonal or otherwise irregular flow regimes (Knighton and Nanson, 1993). For this reason, the in-situ development of floodplain-surface channels along anastomosing rivers is common (Nanson and Croke, 1992). The diversity of floodplain-surface channel patterns on Cooper Creek offers a good opportunity to study controls on their morphology and formation.

2. Study area

2.1. Climate and hydrology

Cooper Creek is one of the Channel Country rivers which drain the eastern side of the 1.14 million km^2 Lake Eyre Basin in Australia (Fig. 1), one of the largest internally drained catchments in the world (Kotwicki, 1996; Nanson et al., 1988). The catchment is subject to a semi-arid to arid climate classified as BSh to BWh under the Köppen system. Hot summers alternate with cool winters and precipitation decreases down Cooper Creek as aridity and evaporation increase towards Lake Eyre. Summer monsoonal rains with their source north of the catchment margins account for approximately 70% of the yearly precipitation total, with a significant secondary winter rainfall maximum of 15–20% from southern maritime and continental, easterly tracking air masses (Kraus, 1955).

The study area covers the ~370 km long middle reach of Cooper Creek between the confluence of the Thompson and Barcoo Rivers near Windorah upstream, and the constriction of the river into a single channel by the Innamincka Dome near Nappa Merrie (Fig. 2). Floodplain width in the study area varies between ~100 m and ~60 km. Due to the aridity of the catchment, the river flows seasonally. Bankfull stage is attained on average every 2 years, and, as is typical of dryland rivers, flood frequency curves are very steep. The 20-year flood on Cooper Creek is an order of magnitude larger than the mean annual flood (Knighton and Nanson, 2000), and the mathematical average flow is equalled or exceeded only 9% of the time due to skewing of the mean by large, infrequent flood events (Kotwicki, 2002). The largest recorded flood occurred in 1974 following an exceptionally strong monsoon (Baker, 1986). Peak flow at Innamincka was 6400 $m^3\ s^{-1}$, over a hundred times greater than the 1973–1993 average flow of 63 $m^3\ s^{-1}$ (Kotwicki, 2002).

As flow is supplied predominantly from the wetter headwaters of the catchment, transmission losses over the reach can be very significant (Knighton and Nanson, 1994). When flow is confined to the major anastomosing channels, flow loss per kilometre is low, although due to the length of the study reach transmission losses can still reach 100% of flow. As flow begins to invade the floodplain surface transmission losses increase sharply and above a threshold flow of 25% duration exceed 75% of total flow (Knighton and Nanson, 1994). Although channels are perched high above the water table, floodplain sediments seal effectively on wetting, and thus little of the transmission losses are due to infiltration but rather to evaporation and storage. During flood events, floodwaters may expand up to the full floodplain width of up to ~60 km, exposing large surface areas to evaporative losses that are especially large because the peak flow period is the extremely hot summer when temperatures frequently exceed 45 °C.

Vegetation on the floodplain is predominantly patchy and ephemeral, growing in response to occasionally heavy wetting by local rainfall and flood

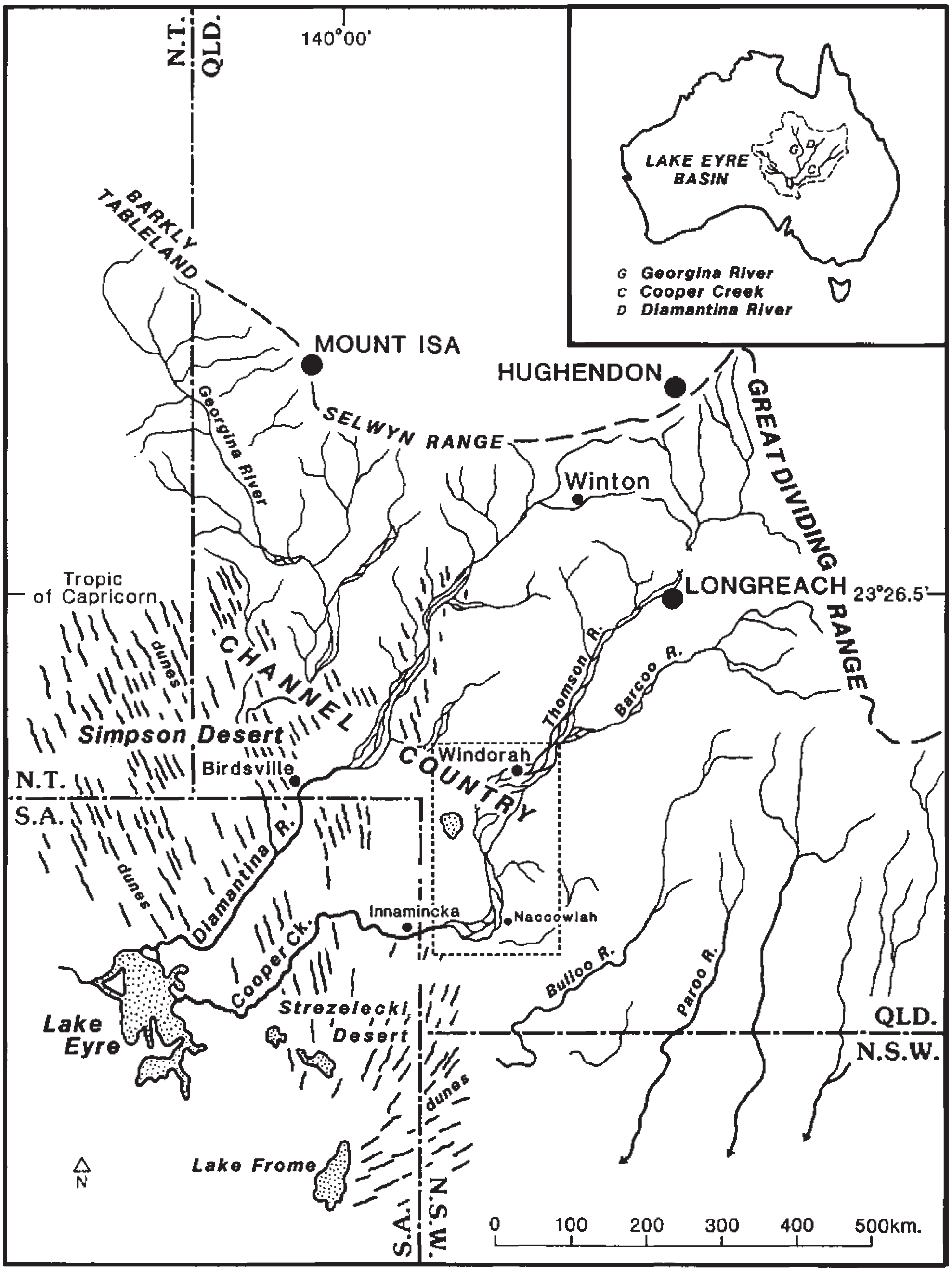


Fig. 1. The northeastern Lake Eyre Basin. Cooper Creek extends from the confluence of the Thompson and Barcoo Rivers to Lake Eyre. The study reach, shown in more detail in Fig. 2, extends from Windorah to Innamincka and is outlined.

