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UPPER-FLOW-REGIME MUD FLOODPLAINS, LOWER-FLOW-REGIME SAND CHANNELS: SEDIMENT TRANSPORT AND DEPOSITION IN A DRYLANDS MUD-AGGREGATE RIVER

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ABSTRACT: Dryland rivers in which fine sediments travel as aggregates are increasingly recognized in modern and ancient fluvial systems. Fowlers Creek, Australia, is an ephemeral dryland mud-aggregate river whose sediments provide insights into the dynamics of mud-aggregate floodplains, the origin of massive mudrocks from arid depositional environments, and the nature of planar bedding. Fowlers Creek's flow conditions were inferred from relationships between landforms and the sediment texture, bedforms, and sedimentary structures remaining after flow ceases.

Floodplain muds, consisting of fine sand and sand-size mud aggregates, are distributed over the floodplain in suspension. As flow decelerates they are deposited as bedload. The shallow depth, high sediment load, and low aggregate particle density promote flow conditions ranging from high in the lower flow regime to upper flow regime, producing coexisting ripples, scours, flat beds, and clay layers. With time, visible signs of aggregate structure are lost, leaving a massive cohesive mud; consolidation is not achieved by burial. Aggregates reappear when muds reenter fluvial transport. In unchanneled reaches, sheetflows deposit sediment with a pervasive horizontal fabric. Channel sediments (coarse sands and gravels) are a minor component of Fowlers Creek's deposits. Widespread lower-flow-regime conditions produce planar beds and 2-D dunes, usually deposited without internal stratification or in horizontal laminae. Lower-flow-regime planar bedding is also observed in fine silty sands. Near the close of flow, rapid shallowing may move channel conditions from lower to upper flow regime, or from lower to higher positions in the lower flow regime bedform stability spectrum, leading to unusual bedform associations.

In the rock record sediments from a river like Fowlers Creek would be characterized by structureless gravelly sands (channel facies), massive red mudstones (floodplain facies), and sediments with horizontal fabric but poorly expressed bedding (sheetflow facies).

INTRODUCTION

Dryland river deposits are relatively poorly documented in comparison to rivers from other climatic zones. Descriptions of desert environments frequently focus entirely on eolian sediments, and where dryland rivers are described, sandy and gravelly examples often predominate (e.g., Reineck and Singh 1980; Miall 1996; Reading 1996; Graf 1988; Bourke and Pickup 1999; Cohen and Laronne 2005; Hassan 2005). However, arid-zones or dryland rivers display a great variety of form and process (Nanson et al. 2002), and when preserved in the rock record contain mudrock as well as sandstone (e.g., Wells 1983; Cowan 1993; Meadows and Beach 1993; Gierlowski-Kordesch and Rust 1994; Gierlowski-Kordesch 1998; Müller et al. 2004; McKie and Audretsch 2005). Dryland rivers in which fine sediments travel as mud aggregates are increasingly becoming recognized in modern and ancient fluvial systems, with Cooper Creek being the best-documented modern river (Nanson et al. 1986; Ekes 1993; Marriott and Wright 1996; Gibling et al. 1998; Gierlowski-Kordesch and Gibling 2002; Fagan and Nanson 2004; Müller et al. 2004).

The most direct way to investigate the behavior of a river is to measure its flow parameters while observing its interactions with bounding landforms. However, gathering direct data for Australian ephemeral streams is often unachievable due to their remoteness, their ungauged state, and the brevity and unpredictability of their flow events. On the other hand, dry creek beds offer good opportunities to study sediments preserved at the close of flow, allowing understanding of flow conditions which could not otherwise be observed. The genesis of unusual or ambiguous sedimentary structures can be inferred from the formative conditions of nearby known structures (Picard and High 1973). In this study, sediments, sedimentary structures, and bedforms from an Australian mud-aggregate ephemeral stream are described and used to infer recent flow conditions. The characteristics of the sediments described here will be relevant to the interpretation of rocks (especially mudstones) of dryland fluvial origin, and provide insight into the nature of planar bedding associated with dryland rivers.

Study Area

Fowlers Creek is an ~ 55-km-long endorheic ephemeral river in western New South Wales, Australia (Fig. 1). The catchment has an arid climate with hot, dry summers and mild winters. Average annual potential evaporation (~ 2800 mm) greatly exceeds the median annual rainfall (200 mm) (Australian Bureau of Meteorology 1988). Rain may occur at any time, from gentle showers to intense cloudbursts, and rainfall is spatially as well as temporally variable (Dunkerley and Brown 1999). Fowlers Creek is usually dry, but it may flow several times a year, to sub-bankfull, bankfull, or overbank levels. Most flows last only hours to days, and they may start, peak, and finish almost anywhere in the drainage

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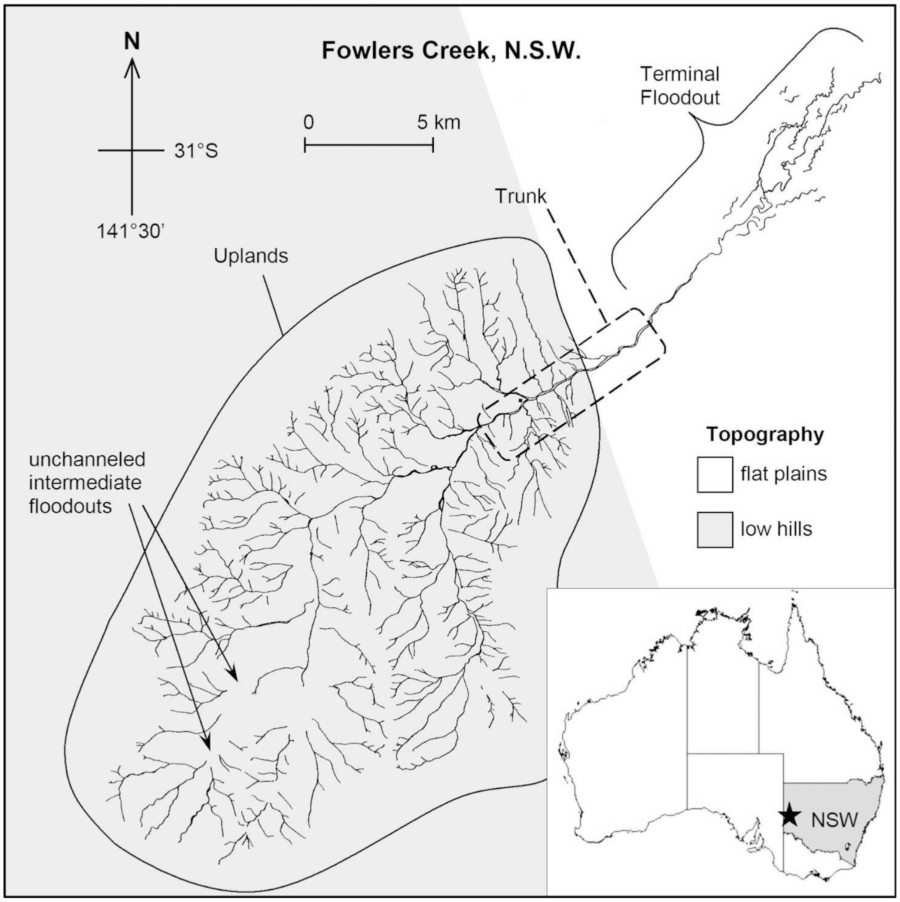

