Anabranching and maximum flow efficiency in Magela Creek, northern Australia

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[1]   Anabranching is the prevailing river pattern found along alluvial tracts of the world's largest rivers. Hydraulic geometry and bed material discharge are compared between single channel and anabranching reaches up to 4 times bank-full discharge in Magela Creek, northern Australia. The anabranching channels exhibit greater sediment transporting capacity per unit available stream power, i.e., maximum flow efficiency (MFE). Simple flume experiments corroborate our field results showing the flow efficiency gains associated with anabranching, and highlight the prospect of a dominant anabranch, which is found in many anabranching rivers. These results demonstrate that anabranching can constitute a stable river pattern in dynamic equilibrium under circumstances in which a continuous single channel would be unable to maintain sediment conveyance. We propose the existence of a flow efficiency continuum that embraces dynamic equilibrium and disequilibrium (vertically accreting) anabranching rivers.

KEYWORDS: anabranching, bed material discharge, flow efficiency, flume experiments, hydraulic geometry, northern Australia

1.   Introduction

[2]   Many rivers feature divided flow around large alluvial islands, yet, ironically, anabranching was long regarded as unusual and therefore peripheral to the fluvial trinity of braiding, meandering and straight river patterns [*Leopold and Wolman*, 1957; *Leopold et al.*, 1964]. Regarded here as rivers of the fourth kind, anabranching represents a diverse group of alluvial rivers comprising multiple interconnected channels separated by large, stable alluvial islands, which divide flows at bank-full discharge [*Nanson and Knighton*, 1996; *Knighton*, 1998; *Nanson and Huang*, 1999]. The world's five largest rivers (viz. Amazonas-Solimões, Congo, Orinoco, Chang Jiang, and Padma-Jamuna-Brahmaputra) all constitute anabranching over more than 90% (by length) of their alluvial tracts, indicating the fundamental importance of this river pattern. Anabranching rivers are globally widespread and include relatively steep, wandering gravel bed rivers, sand-dominated ridge-forming rivers, and low-gradient anastomosing mud- and/or organics-dominated rivers; hence the presence of anabranching is not regionally constrained either by hydrologic or sedimentologic conditions [*Nanson and Knighton*, 1996].

[3]   Anabranching rivers are the least understood of the river patterns and recent efforts have sought to unravel controls on their origin and maintenance [e.g., *Knighton and Nanson*, 1993; *Nanson and Knighton*, 1996; *Nanson and Huang*, 1999; *Makaske*, 1998, 2001; *Abaddo et al.*, 2003]. It is widely held that most rivers form a single channel in order to minimize boundary resistance while conveying water and sediment [e.g., *Wolman and Brush*, 1961; *Pickup*, 1976; *Chang*, 1979]. However, do all rivers ultimately function most efficiently with a single channel? And if so, what factors maintain long-term anabranching [e.g., *Smith*, 1986; *Knighton and Nanson*, 1993; *Makaske*, 1998, 2001; *Morozova and Smith*, 1999; *Tooth and Nanson*, 2000a]?

[4]   Disagreement has arisen over whether the anabranching river pattern represents a dynamic equilibrium [e.g., *Nanson and Huang*, 1999], or disequilibrium (transitional) state [e.g., *Makaske*, 2001; *Abaddo et al.*, 2003; *Tabata and Hickin*, 2003]. One view regards anabranching as the product of frequent channel avulsions coupled with slow abandonment of older channels [*Smith et al.*, 1989; *Makaske*, 1998, 2001]. An evolutionary model proposed by *Smith et al.* [1989] ascribes anastomosis to a transitional state of variable duration in which maintenance of a constant number of active channels reflects "quasi-equilibrium" between rates of channel avulsion and abandonment. An alternative position views development of multiple channels as a means of system adjustment (additional to changing slope, bed configuration, and channel cross section) which enables an optimal balance between sediment supply and sediment transport capacity [*Nanson and Knighton*, 1996; *Wende and Nanson*, 1998; *Nanson and Huang*, 1999; *Tooth and Nanson*, 1999, 2000b]. The latter position regards anabranching as a dynamic equilibrium configuration that can optimize system efficiency in terms of sediment and water discharge. In this paper, "dynamic equilibrium" equates with sediment flux balance wherein

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self-regulation tends toward a stable channel configuration that transports just the amount of sediment supplied from upstream (in the sense of *Ahnert* [1994]).

[5] *Huang and Nanson* [2000] define maximum flow efficiency (MFE) as maximum sediment transporting capacity per unit available stream power, a condition commensurate with dynamic equilibrium. In this study of Magela Creek, northern Australia, we test the hypothesis that multiple channels can display dynamic equilibrium behavior and convey sediment more efficiently than their single-channel counterparts. We present: (1) results of field analyses in which hydraulic variables (i.e., width, depth, velocity, water slope), and bed material discharge are measured and compared in single channel and anabranching reaches of the same river; (2) results of an experimental flume study comparing hydraulic variables and sediment flux in single channel versus divided flow; and (3) discussion concerning the origin and maintenance of the anabranching river pattern and its capacity to constitute a stable system in dynamic equilibrium.