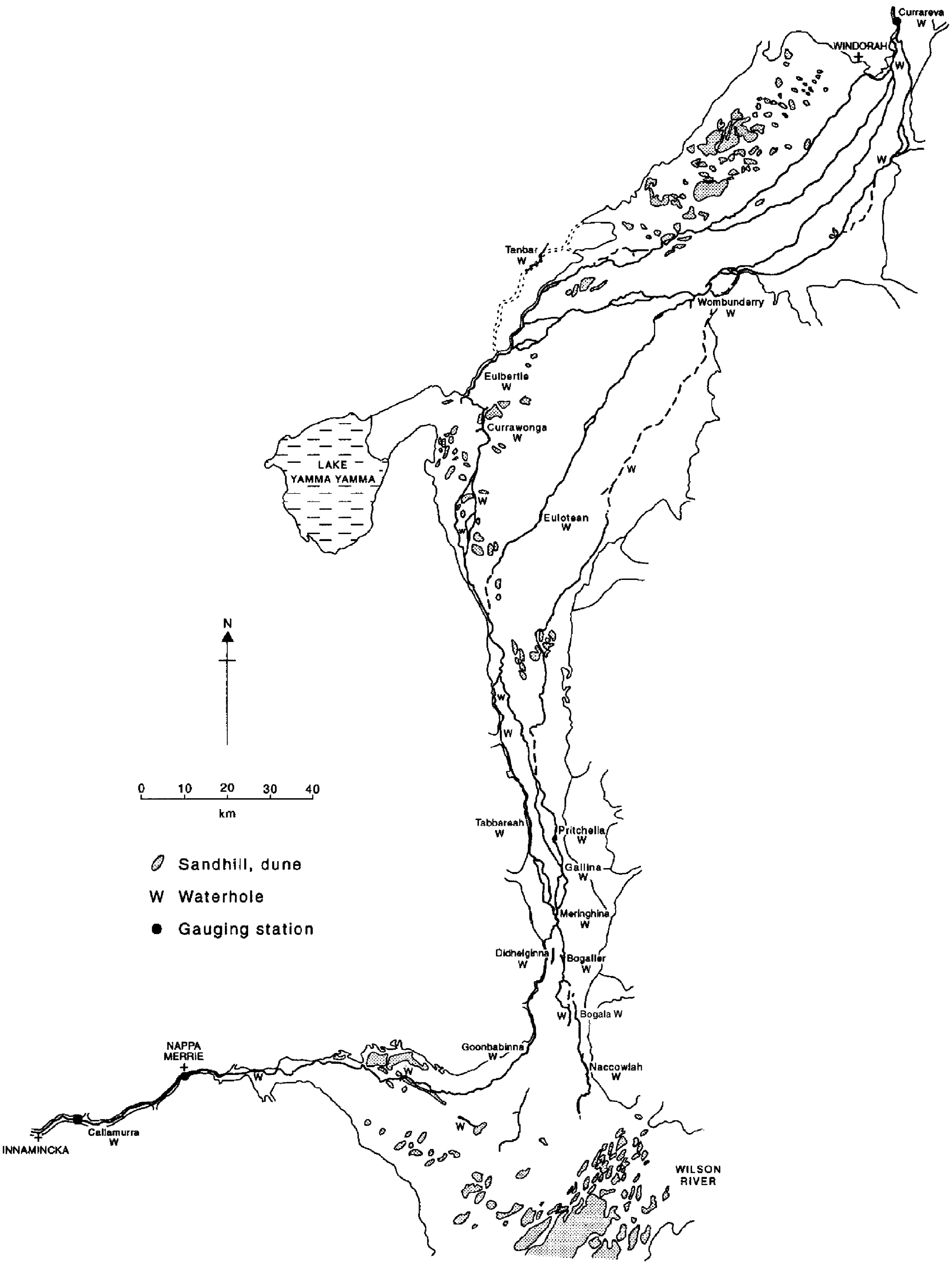


Fig. 2. Detailed map of the study reach between Windorah and Nappa Merrie.

events. Large anastomosing channels provide approximately annual irrigation and are lined by mature coolibah trees (*Eucalyptus microtheca*) up to 8 m high. Lignum (*Muehlenbeckia cunninghammii*) and flowering lignum (*Eremophila polyclada*) bushes 1–2 m high cluster there for the same reason, and are also found scattered more sparsely across the floodplain, concentrating near wetter areas and floodplain-surface channels.

2.2. Floodplain sedimentary characteristics

The fine-grained floodplain deposits are sourced primarily from interbedded Cretaceous and Tertiary sandstones and mudstones in the headwaters and the surrounding hillsides. Smectite, the dominant clay mineral present, experiences strong volume changes in response to soil moisture variations and is responsible for the cracking and swelling of the soil. A deeply cracked, vertisol soil is formed, and cracks up to 2.4 m deep have been reported in the soils of the region (Sturt, 1964). Soil colour varies randomly over a narrow range from greyish-brown (2.5Y 5/2) to olive brown (2.5Y 4/3). Neither soil type nor colour vary systematically across the floodplain or between areas of differing floodplain-surface channel patterns. The texture of floodplain sediments was measured with a Malvern laser size-analysis machine. The disaggregated sediments are typically composed of 35–60% clay, 40–60% silt and 4–9% sand, with a mean grain size of 25–30 μm (Fagan, 2001). Ternary plots of sediment size show a narrow range of textural variation (Fig. 3). The lack of textural distinction between different floodplain environments and surface-channel types was confirmed statistically using the Tukey–Kramer Honestly Significant Difference (HSD) Test ($\alpha = 0.05$) (SAS Institute, 1994).

Gilgai, undulations of the soil surface characteristic of many vertisol soils, are formed across the floodplain. Prominent gilgai with up to 30 cm of relief and a spacing of up to 20 m between mound crests form in reticulate areas where they dominate surface relief variations. Under the classification of Hallsworth and Beckmann (1969), the gilgai are 'normal' or 'round' gilgai, with no orientation to the mound/depression pattern. The formation of gilgai in fine-gained soils like those here occurs because soil does not return to its initial position on re-wetting following drying and

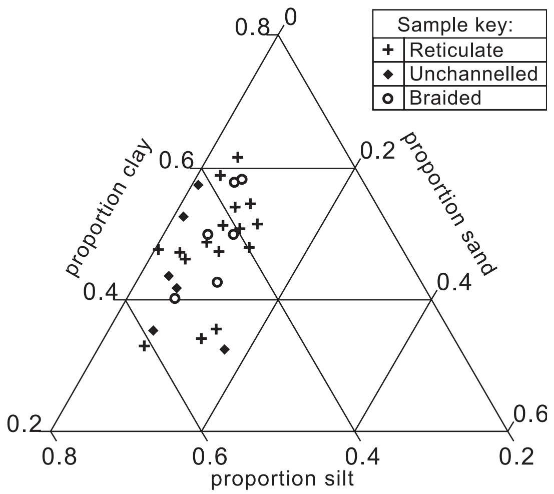


Fig. 3. Sediment texture plots of surface samples from different floodplain pattern areas. Size categories: Clay < 5.69 μm; 5.69 μm>Silt < 76.32 μm; 76.32 μm>Sand. The precise locations of the sediment size–class boundaries were fixed by the output of the machine used for analysis.

cracking (Hallsworth and Beckmann, 1969; Hallsworth et al., 1955; Verger, 1964; Cooke et al., 1993). Two processes are principally responsible. Firstly, by 'self-swallowing', which occurs when during dry periods, peds of soil from surface layers fall down cracks deeper into the soil profile. On wetting, this material becomes incorporated into the lower layers, the increased volume of material there causing excess pressures to be developed on re-wetting and forcing subsoil upwards. Secondly, the uneven wetting of soil following a period of cracking leads to differential volume changes. Soil around cracks receives moisture directly and so is wetted more rapidly and effectively than soil in the centre of intact soil blocks which receives moisture only by infiltration (Hallsworth et al., 1955). The resulting preferential expansion of wetted soil near cracks increases pressures there and causes the deformation of the soil surface. In vertisol soils, differential wetting tends to be especially marked as such soils commonly seal on wetting. Under ponding conditions caused by high rates of water supply to the soil, like those occurring on inundation by floodwaters, the aggregate structure of structurally unstable soils such as vertisols may collapse, with the resulting dense mud layer on the bed impeding the movement of water into layers beneath (Collis-George and Laryea, 1971). This dense, collapsed layer has a significantly higher erosion resistance than the aggregated layers thus impeding erosion as well as infiltration. The sealing of the floodplain sediments on Cooper Creek has been demonstrated by trenching below an adjacent flowing channel, when over a period of days there was no infiltration of water from the channel into the trench.

The scale of gilgai developed in a soil is dependent upon both internal factors such as the swelling potential of the clay type present (Hallsworth et al., 1955), and external factors such as the frequency of wetting and drying cycles. Gilgai development will tend to be greatest where the frequency of wetting and drying cycles that drive gilgai formation is highest. This tends to be under a seasonal climate regime. In wetter climates, the most highly swelling soil layers may never dry out, while in dry climates, the subsoil may never be wetted. In arid areas, subsurface soil movements and gilgai formation tend to only occur in particularly wet years when high rainfall breaks the pattern of drought (Hallsworth and Beckmann, 1969). Another important external factor is the rate of surface erosion (Elberson, 1983; Paton et al., 1995), which may prevent gilgai occurrence by destroying the pedogenic organisation of the soil surface.

2.3. Soil erodibility

Although the slope of the floodplain in the study area is extremely low, a number of factors act to promote soil erodibility. Firstly, even where vegetation is densely developed, ground cover percentages are well below the 50% level at which vegetation begins to have an ameliorating effect on erosion (Lang, 1984). Secondly, the soil is self-mulching and pedogenic aggregates are formed in response to wetting and drying of the floodplain surface (Nanson et al., 1986; Rust and Nanson, 1986). Wetting of the soil by the leading edge of a flood wave, immersion wetting, is the most significant process of soil wetting here and is rapid, leading to large quantities of aggregates being formed as the quantity of aggregate production is proportional to wetting speed (Probert et al., 1987). Further, the aggregates formed on immersion wetting here are smaller than those produced by slower wetting processes such as rainfall wetting (Maroulis and Nanson, 1996). An experimental study on sediment from the floodplain found that the diameters of aggregates formed under simulated rainfall wetting conditions were 0.70–0.75 mm compared to 0.15 mm of those formed in response to immersion (Maroulis and Nanson, 1996). The aggregates are significantly lower in density than quartz sand (2.34 g cm^{-3} cf. 2.65 g cm^{-3}) and, since aggregate transportability is largely a function of size and density (e.g. Loch and Donnollan, 1983), are readily transportable. Calculations with the Shield's criterion indicate the aggregates are transportable by flow depths as low as 0.2 m (Nanson et al., 1986), a common occurrence during flood events when flow depths in areas of the floodplain commonly exceed 1.5 m.