FIG. 1.—The location of Fowlers Creek in New South Wales (Australia), and its three geomorphic subregions: uplands, trunk, and terminal floodout. Flow is from southwest to northeast.

network, according to how many and which tributaries receive rain. Short flows tend to show flashy single-peaked hydrographs, and longer flows are often multi-peaked, reflecting input from different tributaries.

Most of the water and sediment in Fowlers Creek comes from the piedmont reaches (the uplands, Fig. 1). Low hills of poorly outcropping rocks are partially covered by a ≤ 1 m mantle of silty regolith in a contour-banded stony gilgai landscape. The hillslope regolith contains smectite clays and abundant sand-size mud aggregates (Corbett 1973; Mabbutt et al. 1973; Ward and Sullivan 1973; Chartres 1982a, 1982b). Sediments are brought into the river system by gullies eroding into regolith, or, in the upper catchment areas, into sheetflow-redistributed colluvium accumulating at the foot of steep rocky hills. However, most sediment transported through the creek is recycled from uplands floodplain storage, reentering fluvial transport after floodplain erosion or channel avulsion (Wakelin-King and Webb 2007).

Fowlers Creek is divided into three geomorphic subregions: uplands, trunk, and terminal floodout (Fig. 1), each having a characteristic fluvial style and channel geometry (Table 1). In the uplands, a dendritic network of arroyos is incised into broad floodplains. Discontinuous ephemeral stream processes (Bull 1997) dominate the lower-order uplands tributaries, and in the higher-order main river the arroyo is prone to catastrophic reach-scale channel relocation resulting in irregular areas of floodplain erosion and deposition (Wakelin-King and Webb 2007). Many tributary junctions are unchanneled, forming intermediate floodouts (*sensu* Tooth 1999) in which creek waters travel as unconfined sheetflow. In the trunk, the central reaches of the creek are constrained into narrow floodplains between moderately steep rocky hills. The creek is anabranching, and the primary channel varies between narrow, deep, muddy chutes (the largest forming semipermanent waterholes) and wide shallow gravelly riffles with gum trees (*Eucalyptus camaldulensis*) growing along the channel bed. In the terminal floodout, away from the hills, the creek is a single channel: meandering, straight, or incised; surrounded by cracking gilgai plains. Discharge decreases downstream (Dunkerley 1992; Dunkerley and Brown 1999), and the creek diminishes in size and eventually disappears.

Methods

Sites were established at 1–2 km intervals along Fowlers Creek. At each, the cross-section profile was surveyed and thalweg (lowest-channel) and bank sediments were sampled. The percentage of gravel cover over the total channel was estimated and the β axes measured of the 10 largest clasts (excluding lag). Geomorphology, sedimentology, and stratigraphy were described at all scales, and relationships were identified between landform groups, sediment characteristics, and (for modern sediments) size of the flow event. Quantified discharge data are not available, so information from local residents was used to classify flow events as "normal" and "floods" (recurrence intervals of ≤ 10 years and 10–60 years, respectively). Bank stratigraphy was examined with particular reference to the distribution of old floodplain muds (aged > 150 years) and modern floodplain muds (aged < 150 years). The age of the floodplain muds was established by stratigraphic position, burial of European artifacts, and dating by optically stimulated luminescence.

Grain size analyses were performed on sediments from each site. To preserve any aggregates which may have been whole during fluvial transport, one should avoid standard laboratory pretreatments (Lewis and McConchie 1994a; Lewis and McConchie 1994b). Floodplain mud samples were therefore analyzed twice, with and without pretreatment, resulting in grain size analyses of the fully disaggregated and the as-

TABLE 1.—*Dimensions of representative channels in the geomorphic subregions of Fowlers Creek. Dimensions are for the reach's main channel, which is only part of the flow path in anabranching or floodout reaches.*

Geomorphic Subregion	Channel Type	Cross-section Area (m^2)	Channel Depth (m)	Width:Depth
Uplands — lower-order tributaries	arroyo	6.3	0.6	32
Uplands — intermediate floodout	no channel	–	–	~ 50–300*
Uplands — higher-order main channel	arroyo	33.1	1.8	7
Trunk	chute	51.8	3.3	7
	riffle	22	1.8	28
Terminal Floodout	straight, meander	19.4	2.1	9

* In the intermediate floodout, the width:depth ration of the flow is controlled by floodplain topographic irregularity.

transported states of each sample. Comparison revealed the proportion of sediment present as sand-size mud aggregates (Wakelin-King and Webb 2007). Channel sediments were measured in the as-transported condition only. In this paper, fully disaggregated sediments are mentioned only in the context of assessing the proportion of fine sediments traveling as mud aggregates. All other grain size descriptions refer to sediments in their as-transported condition.

SEDIMENTS, BEDFORMS, AND SEDIMENTARY STRUCTURES

Fowlers Creek is a mixed-load creek, and channel and floodplain sediments are dissimilar. The floodplains hold red-brown muds, generally without any coarse component, and most channels carry clean sands and gravels. Only in the intermediate floodouts are floodplain muds and channel sands intermingled. Fowlers Creek sediments are dominated by floodplain deposits: channels occupy only a small proportion of the floodplain, and few channel deposits are evident in bank exposures.