3. Floodplain-surface channel patterns

A network of anastomosing channels ranging between 10 and 125 m in width are inset into the floodplain surface. The largest and deepest receive flow at all discharges while the smallest operate only at or near bankfull. In addition, two types of floodplain-surface channel patterns are found: a braided pattern that occupies 44% of the floodplain surface and a reticulate pattern that occupies 39%. Only 17% of the floodplain surface is unchannelled.

The braided pattern is the most common floodplain surface pattern type in the study reach and is composed of elongate floodplain highs or islands divided by small channels (Fig. 4). Individual braided islands may be very large, ranging between 400 and 3500 m in length and 90 and 630 m in width. However, the relief of the pattern is very subdued. Island summits are generally no more than 1 m above the beds of the channels bounding them. Braided channels are inset slightly into the floodplain surface and wide and shallow, with channel widths of 4–32 m and width–depth ratios of 30–200 (Table 1). Gilgai development is limited in braided areas. At small scales surface elevation varies randomly with amplitudes of 1–2 cm, at larger scales the relief of the braided pattern dominates.

The reticulate pattern is characterised by an extremely high drainage density and a prevalence of approximately right-angled confluences and bifurcations between channels (Fig. 5). Complex networks of channels with jagged, irregular planforms are developed, and it was estimated that areas where reticulate

Fig. 4. Oblique aerial photograph of the braid-form floodplain-surface pattern showing the relatively subdued topography of the island highs and the wide, shallow dividing channels.

patterns are strongly developed typically contain over 30 000 channel links per square kilometre with many links extending for tens of metres only. In cross section, channels are small and simple in form, ranging from 2 to 8.5 m in width and 0.2 to 0.6 m in maximum depth (see Table 1). Reticulate patterns always co-occur with prominent gilgai development (Whitehouse, 1948; Mabbutt, 1967; Rundle, 1977), and it is the complex, undulating topography of the gilgaied surfaces which promotes the division and recombination of flood flows leading to the formation of dense networks of floodplain-surface channels.

Table 1
Floodplain channel morphological characteristics

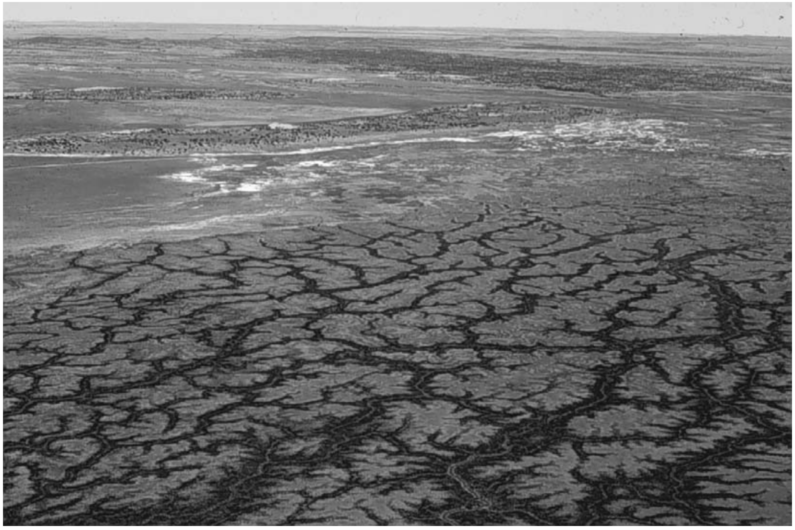
	Braided ($n = 19$)		Reticulate ($n = 16$)	
	Range	Mean	Range	Mean
W (m)	3.5–32	15.2	1.8–8.5	5.3
d_m (m)	0.13–0.90	0.39	0.18–0.63	0.42
d_{av} (m)	0.07–0.44	0.19	0.12–0.31	0.20
W/d_{av}	28.6–198.8	86.4	14.6–58.3	26.2
A (m^2)	0.4–14.1	3.4	0.2–2.6	1.1

W denotes channel width, d_m maximum depth, d_{av} average depth, W/d_{av} the width depth ratio, and A channel cross-section area.

Individual channels are inset into the floors of depressions between gilgai mounds, with bankfull being the level of the depression floor (Figs. 5 and 6).

In unchannelled areas, the dominant scale of surface irregularity is very small (1–2 cm amplitude) and a result of random variations in surface elevation (Fig. 6). On Cooper Creek, as the previous discussion has summarised, pedological characteristics such as gilagi expression, the morphology of the floodplain surface and floodplain-surface channel pattern occurrence are intrinsically linked.

The common dominance of high magnitude–low frequency (HMLF) events in determining dryland channel morphology is well known (e.g. Wolman and Gerson, 1978; Baker, 1977), however, a number of lines of evidence suggest ‘catastrophic’ HMLF adjustments do not affect either the anastomosing channels or the floodplain-surface channels here. Firstly, during the period of aerial photograph record a number of extremely large flood events such as the 1974 flood have occurred without causing noticeable change. Events such as the 1974 flood, when discharge exceeded the average discharge by over 100 times, would have been expected to cause marked a)



b)

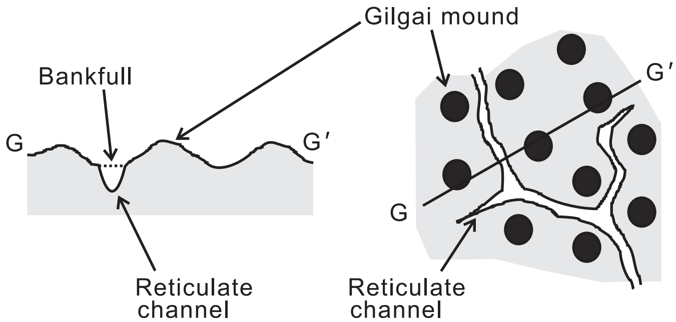


Fig. 5. (a) An oblique aerial photograph showing the reticulate pattern and (b) a schematic diagram illustrating the location of individual channels in the depressions between gilgai mounds.

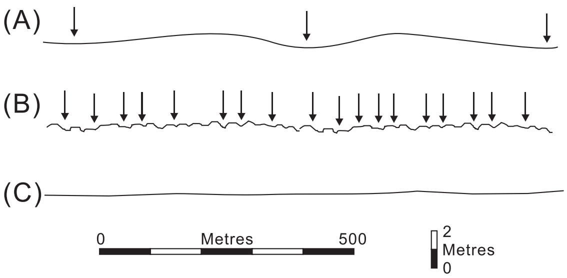


Fig. 6. Schematic representations of floodplain topography variations in (A) braided areas, (B) reticulate areas, and (C) unchannelled areas. Arrows indicate channel positions. Braided areas are characterised by minor small-scale surface variations superimposed on larger scale variations representing braid islands. Reticulate areas lack the large-scale cyclic variations seen in braided areas, and are dominated by medium- and small-scale variability caused by prominent gilgai. Unchannelled areas show only minor small-scale variability. Scales approximate only.

changes in channel patterns, were they to occur at all. Secondly, elements of the anastomosing channel morphology show adjustment to frequent, moderately sized flows, such as the plan-geometry of actively meandering anastomosing channels which is adjusted to bankfull channel dimensions (Fagan, 2001).

4. Aims and methods

In broad terms, floodplain-surface channel formation in the reach, like channel pattern formation generally, is controlled by flow discharge, valley gradient, sediment load and sediment erodibility (e.g. Ferguson, 1981, 1987; Knighton, 1984; Nanson and Knighton, 1996). On Cooper Creek, the influence of variations in valley slope may be discounted as a controlling factor as slope remains effectively constant over the reach at ∼0.00015. The width of the floodplain surface may be important through its influence on the distribution and energy of flood flows. Where the floodplain is very wide, inundating flows are dispersed over a much greater area than narrow floodplain sections, and overbank flow depths and velocities will be significantly lower in wider sections of floodplain. Variations in the elevation of areas of the floodplain surface exert a similar influence through its influence on inundation frequencies, depths and durations. As noted previously, transmission losses may be important. These losses will tend to cause flood flows through the study reach to decrease in depth and velocity downstream. A detailed analysis of the distribution of floodplain-surface channel pattern types in the study reach was undertaken in order to assess the influence of these factors.