Channels

Fowlers Creek channels carry poorly sorted gravelly coarse sand or sandy gravel in the uplands, trunk, and proximal terminal floodout (Table 2). Cobbles are often present, as lag in the uplands and also in mobile bedforms in the trunk. Transported gravels and cobbles in the channel sediments are never far from sources of coarse sediment (hillslopes, exhumed old channel sediments). The amount and size of coarse clasts diminishes rapidly downstream from the end of the trunk's rocky hills, and in the distal terminal floodout channel sediments are silty sand fining downstream to mud. Fine sediments (fine sand, silt, or clay) are noticeably absent from the uplands and trunk channels, except in trunk waterholes or as occasional thin waning-flow deposits overlying the bedload.

The prevalence of flat bedding in Fowlers Creek channel sediments is striking. Old buried channel sediments exposed in creek banks are generally flat, structureless single layers. Most modern channels have flat beds extending from bank to bank and from reach to reach, either featureless, with scattered gravel, or with poorly defined gravel patches (Fig. 2). Modern flat beds are commonly associated with 2-D dunes, such that the stoss faces of the dunes extend for tens to hundreds of m upstream from the dune crests, forming the flat channel bed (Table 2). Some 2-D dunes are spur-fronted, with 1–10 thin flow-parallel ridges downstream from the lee face (Fig. 3). In both flat beds and 2-D dunes the surface sediment may be either soft or hard underfoot; there is no pattern as to which occurs where in the channel. In the bedforms with soft surfaces, the sediment consists of very loose sands with unstructured gravelly patches at the top (Fig. 2). Soft bedforms are either without internal structure, or display a crude horizontal fabric poorly defined by clast orientation, slight variations in grain size, and pea-gravel clusters. Their tabular lee faces produce no, or only slight, cross-bedding. Bedforms where the upper surfaces are hard are often marked by current streaming lineation (Fig.3). Underlying sediments are tightly packed, and the internal structures are well-defined millimeter- to centimeter-scale medium and coarse sand layers, flat-lying beneath the dune top and forming tabular cross-bedding on the lee faces.

Three-dimensional dunes are rare in Fowlers Creek, except in the narrow, deep chutes of the trunk, where they are a common bedform. Their sloping stoss faces consist of gravel and cobble armor over coarse sand, and the steep lee faces of silty sand may be fronted by a scour.

At Fowlers Creek, sediment transported within the channel is rich in fine material, and flows are visibly muddy (Dunkerley and Brown 1999), but fine sand and mud are rarely deposited in uplands channels. Instead, fine sediments are often transported out of the channels as suspended load, at least during peak flow, and deposited across floodplains. For example, during this study modern muds were deposited on a floodplain ~ 1.5 m above a channel where the same flow event transported clean coarse bedload in the channel (Fig. 2). In flows which remain in-channel, fine sediments are generally flushed out of the uplands and trapped in chute waterholes or transported to the terminal floodout. Rarely, after a flow event so brief that the flow front never leaves the uplands, a pulse of fine sediments remains within the main channel, deposited as continuous horizontal laminae (Table 2). Mud drapes, deposited from suspension and forming mud curls when dried, are rare.

Floodplains

Much of the Fowlers Creek floodplain muds are aggregated particles containing clay and silt: sand-size mud aggregates constitute ~ 70% of the silt + clay fraction, and ~ 40% of the total floodplain sediment (Table 3A). Mud aggregates the size of coarse silt are also likely to be present (Wakelin-King and Webb 2007). The non-aggregate fraction of the floodplain muds is mostly very fine to fine quartzose sand. Floodplain muds in their as-transported state are mostly sand-size grains, with little free silt and only minor clay (Table 3B), but fully disaggregated they are dominated by silt, have a greater clay content, and are much less sandy.

The modern floodplain sediments of Fowlers Creek look like loose silty fine sands, whereas old floodplain sediments are hard and cohesive, apparently consisting of silty clays. However, both have the same grain size distribution (Wakelin-King and Webb 2007); they differ only in that aggregates in the modern muds remain discrete, whilst the old muds are consolidated and the aggregate structure is no longer visible. When wetted, the old muds re-separate into their constituent aggregates, sands, and silts: this was demonstrated in the laboratory, and observed in the field, where erosion of old muds was linked by fluvial transport to downstream deposits of modern mud-aggregate sands.

Unconsolidated modern floodplain muds are free of bioturbation or pedogenic features. They are red-brown and characterized by a loose, soft surface and abundant fine sedimentary structures, in two associations. Most commonly, modern muds occur as discontinuous wavy and planar laminae, in a chaotic association with channel-scale cut-and-fill structures, ripple and small dune cross-lamination, infilled shallow scours (centimeter-scale, but unrelated to ripple or dune cross-sets), centimeter-

TABLE 2.—*Fowlers Creek channel types, sediments, bedforms and sedimentary structures.*

	Channel Type	Typical Texture	Bedform	Bedform Length (m)	Bedform Thickness (m)	Sedimentary Structures	Comments	Associations	Process
Uplands	none	extremely poorly sorted gravelly muddy sand [1]				horizontal orientation of nonspherical clasts (vc)	sediment texture similar at every flow event		sheetflow redistributing colluvium
		mud with interbedded gravelly sand [2]				horizontal orientation of nonspherical clasts (vc), layer boundaries lack erosional contacts or clay partings (vc), imbrication (r)	sediment texture can vary between flow events; layers sharply defined by grain size variations		sheetflow depositing fine or coarse sediments
	arroyo	fine sediments (silt, aggregates, fine sand)	flat beds or 2-D dunes (r)	irregular: 2 to > 100 m between crests	0.1–0.5	continuous horizontal planar laminae (c)	sharp lower boundary with underlying coarse channel sands; fine sands and mud aggregates; also found in floodplain shadow bedforms	mud-aggregate current ripples (r)	traction transport, waning-flow deposit
		medium to coarse sand, to very fine gravel	flat bed (vc)	> 100		scattered gravel (vc), poorly defined gravel patches (vc), cobble clusters (r), internal stratification as for 2-D dunes below	soft and hard surfaces, as for 2-D dunes below	2-D dune (vc), lateral gutters (fc)	traction transport
			2-D dune (vc)	irregular: 2 to > 100 m between crests	0.1–1.5	no internal structure (fc), crude layers (grain size variation, granule clusters) (c)	soft upper surface showing unstructured gravel patches, loose underlying sediments	flat bed (vc), lateral gutters (fc), current ripples (r)	no, or only incipient, flow separation and eddy formation
						well-defined mm- to cm-scale layering, horizontal beneath flat stoss face and inclined behind lee face (c), streamwise spurs extending from lee face (fc)	hard upper surface with current-streaming lineation, tightly packed underlying sediments		
		cobble lag (c)						adjacent sediment source	low competence of normal flow events