Cross-floodplain transects were drawn and the floodplain surface classified by pattern type. The study reach was covered by a total of 57 transects. Transects were normally spaced 5 km apart and perpendicular to the mean flow direction. Where the valley centreline meandered significantly transects were more widely spaced to avoid sampling the same area of floodplain twice. In all but four cases, spacing between transect mid-points was below 9 km with a maximum of 15.4 km. Transect position measured from the head of the study reach (km) was used as a surrogate for transmission losses which, as defined by this variable, are assumed to increase linearly with distance downstream. As is typical of arid areas generally, central Australia and the Channel Country are very sparsely gauged. Permanent gauges exist at Currareeva near the head of the study reach (see Fig. 2), and at Nappa Merrie at the downstream end of the

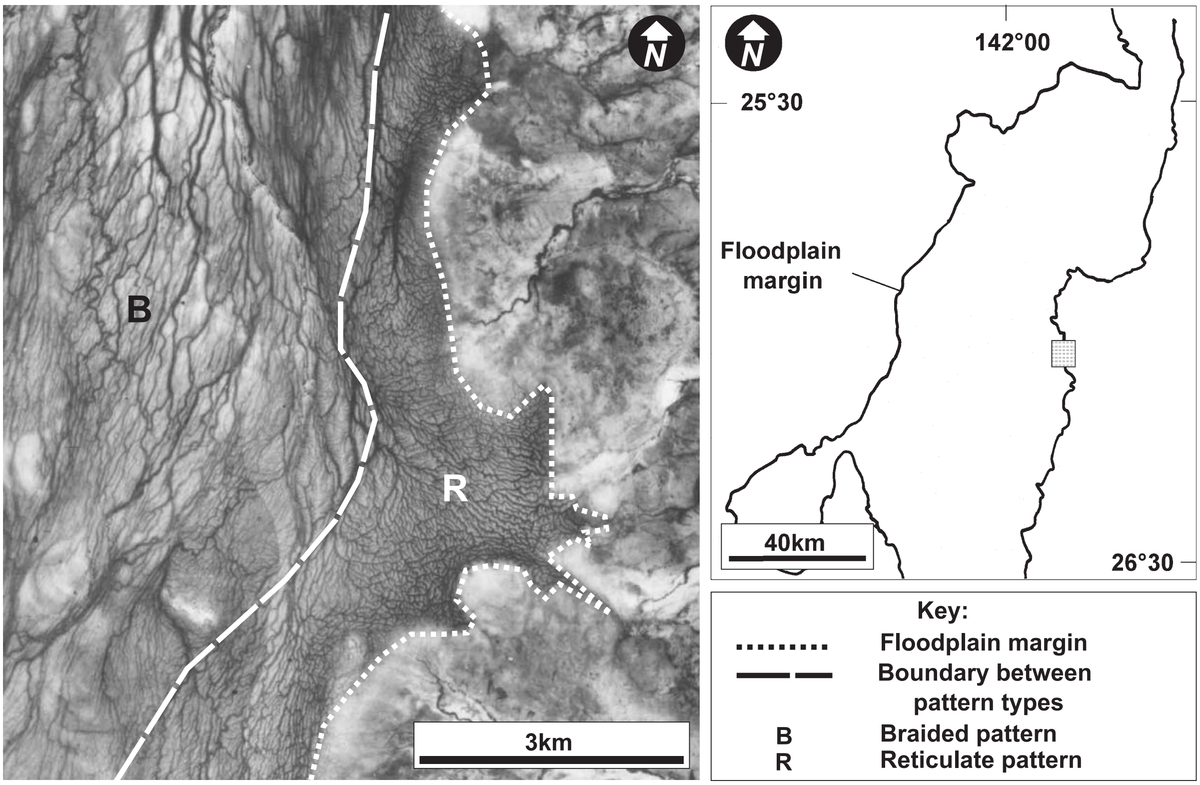


Fig. 7. Aerial photograph showing braided and reticulate patterns north of Lake Yamma Yamma. The reticulate pattern is formed by flow diverging into an embayment in the valley side, as commonly occurs over the study reach. The boundary between patterns is clearly recognizable.

study reach. However, there are no permanent gauges along the reach and so no detailed data on transmission losses are available.

Classes recognised were unchannelled floodplain, aeolian dunes, reticulate and braided patterns. Boundaries between differing pattern types were generally clear and easily recognisable. This is illustrated in Fig. 7, which shows braided and reticulate areas near the floodplain margin. Aeolian dunes occupied up to 9.3 km or 15% of some transects. Dune relief greatly exceeds inundation depths, meaning that dunes reduce the extent of floodwaters and thus floodplain width where they occur. To account for this, in analysis the length of transect occupied by dunes was subtracted from total floodplain width in order to obtain a value for the maximum width of floodwaters, with regression analyses used to determine the nature and significance of relationships found.

The influence of elevation on pattern distribution was assessed using survey collected by Santos Pty. Ltd. The horizontal position of survey points is accurate to ± 10 cm and the vertical position to $\pm 1-2$ cm. The resolution of the data was thus sufficient for the analysis of floodplain topography variations, however spatial coverage was not extensive enough to enable a 3-D model of floodplain topography to be constructed.

5. Results

5.1. Influence of floodplain width and transmission losses

Analysis shows that the occurrence of pattern types is non-random, with only a limited number of the possible combinations of patterns occurring (Fig. 8). Braided patterns occur separately or in combination with other patterns on every one of the 57 transects, while reticulate patterns and unchannelled areas are found on only 46 and 30 transects, respectively. Where transects are occupied by a single pattern type only, as in 10 cases, this is uniquely the braided pattern. On 17 transects, braided and reticulate channels co-occur, while on the majority (29) of transects braided, reticulate and unchannelled areas coexist. In only a single instance do braided and unchannelled patterns occur in the absence of the reticulate pattern. Variations in floodplain and pattern widths are shown in Fig. 9. Both the absolute width of pattern develop-

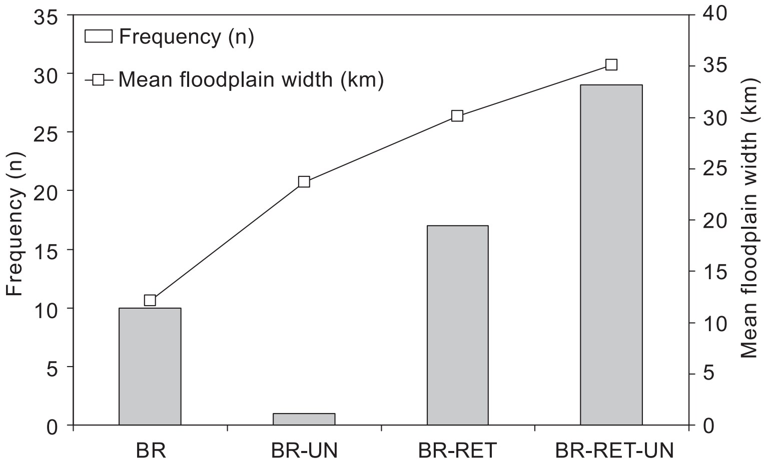


Fig. 8. The histogram bars represent the frequency of occurrence of the pattern or combination of patterns from the 57 cross-floodplain transects. The squares show mean floodplain width for the set of transects with that pattern type or combination of pattern types. Almost exclusively, transects are occupied by braided (BR) patterns only, braided patterns and reticulate (RET) patterns together, or braided and reticulate patterns combined with unchannelled (UN) floodplain areas. Other combinations are insignificant or absent. The figure shows that narrow transects tend to have only braided patterns. As transects become wider, reticulate patterns also occur and, in the widest transects, areas of unchannelled floodplain are also found.

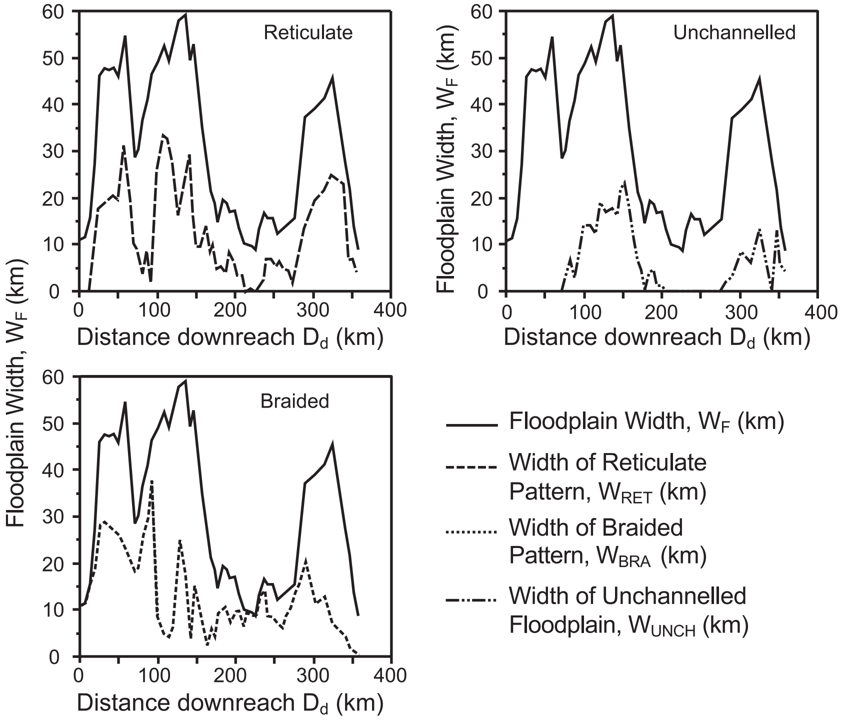


Fig. 9. The width of reticulate, braided and unchannelled floodplain along the 370-km-long study reach from Windorah to Nappa Merrie.

ment and the relative abundance of a pattern along transects were considered and results are summarised in Table 2.

5.1.1. Reticulate patterns

Floodplain width (W_F) is a good predictor of the absolute width of the reticulate pattern (W_{RET}), the strong positive relationship ($r^2=0.69$) indicating that as floodplain width increases so does the width of reticulate networks found. This regression relationship is shown in Fig. 10. Distance downreach (D_d) alone does not significantly influence the width of the reticulate patterns and multiple regression with both predictor variables together produces only a slightly stronger relationship ($r^2=0.71$) than floodplain width alone.

As with absolute width (W_F), distance downreach alone is a poor and insignificant predictor of the relative abundance ($\%_{RET}$) of reticulate patterns. Floodplain width is a significant although still poor predictor ($r^2=0.16$), the relationship indicating that the relative abundance of the reticulate pattern increases with an increase in floodplain width. The two variables combine to produce a much stronger relationship ($r^2=0.32$) indicating that both exert a significant influence. However, the relative abundance of reticulate channels is still much less predictable using these variables than is the absolute width of the reticulate pattern by floodplain width alone ($r^2=0.69$).

5.1.2. Braided patterns

Like for the reticulate pattern, as floodplain width increases so does the absolute width of the braided pattern (W_{BR}) (Fig. 10). However, the relationship is much weaker ($r^2=0.21$ cf. $r^2=0.69$) and the rate of increase of pattern width almost exactly half as rapid (0.25∗Fp compared to 0.49∗Fp for the reticulate pattern). Thus the width of the braided pattern is less strongly influenced by changes in floodplain width than the reticulate pattern and, where floodplain extent does expand, a much greater proportion of any additional area tends to be occupied by reticulate rather than braided patterns. Whereas floodplain width was the best single predictor of reticulate pattern width,

Table 2
Results of pattern occurrence regression analyses ($n=57$)

Response variable	Predictor variable/s	Equation	r^2
W_{RET}	W_F	$W_{RET}=-2.943+0.49W_F$	0.69
W_{RET}	D_d	$W_{RET}=14.5714-0.018D_d$	0.04*
W_{RET}	W_F and D_d	$W_{RET}=-7.32+0.54W_F+0.017D_d$	0.71
$\%_{RET}$	W_F	$\%_{RET}=21.370+0.465W_F$	0.16
$\%_{RET}$	D_d	$\%_{RET}=28.120+0.04D_d$	0.04*
$\%_{RET}$	W_F and D_d	$\%_{RET}=-0.028+0.69W_F+0.086D_d$	0.32
W_{BR}	W_F	$W_{BR}=5.43+0.25W_F$	0.21
W_{BR}	D_d	$W_{BR}=21.47-0.05D_d$	0.34
W_{BR}	W_F and D_d	$W_{BR}=15.14+0.15W_F-0.039D_d$	0.41
$\%_{BR}$	W_F	$\%_{BR}=74.86-0.81W_F$	0.24
$\%_{BR}$	D_d	$\%_{BR}=64.57-0.08D_d$	0.07
$\%_{BR}$	W_F and D_d	$\%_{BR}=114.55-1.22W_F-0.16D_d$	0.47
W_{UN}	W_F	$W_{UN}=-2.48+0.25W_F$	0.36
W_{UN}	D_d	$W_{UN}=4.77+0.00095D_d$	0.0002*
W_{UN}	W_F and D_d	$W_{UN}=-7.82+0.31W_F+0.021D_d$	0.42
$\%_{UN}$	W_F	$\%_{UN}=3.77+0.34W_F$	0.10
$\%_{UN}$	D_d	$\%_{UN}=7.30+0.04D_d$	0.05*
$\%_{UN}$	W_F and D_d	$\%_{UN}=14.52+0.53W_F+0.07D_d$	0.23

Predictor variables W_F is floodplain width (km) and D_d distance downreach (km). W_{RET} is the width of the reticulate pattern, W_{BR} the width of the braided pattern and W_{UN} the width of the unchannelled area. $\%_{RET}$ Denotes the percentage of the floodplain occupied by the reticulate pattern, $\%_{BR}$ and $\%_{UN}$ the percentage occupied by the braided and unchannelled areas.

*Not significant at $\alpha=0.05$.

distance downreach is the best single predictor of braided pattern width. The width of braided pattern development decreases with distance downreach (Fig. 9), suggesting that the influence of transmission losses is significant. Multiple regression analysis showed that considering both predictor variables simultaneously markedly increased the strength of the relationship ($r^2=0.41$ compared to cf. $r^2=0.34$ for D_d alone).

The relative abundance of the braided pattern ($\%_{BR}$) decreases markedly with increased floodplain width (Fig. 10). To illustrate this tendency, transects were divided into two approximately equal groups by width. A mean of 40% of the wider (W_F>25 km, $n=29$) transects were occupied by braided patterns compared to 63% of the narrower ($W_F<25$ km, $n=28$) transects, a statistically significant difference (Tukey–Kramer HSD test, $\alpha=0.05$). Relative abundance is also weakly and negatively related to distance downstream. The influence of transmission losses can be inferred from Fig. 9. There are three main narrow (<20 km) areas of floodplain: 0–15 km, ~ 160–270 km, and from 350 km to 370 km (the end of the study reach). The most upstream of the areas is dominated by the braided pattern to the exclusion of other patterns, in the area in the middle of the reach the braided pattern dominates but co-exists with reticulate patterns and very minor unchannelled areas, while in the most downstream area the reticulate pattern and unchannelled floodplain dominate. Multiple regression analysis produces a significantly improved relationship ($r^2=0.47$ compared to $r^2=0.24$ for W_F alone), in which the relative abundance of the pattern decreases with increases in both floodplain width and distance downreach, the opposite trends to those for reticulate patterns.

5.1.3. Unchannelled areas

Distance downreach is not a significant predictor individually of the absolute extent (W_{UN}) or relative abundance ($\%_{UN}$) of unchannelled floodplain ($\alpha=0.05$). Both W_{UN} and $\%_{UN}$ are positively related to floodplain width. For $\%_{UN}$ this relationship is weak ($r^2=0.10$), while for W_{UN} the relationship is moderate ($r^2=0.36$, Fig. 10). The weakness of these relationships is due in part to the large numbers of zero values in the data set as there is a large number of transects where no unchannelled floodplain is present. A better illustration of the influence of floodplain width is shown by Fig. 9, where unchannelled areas are seen to be largely confined to wide areas of floodplain. Transects with no areas of unchannelled floodplain have a mean width of 23.44 km compared to a mean width of 34.8 km for transects with unchannelled areas, a statistically significant difference (Tukey–Kramer HSD test, $\alpha=0.05$). The combination of both predictor variables in multiple regression markedly improves the strength of the relationships for both W_{UN} ($r^2=0.42$ compared to $r^2=0.36$ for W_F alone) and $\%_{UN}$ ($r^2=0.23$ compared to $r^2=0.10$ for W_F alone). As with reticulate pattern occurrence, both increase with increasing floodplain extent and distance downreach.