TABLE 2.—*Continued.*

	Channel Type	Typical Texture	Bedform	Bedform Length (m)	Bedform Thickness (m)	Sedimentary Structures	Comments	Associations	Process
Trunk and Proximal Terminal Floodout	chute	silty and gravelly medium to coarse sand	3-D dunes (vc)	3–14 m wave-length	0.3–1.4	(not investigated)			flow separation and eddy formation
			2-D dunes (fc)	irregular: 2 to > 100 m between crests	0.1–2.3	horizontal and inclined layering (fc)	soft upper surface showing unstructured gravel patches, loose underlying sediments; or hard upper surface with current-streaming lineation, tightly packed underlying sediments	gravel-armored stoss faces (fc), cobbles at base of lee face (fc)	no, or only incipient, flow separation and eddy formation
	riffle	sandy gravel	flat beds (vc)	> 100		(not investigated)			traction transport
		sandy gravel	2-D dunes (c)	irregular: 2 to > 100 m between crests	0.2–2.3	horizontal and inclined layering (fc)	common where narrow channel enters wide channel	gravel-armored stoss faces (fc), cobbles at base of lee face (fc), imbrication (r), cobble clusters (r), current ripples (r)	no, or only incipient, flow separation and eddy formation
		sandy gravel to very coarse gravel, with cobbles	poorly defined lateral bars (c)	~ 10–50	~ 1	imbrication (fc)		in-channel gum trees with scours (≤ 0.5 m wide, ≤ 1 m deep) around trunks (vc). imbrication (vc)	deposition during > 100-year recurrence interval floods
T.F.	meander / incised meander	silty fine to medium sand	flat beds (vc)	> 100		(not investigated)	central terminal floodout		
		silty fine sand to mud aggregates	flat beds (fc), baked-hard mud floor (vc)			(not investigated)	distal terminal floodout		

Occurrence: (v) = very common, (c) = common, (fc) = fairly common, (r) = rare. T.F. = Terminal Floodout. No-channel (sheetflow) reaches: 1, upper-catchment footslopes; 2, intermediate floodouts.

FIG. 2.—In an uplands arroyo, the channel is floored by loose coarse sand with diffuse patches of gravel and cobbles (foreground). The flat surface extends from bank to bank and for hundreds of m downstream. Flow direction is away from the camera, 1 m scale.

scale clay layers, clay intraclasts, and structureless mud layers up to 10 cm thick (Fig. 4A). These types of laminae are irregular in the sense that there is no periodicity to their features (for example, the scale and angle of different pinch-offs by wavy laminae varies widely even over a small area, and bears no relationship to the location or scale of ripple cross-lamination or minor scours). They can occur in thick layers (≤ 2 m), or they can be thin-bedded (5–20 cm) in disrupted or variably thick beds, or beds of even thickness (Fig. 4B). Less commonly, the floodplain muds show planar and wavy laminae which lack the chaotic associations described above, and are more regular: continuous planar laminae, or combined wavy laminae, planar laminae, and ripple cross-lamination, in which the distribution and geometry of pinch-offs by wavy laminae is roughly similar to that of the ripple cross-lamination (Fig.4C).

The chaotic laminae and the regular laminae occur anywhere across the floodplain, but certain landform associations are apparent: the chaotic laminae are never found within the creek channels, the regular wavy and planar laminae are usually the upper 5–30 cm accreted onto sloping bank faces, crosscutting the layers beneath, and the continuous planar laminae are typically the upper 5–10 cm of shadow bars behind floodplain vegetation, or the upper 5–20 cm of channel sediment, overlying coarse sands (Table 2).

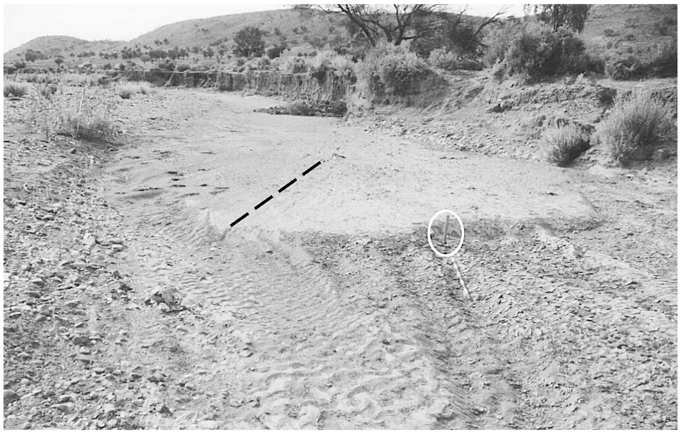

FIG. 3.—An uplands channel contains a spur-fronted 2-D dune, with flanking gutters, mud-draped ripples downstream from the lee face, and current-streaming lineation (dashed line) on the hard flat top (stoss face). Flow direction is towards the camera, 1 m staff in spur trough, hammer for scale (circled) standing upright between staff and lee bedform face.

TABLE 3.—*Textural analyses of Fowlers Creek floodplain muds.* ***A)*** *Sand-size aggregates as a percentage of the fine fraction, and of the total sediment.* ***B)*** *Comparison of sediments analyzed in the as-transported state and in the fully disaggregated state.*

A) Percentage of Sediment as Aggregates:	Minimum (%)	Maximum (%)	Median (%)
silt and clay fraction	37	81	72
total floodplain muds	14	59	42

B) Floodplain Mud Texture	Sand (%)	Silt (%)	Clay (%)
As transported	66–95	2–31	1–8
Fully disaggregated	10–76	19–75	3–23

Old muds are visible at many floodplain surfaces, and two to six layers are usually exposed in channel banks. They are dark red-brown to dark brown, hard and cohesive, and present a monotonous appearance, showing no sedimentary structures. Faint blocky or pedal structure in some layers, and sparse soil carbonates in the oldest layer, indicate that some pedogenesis has occurred. Layers become darker and more consolidated with depth, but boundaries between layers are nonetheless very difficult to discern. Sporadic stone lines demonstrate significant hiatuses in deposition, and provisional OSL dates range from 600 to 14,000 years (Wakelin-King 2005). The boundary between the modern and the older muds is generally sharp, but is gradational in places, showing decreasing clarity of the sedimentary structures, and/or increasing blockiness, with depth.