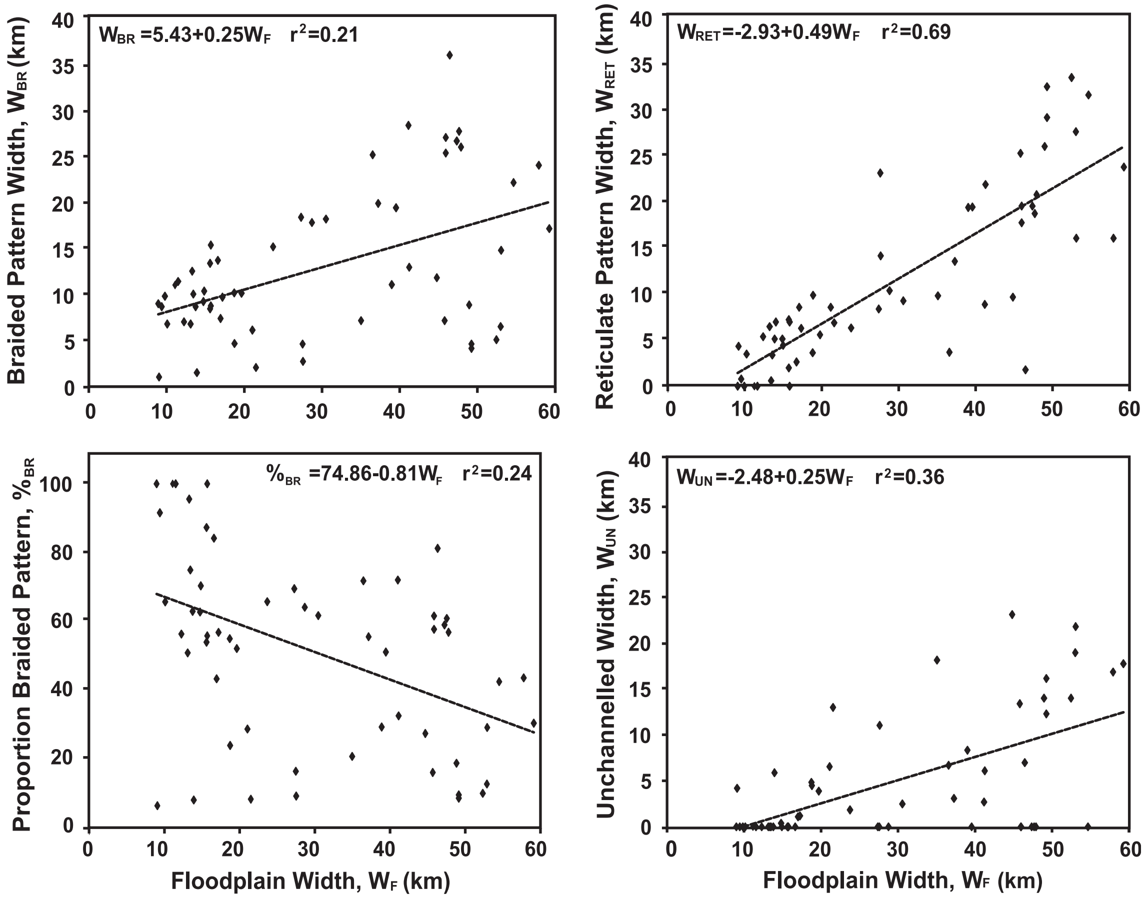


Fig. 10. Examples of single variable regression plots showing the variation with floodplain width of the widths of the reticulate pattern, the braided pattern, unchanneled area, and the dominance of the braided pattern.

5.1.4. Summary of regression results

All pattern types showed significant responses to changes in floodplain extent (Table 2). Particularly narrow floodplain transects may be entirely braided with no reticulate or unchannelled areas, suggesting that braiding may be associated with a concentration of flow energy. All transects possess areas of braided channels suggesting that all transects have some zones of concentrated overbank flow. An increase in floodplain width results in an increase in the width of all floodplain surface patterns. Reticulate and unchannelled areas increase at a greater rate than braided patterns to occupy significantly greater proportions of wider than narrower floodplain areas. Individual relationships between pattern abundance variables and distance downreach (D_d) were generally weak, but D_d was the best predictor of the absolute width of the braided pattern that tends to decrease downreach. In all but one case (W_{RET}) multiple regression relationships were markedly stronger than relationships between the predictor variables individually, suggesting that both floodplain extent and transmission losses exert a significant influence on pattern occurrence, but that when variables are examined individually the influence of transmission losses tend to be masked by the influence of variations in floodplain width.

5.2. Floodplain topography

Typical examples of the topographic distribution of pattern types for the study reach are shown in Figs. 11 and 12. Profiles A and B show areas of floodplain

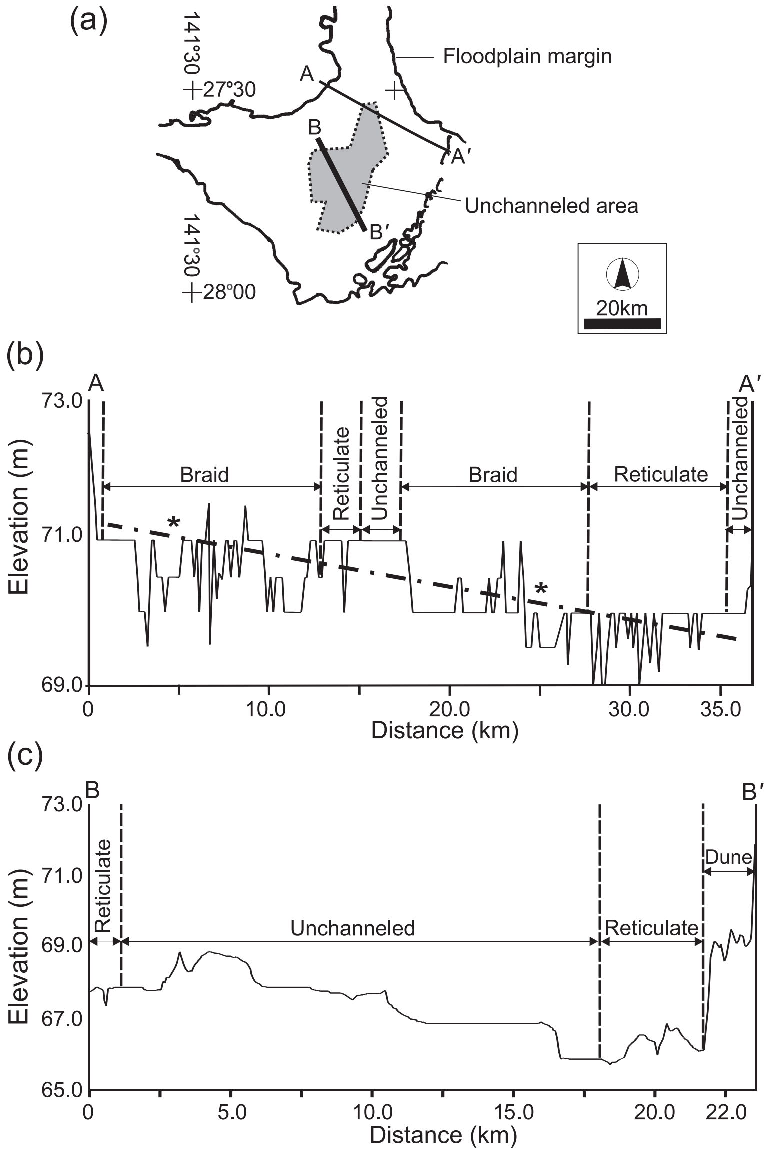


Fig. 11. (a) Topographic distribution of floodplain-surface channel pattern type. Reticulate and braided patterns are found in both higher and lower areas of the floodplain. Dotted/dashed line in Profile A–A′ shows general surface trend. Major anastomosing channels are marked by *, shaded area in map shows extent of the unchannelled area. (b) Vertical exaggeration of Profile A–A′ is 3352 times. (c) Vertical exaggeration of Profile B–B′ is 1850.

near the downstream end of the of the study reach where the Cooper valley widens at its confluence with the Wilson valley. Profile R shows a narrower area of floodplain in the middle of the study reach. The floodplain here is contracting from a maximum width of 62 km near the offshoot of Lake Yamma Yamma to ~10 km just 60 km downstream. Plotted with extremely large vertical exaggerations all show low, but geomorphically very significant cross-floodplain elevation variability (Profile A—1.5 m, Profiles B and R—3.5 m). All three profiles show a clearly definable zonation of pattern types. Although previously de-