Given the arid climate, mud cracks and mud curls might be expected to occur commonly in the floodplain sediments of Fowlers Creek, but in fact they are extremely rare.

Sheetflow

Sheetflow occurs in reaches without channels: in the upper catchment, near the steeper rocky hills of the drainage divide where hillslope runoff distributes silty and gravelly colluvium across adjacent valley floors, and in the intermediate floodouts at uplands tributary confluences (Fig. 1), where channels disappear and shallow flows spread out across the floodplain (Wakelin-King and Webb 2007). Sheetflow events deposit thin layers (~ 1–20 mm) of sediment in which nonspherical clasts are oriented parallel to the valley floor, giving a pervasive horizontal fabric. Rarely, more vigorous sheetflows scour a few millimeters into the floodplain surface, depositing a sheet of imbricated gravel. More commonly, sheetflows deposit sediment without initial scouring. The transitory nature of sheetflows and the low content of non-aggregated clays prevents the settling-out of clays when flow ceases, and thus bedding surfaces generally lack both erosional contacts and clay partings.

Where grain size differs between layers the change is sharp, and where there is no textural variation the absence of erosional contacts and clay partings makes layer boundaries impossible to discern. If the sediment source is uniform (the same grain sizes are deposited at each flow event), bedding is absent or only poorly defined. In the upper catchment, where each flow event distributes poorly sorted colluvium, the deposit is almost massive; the only sign of bedding is the slight differences in resistance to erosion that are expressed in the bank profile (Fig. 5A). If the sediment source is non-uniform (different flow events carry sediments of different textures), then layering is expressed by abrupt grain-size changes along planes parallel to the valley floor. In the intermediate floodouts, where different flows can have different ratios of bedload to suspended load, the

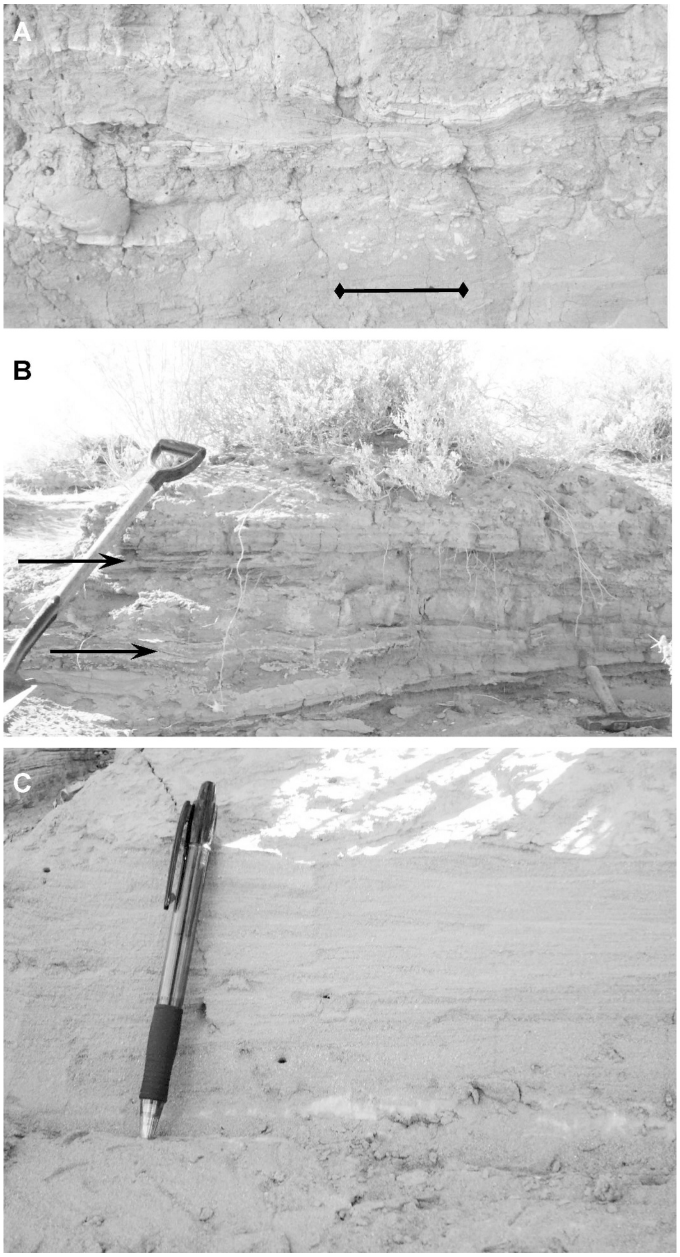

FIG. 4.—Thinly laminated modern floodplain muds. **A)** A chaotic assemblage of irregular flat and inclined laminae, structureless mud layers, clay layers, and clay intraclasts. In a bedform trough (arrowed), three clay layers are separated by aggregate ripples. From a 2 m thick layer filling an old channel; 7 cm scale bar. **B)** Fine sediments in flat but irregular layers (arrows); shovel handle for scale. **C)** Wavy laminae accreted onto a bank face. Small lenses of ripple cross-laminae are also present. Pen for scale.

sheetflow deposits are muds interbedded with muddy gravelly sands (Fig. 5B); each layer represents several or many flow events.

DISCUSSION

Sediment Transport and Deposition in the Channels

Fowlers Creek channels throughout the study area are dominated by flat beds and 2-D dunes deposited under lower-flow-regime conditions. While planar beds can result from upper-flow-regime conditions, this is not the case in Fowlers Creek, where the rainfall distribution precludes high-velocity flow occurring simultaneously over all tributaries. Furthermore, upper-flow-regime planar beds would hardly form so evenly across the full width and length of individual channels, or routinely survive modification by waning flows. The close association of planar beds with 2-D dunes indicates lower flow regime; this and other studies have demonstrated that 2-D dunes can lack internal structure, or produce horizontal laminae instead of tabular crossbeds (Smith 1971; Leeder 1999). Cobble clusters, gravelly patches, and crude stratification are all features of lower planar beds (Bridge 2003). Fowlers Creek's cobble lags and short distances of gravel transport show that peak-flow velocities are normally not much greater than those under which the 2-D dunes and planar beds are deposited.

Only in the chute channels of the trunk are 3-D dunes and transported cobbles found, indicating greater flow velocities in these reaches. The chutes are narrow and deep (Table 1), and they are in anabranching reaches; both channel geometry and river style work towards increased stream power by means of increased flow depth (Knighton 1998; Nanson and Huang 1999). Some chutes show flat floors or 2-D dunes, but often the post-peak decrease in flow velocity is so rapid that 3-D dunes are not replaced by lower-velocity bedforms.

Lower-flow-regime planar beds are not generally described as occurring in sediments finer than coarse sands (Reineck and Singh 1980; Allen 1982; Collinson and Thompson 1982; Southard and Boguchwal 1990; Miall 1996; Leeder 1999; Bridge 2003). However, some reports indicate that lower-flow-regime planar-bed transport may occur in fine sands (Reineck and Singh 1980), and Picard and High (1973) considered that an absence of experimental reports may reflect a dearth of low-velocity studies. In Fowlers Creek, the fine-sediment continuous planar laminae sometimes deposited in-channel at the close of flow (Table 2) are similar to those observed by Picard and High (1973), deposited from flows too slow to produce ripples and too fast to allow mud to settle out. This bedform relationship indicates lower-flow-regime conditions. Frostick and Reid (1977) described parallel lamination formed by medium sand grains under traction at the threshold of transport competence; similarly, partial bedload transport at the threshold of motion forms lower-flow-regime planar beds in gravelly sediments (Bridge 2003). An interpretation that lower-flow-regime planar bedding can form in grain sizes finer than coarse sand is consistent with Picard and High (1973), Frostick and Reid (1977), and the observations presented here.

Horizontally laminated fine sediments are a common feature of arid-zone rivers (Smith 1971; Picard and High 1973; Frostick and Reid 1977; Baker et al. 1983; Reid and Frostick 1997; Bourke and Pickup 1999; Scheepers and Rust 1999), and are often interpreted as indicating the upper flow regime. A unit dominated by horizontally bedded sandstones, in fining-upward sequences (trough crossbeds to horizontal lamination to ripples and mudstone) might be interpreted as having been deposited during mostly upper-flow-regime flood pulses, with lower-flow-regime conditions occurring only occasionally (e.g. Stear 1983). Using Fowlers Creek as an analogue, however, the sequence might also be interpreted as recording a lower-flow-regime waning flow, progressing from 3-D dunes at the peak, through 2-D dunes and lower planar beds, to mud at the close of flow.

Sediment Transport and Deposition Across the Floodplain

Mud aggregates are common in soils. Some stronger types of aggregate survive fluvial transportation (Nanson et al. 1986; Maroulis and Nanson 1996), traveling like sands and deposited in bedforms (Rust and Nanson 1989; Gierlowski-Kordesch 1998; Gierlowski-Kordesch and Gibling 2002; Müller et al. 2004). They originate in vertisols or other soils containing swelling clays (Nanson et al. 1986; Rust and Nanson 1989;

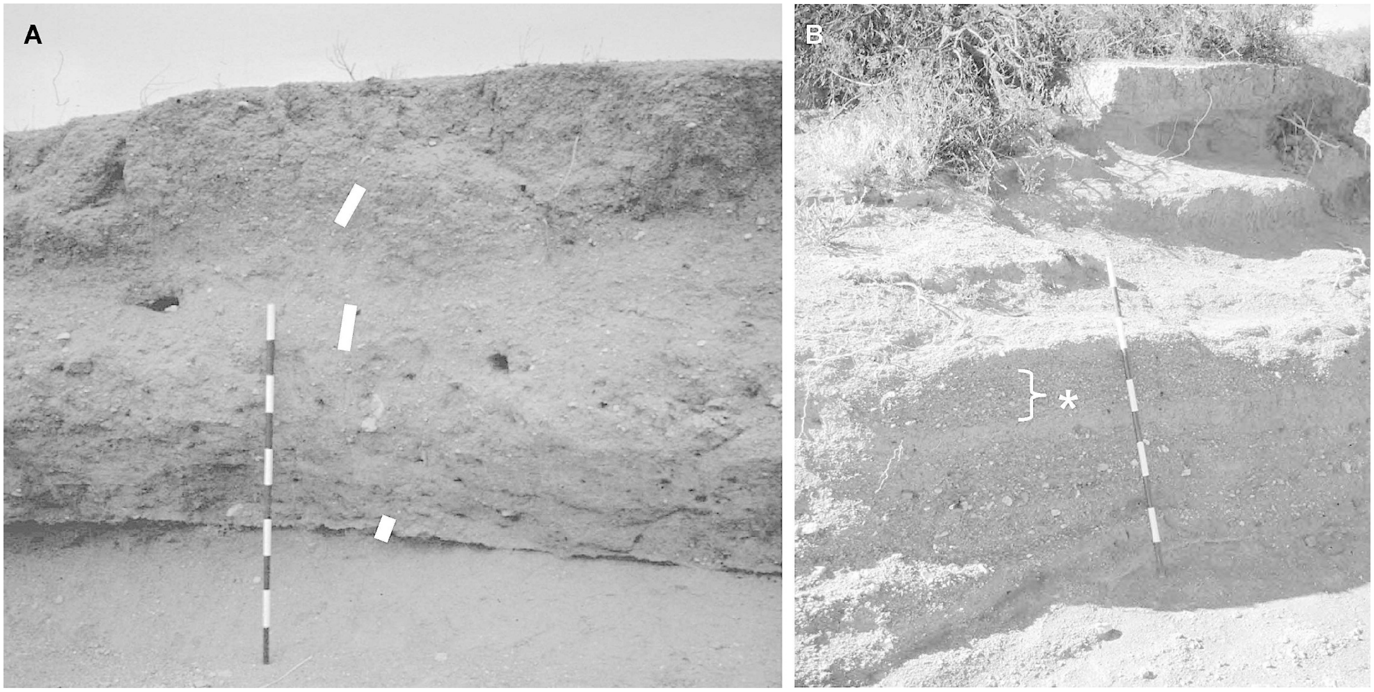

FIG. 5.—Sheetflow sediments. **A)** Redistributed colluvium (very poorly sorted silty gravelly sand) forms a massive deposit. White rectangles mark sample locations; one meter staff for scale. **B)** Interlayered muds and muddy coarse sediments in an intermediate floodout show flat bedding and horizontal clast orientation. Each layer (e.g., *) is the product of several flow events. One-meter staff for scale.