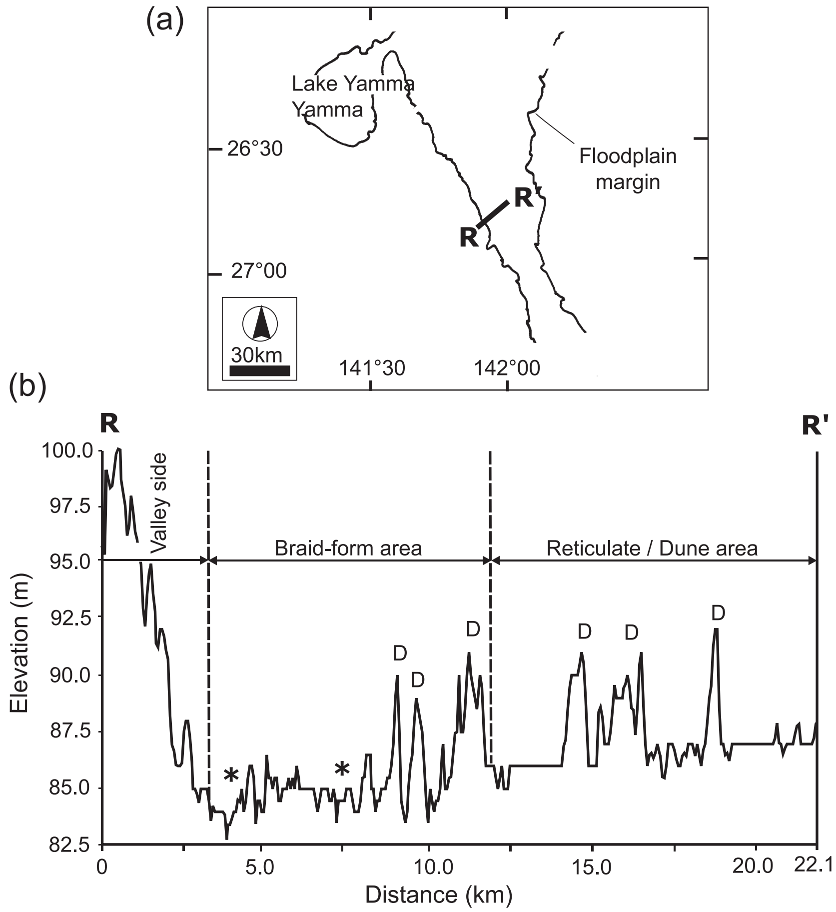


Fig. 12. Topographic distribution of floodplain-surface channel pattern types, south of Lake YammaYamma. Braid-form channels occur in the lower areas of floodplain towards the western side of the transect. Position of dunes indicated by ‘D’, anastomosing channels indicated by *. Vertical exaggeration of Profile R–R′ is 699.

scribed as backswamps or sumps (Whitehouse, 1948; Rundle, 1977), reticulate channels are not confined to lower, wetter areas of the floodplain. Profiles A and B show that reticulate channels do occur in low areas, but all three profiles show reticulate patterns developed in higher areas of the floodplain and in Profile R reticulate patterns are developed on the most elevated floodplain area only. This is evidence that floodplain elevation is not the sole control on the distribution of the reticulate pattern. The co-occurrence of the reticulate pattern and the development of large gilgai suggests that prominent gilgai formation here may also be a more complex issue than previous authors believed.

A comparison of Profiles A and R illustrates that, like the reticulate pattern, the braided pattern also occurs across the full spectrum of floodplain elevation situations, occurring in both high and low areas of the floodplain. Major anastomosing channels are confined to braided areas and never occur within reticulate or unchannelled floodplain areas. The spatial sequence across the floodplain of anastomosing channel, adjacent braided pattern, reticulate pattern, to unchannelled area occurs throughout the study reach. As the anastomosing channels are the sources of overbank flows, the braided areas proximal to them are subject to highest inundation frequencies.

In contrast to braided and reticulate patterns, unchannelled areas are confined to the highest areas of the floodplain surface. Satellite imagery and gauging records were used to estimate the frequency of flooding of the unchannelled area in the south of the study reach crossed by Profiles A and B. The area was found to have been inundated during the 1990 flood event when the peak gauge height at Nappa Merrie was 9.38 m, but not in 1989 when peak gauge height was 6.9 m. Using these values as a guide to the size of flood necessary to inundate the area suggests that the area has been flooded only four times since gauging records began in 1949. Other areas have not been inundated over the period of record, as shown by satellite imagery of the 1974 flood (Fig. 13). Similar calculations indicate that other unchannelled areas have not been inundated at all over the period of record.

On the basis of these observations, studying down-reach transitions between pattern types may thus help to elucidate the controls on pattern formation. The transition from a braided to reticulate pattern was studied south of Naccowlah Waterhole (Fig. 14). This location was selected for two reasons. Firstly, the transition here is typical of that observed in other places across the reach; and secondly the accessibility of the area allowed field observations to be made to augment the aerial photograph analysis. The braided pattern forms proximal to anastomosing channels on the east of the floodplain draining Naccowlah Water-hole, which upstream (north) of the area shown in Fig. 14 have swung westwards to dissipate in the high area

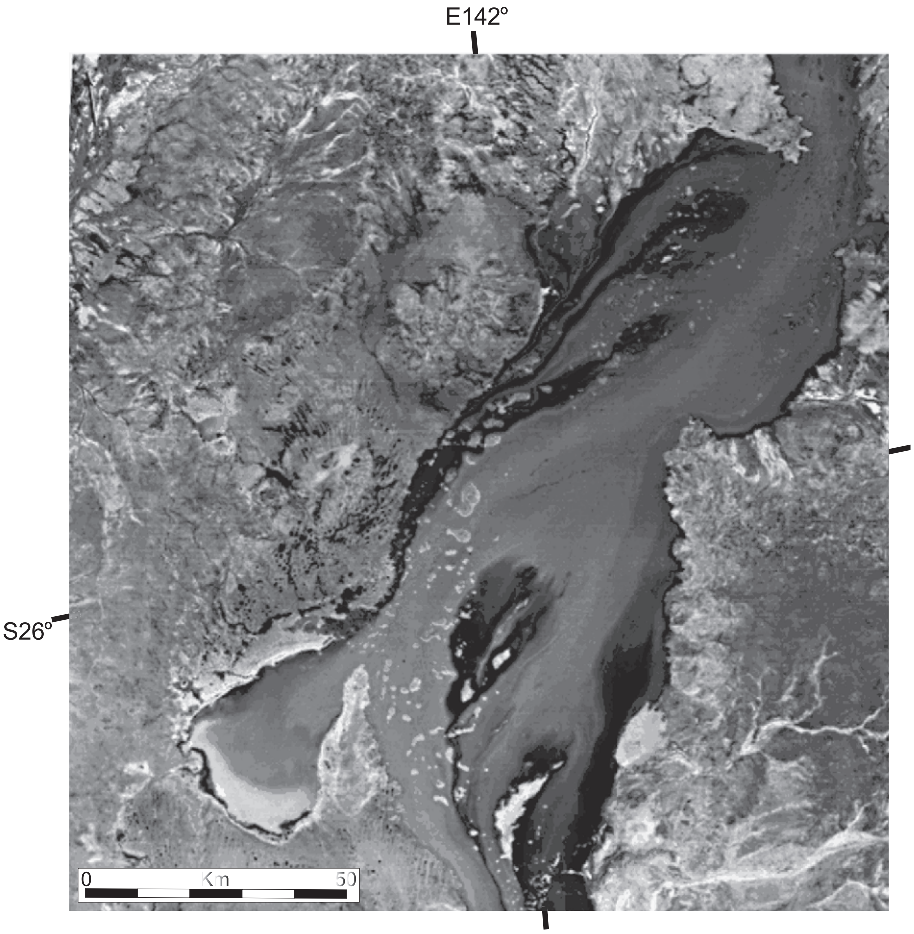


Fig. 13. The 1974 flood of the Cooper Creek. Light grey areas of the floodplain surface represents water, black areas are wet but not inundated. Highly reflective islands within the floodplain represent dry, higher areas or aeolian dunes.