Rust and Nanson 1991; Maroulis and Nanson 1996; Gibling et al. 1998; Müller et al. 2004). Vertisols form in arid or strongly seasonal climates, 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; this feature is sometimes associated with a lower clay content (Blokhuis 1996).

The fine sediments of Fowlers Creek are dominated by fine sands, and sand- and silt-size mud aggregates. The aggregates are probably pedogenic, because they have developed in an arid environment, contain smectite, and are associated with gilgai and cracking soils in nearby hillslopes and plains. Fowlers Creek floodplains show no evidence of shrink–swell behavior (such as gilgai), so the aggregates are less likely to be forming in alluvium, unlike the floodplain-created aggregates of Cooper Creek (Fagan and Nanson 2004). Fowlers Creek aggregates are delivered into the fluvial system by gullies, and then recycled from and back into floodplain storage by erosion, in-channel transport, and overbank flooding across successively higher-order floodplains.

Because the channels are incised (Table 1, Fig. 2), the fine sediments must be carried high in the water column (that is, in suspension) to reach the floodplains. However, they are not deposited from suspension because the fine sediments' shadow bars, current ripples, intraclasts, and scours all attest to deposition from flowing waters. As floodwaters leave the channels and spread across the floodplain, the decreased depth and increased roughness (from topography and vegetation) suppress flow velocity to the point where fine sediments drop out of suspension, becoming bedload before coming to rest. The two types of sedimentary structures (regular, and irregular or chaotic) suggest deposition under flow conditions ranging from lower flow regime to upper flow regime.

The regular, continuous planar laminae deposited on the floodplains of Fowlers Creek are deposited from low-velocity waning flows and, like the fine-sediment continuous laminae in the channel, are probably lower-flow-regime planar beds. The combined planar and wavy laminae which are regular in appearance (Fig. 4C) are similarly likely to be lower planar beds deposited by overbank floodwaters draining back into the channel. The wavy laminae arise firstly from transition into ripples, and secondly from local flow variations created by riparian vegetation.

The irregular, chaotically laminated fine sediments of Fowlers Creek are never found in a lower-flow-regime context. Scours and small dunes indicate flow conditions higher in the bedform stability spectrum than those producing lower-flow-regime planar beds, and the discontinuous planar laminae resemble those described by Picard and High (1973) as possibly resulting from upper-flow-regime conditions. A little clay in fine sediments promotes coexisting scours, ripples, and areas of flat bedding between the stability fields of ripples and upper-flow-regime planar beds (van den Berg and van Gelder 1993), a sediment texture and suite of structures similar to that examined here. In Fowlers Creek, therefore, the irregular, chaotic laminated fine sediments probably result from flow conditions ranging from high in the lower flow regime, to upper flow regime. Floodplain conditions which are likely to promote upper planar bedding include the high-density fine sediment load (probable during at least some decelerating flows), which creates upper planar bedding (Bridge 2003) even in subcritical fully turbulent flow (Leclair and Arnott 2005), and the relatively low density of the mud aggregates, which deflects their bedform stability fields towards lower depths and velocities (Maroulis and Nanson 1996). The clay layers in the high-energy chaotic association might reflect periods of quiescence, but flume studies show that clay from the partial disintegration of mud aggregates can coat and protect preexisting ripples, even during vigorous flow (Maroulis and Nanson 1996).

After deposition, floodplain muds fail to develop cracks and curls, because the high aggregate content leads them to dry out as loose silty "sands" rather than as cohesive muds. Later, the fine sedimentary structures gradually disappear and soil characteristics are acquired; visible clues to the presence of aggregates are lost. With increasing consolidation, the muds become darker and the loose grains become a dense cohesive mass. Burial, usually a major factor in sediment compaction, is not the formative factor here because many of the old muds have never been buried. Likewise, there is no evidence for sufficient bioturbation or intrasedimentary evaporite precipitation to account for the universally structureless nature of the old floodplain muds. Repeated soaking and desiccation of the floodplain is a possible factor: during expansion and contraction of the smectite clays, the plastic nature of the aggregates may allow them to deform as they press against the neighboring grains which confine them. Although the mud aggregates cease to be visible, they are not destroyed. Old floodplain muds separate into their constituent sands, silts and aggregates when they reenter fluvial transport.

Apparent loss of aggregate structure at shallow depths has been observed in modern sediments elsewhere (Maroulis and Nanson 1996). Aggregates are known to survive deep burial and lithification, but their preservation seems to require favorable circumstances: rapid burial rate, early carbonate cementation, or protection by noncompressible clasts (Rust and Nanson 1989; Gierlowski-Kordesch and Gibling 2002; Müller et al. 2004). Massive or weakly stratified mudstones are commonly present in sequences also containing preserved aggregates (Rust and Nanson 1989; Gierlowski-Kordesch and Gibling 2002; Marriott and Wright 2004; Müller et al. 2004). It is likely that unless conditions were favorable, aggregate muds would be lithified as massive mudrock, and that the aggregate origin of such rocks may be overlooked.

Although mudstones are usually interpreted as resulting from the settling-out of fine sediments in quiet depositional environments (Nanson and Croke 1992; Makaske 2001), Fowlers Creek joins Cooper Creek in showing that in mud-aggregate rivers fine sediments can be deposited across a floodplain submerged in actively flowing water, in a way that would not occur in a river carrying non-aggregated muds.

Bedform and Flow Depth

Flow velocity and sediment grain size are not the only determinants of bedform type: depth is also a variable. In very shallow water, upper-flow-regime bedforms can be created at low velocities (Picard and High 1973; Reineck and Singh 1980; and see Leeder 1999, fig. 7.10d, e). The boundary between lower to upper flow regimes, at the transition between dunes and upper planar beds, occurs at lower velocities with decreasing depth (Southard and Boguchwal 1990, their fig. 3). During waning flow, discharge reduction by velocity decrease replaces higher-energy bedforms with lower, as flow conditions move from one bedform stability field to another (e.g., 3-D dunes to 2-D dunes; Southard and Boguchwal 1990, their fig. 8). Alternatively, at certain flow velocities and sediment grain sizes, discharge reduction by depth decrease might instead move flow conditions from a lower to a higher position within the bedform stability spectrum: ripples to dunes, for example (Southard and Boguchwal 1990, their fig. 5B).