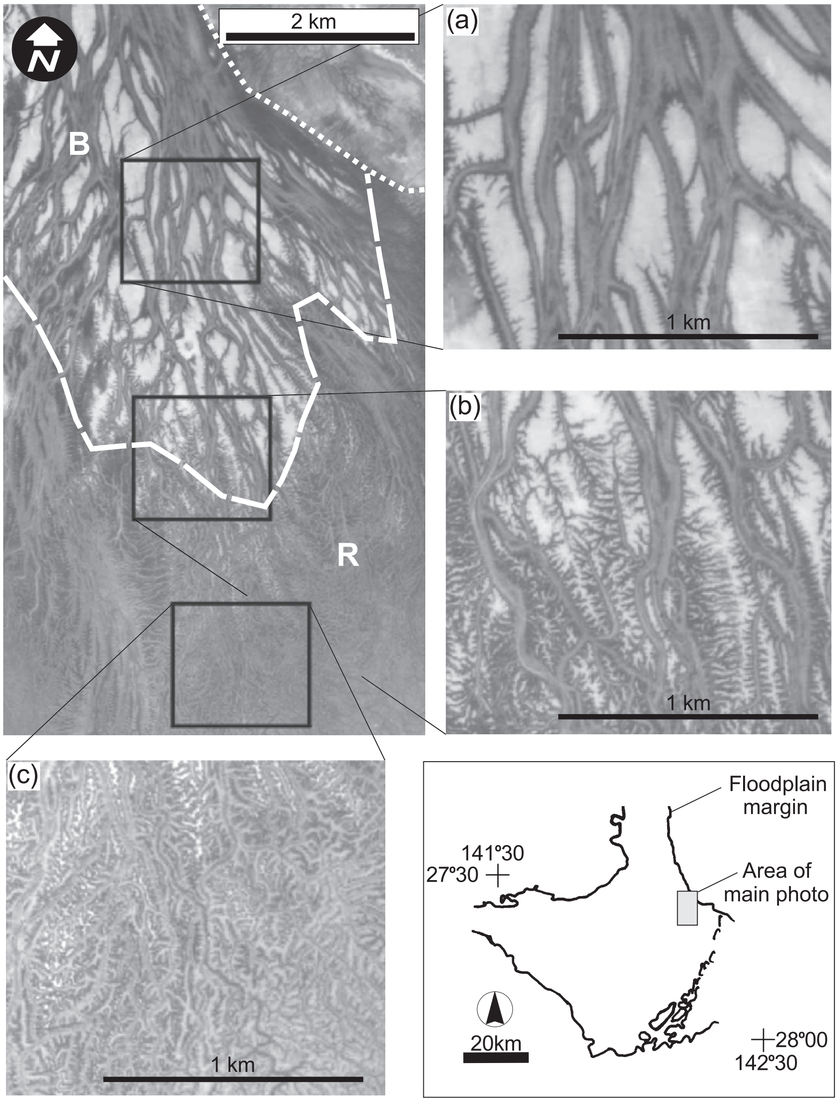


Fig. 14. The transition between braided and reticulate floodplain-surface patterns near the confluence of the Cooper and Wilson Rivers. Note the dispersion of flow indicated by the paths of the braid channels into the transition. Dotted line denotes the floodplain margin, dashed line the boundary between braided (B) and reticulate (R) pattern types.

of floodplain crossed by Profile A (Fig. 11). The floodplain here is widening approaching the junction of Cooper Creek with the Wilson River and the orientation of the braid channels in Fig. 14(a) indicates that flow is diverging and weakening. In the intermediate stage of the transition (Fig. 14(b)) individual braid channels become highly "fretted" by large numbers of small channels which diverge from the braid channels and persist only for short distances. Despite their appearance, these channels do not represent local floodplain drainage. This is indicated by the intensity of the fretted pattern being greater in the middle of the transition shown in Fig. 14 where the braid islands are smaller in area and more subdued in height than those upstream. Overland flow from local rainfall on the islands here has both a smaller catchment area than immediately upstream and, since rainfall across the floodplain will be approximately constant and island relief and so slope is lower, less energy. Instead, the frets represent the beginning of the influence of gilgai on the braided pattern, forming when flow is diverted from the braid channels into depressions formed by gilgai which are becoming prominent on the surface of the braided islands. The initially short length of the frets is due to the relative height of the braided island acting as a barrier to flow from the braid channels into the frets.

Further downstream as flow continues to diverge, reducing in energy, the relief of the braid islands becomes more subdued. This allows flow to penetrate further into the gilgai pattern and the lengths of the fretted channels to increase. Gilgai become larger and more prominent, increasing the tendency of the braid channels to bifurcate and leading to greater flow dispersion. This dispersion process continues with the fretted channels growing and branching until they become integrated into a reticulate channel system that becomes progressively more connected until no trace of the braided pattern can be seen.

6. Discussion

The origin of floodplain-surface channel patterns on Cooper Creek have been the subject of much debate. Rundle (1977), Rust (1981) and Rust and Legun (1983) considered the braided pattern to be the surface expression of a relict, inactive sand-bed braided channel system which the mud deposits of the contemporary floodplain were merely draped over. This system was supposed to have formed during a prior, wetter climate when the river had a more persistent flow regime than exists at present. Subsequent auguring of the floodplain surface falsified this theory by demonstrating that the positions of the braided channels are unrelated to the surface-form of the underlying sand sheet and thus do not reflect underlying relict features (Nanson et al., 1986; Rust and Nanson, 1986). These authors state that the braided pattern is contemporary, formed under the current, ephemeral flow regime and is braided in form and process. This conclusion is supported by the relationships that have been described here between pattern distributions and floodplain characteristics.

Previous study of the reticulate networks on Cooper Creek concentrated on noting the co-occurrence of the pattern and gilgai development. A similar pedogenic influence on channel development and organisation has been described by White and Law (1969) on soils in Iran and Sudan. Depressions in the clay soil surface there form by differential compaction during weathering and are subsequently occupied by networks of interlocking channels termed ‘tabra’ channels after the soil type on which they occur (White and Law, 1969). The reticulate pattern was said by previous authors to be confined to lower, sump areas of the floodplain where water ponds (Whitehouse, 1948; Rundle, 1977). This assertion was not based on survey data but on the assumption that gilgai development must be greater in wetter areas where the duration of periods of inundation, if not inundation frequencies, were greater, and thus that heavily gilgaied areas where reticulate patterns were present must be topographic lows. As data in Section 5.2 demonstrates, these assumptions are incorrect. Heavily gilgaied areas of floodplain with reticulate channels occur in various topographic situations including floodplain lows but also including higher areas of floodplain.

The distribution of channel patterns revealed by this study allows a number of inferences to be drawn

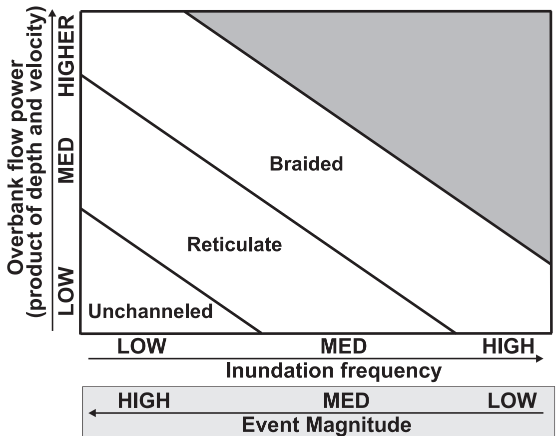


Fig. 15. A continuum model of floodplain-surface channel pattern distribution controls. Characteristics of areas in which patterns occur are summarised. The grey area indicates combinations of overbank flow power- and event magnitude and inundation frequency not found.

regarding the controls on channel pattern formation and occurrence and the formulation of a model describing the controls on floodplain-surface channel pattern formation operative here (Fig. 15). Locations where overbank flood flow is concentrated and relatively high in energy are dominated by braided patterns. These areas are frequently inundated and experience relatively deep, high velocity overbank flow. In narrow sections of the floodplain, the limited width is sufficient to cause higher flow energies and a braided pattern, whereas in wider areas the principal cause of the braided pattern is the proximity to anastomosing channels which are the source of inundating flows. This ensures that these areas experience greater frequencies of inundation than more distal areas. The dominance of the braided pattern in narrow areas of the floodplain decreases downstream as transmission losses attenuate flow volumes and the depth and velocity of flood flows thus causing the energy of overbank flood flows to decrease. The cause of the suppression of large gilgai in braided areas would seem to be the relatively high energy of flood flow here, which erodes any gilgai that may form. This flow causes the larger-scale sculpting of the surface into the mosaic of braid channels and islands characteristic of these areas.

In terms of the energy of flood flows and inundation frequencies, reticulate areas occur in locations intermediate between braided and unchannelled areas. Here the intermediate frequencies of inundation are sufficient to stimulate gilgai formation while the intermediate flow strengths are insufficient to cause the removal of gilgai by fluvial erosion. That the occurrence of flow ponding is not necessary for the development of large gilgai is shown by the development of large gilgai and the associated reticulate networks in higher areas of the floodplain. It seems likely that if gilgai did not form in reticulate areas then the areas would be unchannelled, as the concentration of floodwaters by the gilgai pattern seems necessary for channel formation.

Unchannelled areas always occur in higher areas of the floodplain and where flood flows are either highly dispersed in wider areas of the floodplain, or in the lower part of the reach where flow volumes have been highly attenuated by transmission losses. Inundation frequencies in these areas are low, as is the energy of inundating flows on the rare occasions they occur. The lack of prominent gilgai development in these areas implies that due to the aridity of the area rainfall wetting is insufficient to cause sufficiently frequent wetting and drying cycles in the soil, and that more frequent inundation such as occurs in the other floodplain environments is necessary for prominent gilgai to form.

7. Conclusion

Examination of the Cooper Creek floodplain reveals a complex array of surface channels constructed to transfer and disperse floodwaters over a vast, muddy floodplain of very low relative relief. Only slight changes in flood stage result in extreme differences in the areas inundated. While casual observation of aerial photographs of satellite images might suggest an almost chaotic pattern of floodplain-surface channels, gilgai soils and aeolian dunes, the analysis here reveals a strongly interconnected system of surface channeling and pedogenic characteristics responsive to the depth and frequency of overbank flow. Overbank flow characteristics for any given area are determined by event size, floodplain physiography (width, topography) and transmission losses.

Acknowledgements

The research for this work was supported by UPA and OPRS Scholarships to S.D.F. from the University of Wollongong, and by an ARC Program Grant to G.C.N.

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