The range of channel bedform characteristics in Fowlers Creek, between soft with poorly defined or no laminae, and hard with clear laminae, must relate to some variation in flow conditions that affects both grain packing and the degree of self-organization that creates internal structure. Without direct observation, any discussion of causes is speculative, but the spur-fronted 2-D dunes provide some material for conjecture. Leeside spurs have been observed to migrate simultaneously with their parent bars, and may be created by helical eddies downstream from the main bedform face (Rubin 1987). If the 2-D dune spurs of Fowlers Creek arise from leeside eddies, then flow conditions must be at the upper end of the 2-D dune stability field, since in 2-D dunes flow separation is poorly developed and lee vortices are weak, whereas in 3-D dunes flow separation is well-developed and the vortices are strong enough to affect patterns of sediment deposition (Ashley 1990; Leeder 1999). Yet most spur-fronted dunes occurred in channels where flow conditions never entered the 3-D dune stability field. A flashy river such as Fowlers Creek might experience a rapid depth decrease during waning flow, during which flow conditions could approach the 3-D dune stability field, allowing 2-D dunes to develop spur fronts as shallowing flows strengthen leeside eddies.

Although current-streaming lineations are sometimes described as forming in the lower flow regime (Conybeare and Crook 1982), they are more usually held to be characteristic of upper-flow-regime planar beds (Picard and High 1973; Leeder 1999; Miall 2000; Bridge 2003). The 2-D dunes with associated current-streaming lineations (Fig. 3) thus offer apparently contradictory evidence of formative flow conditions. The evidence would be reconciled under a scenario where the 2-D dune formed in the lower flow regime, but near the close of flow there was a brief period of shallow upper-flow-regime conditions across the dune top. The association between hard bedforms, spur fronts, and current-streaming lineation (Table 2) in Fowlers Creek further suggests that during shallow waning flow, flow conditions in the upper range of the lower flow regime or in the upper flow regime create harder bedforms with closer clast packing and better stratification, whereas conditions at the lower range of the lower flow regime create the less structured soft bedforms.

Similarly, the decrease in flow depth as waters leave the channel to cross Fowlers Creek floodplains is likely to contribute to upper-flow-regime conditions during mud deposition.

The apparent contradiction of coexisting lower-flow-regime channels and upper-flow-regime floodplains results from the interaction between grain size, flow depth, and velocity. Channels carrying coarse sediment in moderately deep water during peak flow have little opportunity to develop upper-flow-regime bedforms. During waning flow, decreasing depth may allow flow conditions to enter the upper flow regime, but at that point the most of the bedload is no longer in motion. On the other hand, when flow depth decreases over the floodplain and flow conditions move towards the upper flow regime, the fine sediments are still undergoing transport and deposition.

Recognizable Criteria in the Rock Record

Floodplain sediments similar to those of Fowlers Creek would be preserved in the rock record as massive red mudstones containing matrix-supported sand grains. Organic material, bioturbation, and mudcracks would be rare, but clay intraclasts may be visible. The loss of the aggregate structure destroys most indications of the relatively high-energy environment of deposition, unless grain-transport mechanisms chance to sort the sediment into aggregate-rich and quartz-rich laminae.

Channel sediments similar to those of Fowlers Creek preserved in the rock record would be represented by thin ribbons of flat gravelly sands or open-framework gravels, isolated within massive mudstones. They would sometimes show structures such as horizontal lamination, tabular and trough cross-bedding, and imbricated gravels, but more frequently would be poorly sorted massive sands with patchy gravel occurrences, lacking obvious fluvial characteristics. The sand would be variably porous, with greater porosity in areas of least structure.

Sheetflow sediments from a river like Fowlers Creek would display a horizontal fabric defined by clast orientation. In poorly sorted sediments, larger clasts will be matrix-supported. Where the provenance area supplies a uniform sediment type, sheetflow deposits will be poorly bedded or massive. Where the texture of the supplied sediment varies, massive red mudstones will be interbedded with sporadic thin coarser layers. Bedding will be outlined by grain size changes but will lack partings along bedding surfaces.

CONCLUSIONS

1. Fowlers Creek is one of only a few documented examples of a drylands ephemeral mud-aggregate river. Although difficult to

observe directly, its fluvial processes are inferred from this study of sediment texture, bedforms, and structures. The results contribute to understanding flow conditions in modern drylands rivers, and to the interpretation of massive mudrock in the geological record.

2. Fowlers Creek sediments are dominated by floodplain muds containing mostly fine sand, and sand- and silt-size mud aggregates. Carried in suspension during peak flow and thus distributed over the floodplain, the fine sediments settle out as flow decelerates, finally being deposited as bedload. They may be deposited in lower-flow-regime planar beds, but they are more commonly deposited under conditions close to or in the upper flow regime, in a chaotic assemblage of laminae, scours, and ripples. Clay layers in this assemblage reflect partial aggregate disintegration during active flow, rather than still water.
3. Unless preserved by favorable conditions, mud aggregates are consolidated after deposition, destroying the sedimentary structures and leaving a monotonous cohesive mud which re-separates into sands and aggregates if it reenters fluvial transport. Lithified, Fowlers Creek floodplain muds would be massive reddish mudstones with a low organic content and matrix-supported sand grains.
4. Fowlers Creek channels carry coarse sands and gravels, generally in lower-flow-regime planar beds closely associated with 2-D dunes. Both bedforms commonly produce either horizontal stratification or massive sands lacking clear structure. In the rock record these sediments would be narrow ribbons of variably porous coarse sediment, sometimes planar laminated but often structureless, isolated within mudstones.
5. Sheetflow sediments are distinguished by horizontal clast fabric, and massive bedding or bedding expressed by grain size change but without erosional contacts or clay partings.
6. Both channel and floodplain deposits demonstrate that fine sediments can be transported in lower-flow-regime planar beds, and that widespread planar bedding need not be the result of high-energy floods. Reexamination of other planar-bedded drylands sediments in the light of this study may lead to more frequent interpretations of lower-flow-regime conditions.
7. The Fowlers Creek floodplain often experiences upper-flow-regime conditions, while the channels are invariably lower flow regime, a paradox reflecting the effects of flow depth and sediment grain size on the position of the depositional environment within the bedform stability spectrum. Abrupt shallowing can lead to the unexpected juxtaposition of lower-flow-regime and upper-flow-regime bedforms. This observation may be particularly applicable to the study of dryland rivers, where rapid decline from peak discharge to no flow can be the normal flow pattern.

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