2. Field Study Area

[6] Magela Creek is representative of several anabranching systems draining the Alligator Rivers region of monsoonal northern Australia (Figure 1). It offers a suitable study site because the channels and floodplains are undisturbed by human activity, apart from regular burning by indigenous people [*Haynes*, 1991]; numerous overbank flows arrive with the annual monsoon, and excellent flow gauge data exist from 1972 to 2002; and previous studies have established a sound understanding of long-term sediment flux and Quaternary evolution [e.g., *Roberts*, 1991; *Wasson*, 1992; *Nanson et al.*, 1993].

[7] Magela Creek drains a 1565 km^2 catchment (Figure 1). Headwaters rise on the Arnhem Land plateau, a rugged 250–300 m asl upland formed of resistant Palaeoproterozoic quartzose sandstone of the Kombolgie Formation. A 200 m escarpment separates the plateau from the fringing lowland comprising a planated complex of Palaeoproterozoic metasediments known as the Koolpinyah Surface [*Needham*, 1988]. Sand-bed anabranching channels carry seasonal monsoon floods across this lowland to Madjinbardi (Mudginberri) Billabong, which marks the end of the bed load-dominated zone about 5 km downstream of the study reach (Figure 1). While vertical accretion predominated over the past 3 ka, the anabranching zone is now essentially unconfined across the right bank and the contemporary rate of aggradation is considerably less than the 1–2 mm/yr prevailing over most of the Holocene [*Roberts*, 1991; *Nanson et al.*, 1993]. Importantly, *Roberts*' [1991] detailed sediment budget study finds little or no measurable contemporary addition to valley sediment storage; it is essentially a system in mass flux balance. Downstream of Madjinbardi, the continuity of the channel is altogether lost across the backwater plain, a very low-gradient 200 km^2 seasonal wetland at 2–5 m asl, which comprises mostly estuarine sediments capped with a veneer of muddy alluvium [*Wasson*, 1992].

[8] Magela Creek's sandy sediment load derives principally from the Kombolgie Formation. Low concentrations of suspended sediment (3–70 mg/L, averaging 12–15 mg/L) [*Hart et al.*, 1987; *Roberts*, 1991] reflect the minor mud component of these rocks coupled with low kinematic viscosities due to high water temperatures (26–34°C). The channel bed comprises predominantly dunes of unimodal medium sands (d_{50} = 0.42 mm, d_{90} = 0.72 mm). For the period 1971–1989, *Roberts* [1991] estimates the annual terrigenous sediment yield transported past GS-8210009 at 12 051 t/yr, consisting of 29% bed load, 14% suspended sand (i.e., 43% bed material load, defined as particles >63 μm), 45% washload and 12% solutes.

[9] Over 80% of the mean annual 1530 mm rainfall occurs within the four months December to March, and less than 2% falls in the May to September dry season when flow in Magela Creek ceases for several months. Mean maximum temperatures are 37°C in October and 31°C in June and July; Class "A" pan evaporation averages 2580 mm/yr (unpublished data, Jabiru airport, 1971–2001). Magela Creek drains 600 km^2 upstream of the flow gauge (GS-8210009) located in the study reach (Figure 1). Characteristic of rivers in monsoonal northern Australia, Magela Creek exceeds bank-full discharge ($\sim$40 m^3/s) about a dozen times each wet season. Floodwaters are overbank at GS-8210009 for 11% of the year (i.e., 40 days), on average, and the mean annual flood ($Q_{2.3}$ = 525 m^3/s) is more than 13-times bank-full discharge. On the annual flood series, the 5-year and 10-year floods are 840 m^3/s and 1180 m^3/s, respectively, and the flood of record (in February 1980) is 1700 m^3/s.

3. Anabranching Magela Creek

[10] The study reach has an average slope of 0.0005 m/m and channel belt sinuosity is 1.1. Individual anabranches are close to straight with simple trapezoidal cross sections divided by narrow ridges 1 to 10 m wide [*Nanson and Knighton*, 1996; *Wende and Nanson*, 1998; *Tooth and Nanson*, 1999] and broader islands up to 1000 m long and 100 m wide. *Tooth and Nanson* [2000b] discriminate ridges and islands based on planform geometry, ascribing to ridges length/width ratios exceeding 10, and to islands ratios less than 10. The river's morphology falls within *Nanson and Knighton*'s [1996] sand-dominated, island-forming Type-2: a low gradient, laterally stable anabranching form in which unit stream power remains low even at high stage.

[11] The islands and ridges are stabilized by thick vegetation with banks reinforced by dense root mats beneath mature *Lophopetalum arnhemicum*, *Syzygium forte*, and *Melaleuca* spp., the largest of which, based on work in tropical northern Queensland, are probably more than a century old [*Fielding et al.*, 1997]. Vegetation affords remarkable stability to the uncohesive sands at the channel boundary [*Erskine*, 2002]. The islands and ridges build chiefly via vertical accretion, although limited floodplain excision associated with occasional channel avulsions probably also occurs [*Nanson and Knighton*, 1996; *Wende and Nanson*, 1998; *Tooth and Nanson*, 1999, 2000b]. Aerial photography from 1950 reveals little planform change in the channel network over the past five decades [*Roberts*, 1991; *Nanson et al.*, 1993]. Lateral stability is consistent with the scarcity of point bars or eroding concave banks, although sporadic crevasse splays suggest infrequent channel avulsion.

[12] Co-existence of reaches dominated alternately by islands and ridges with occasional single-channel zones suggests the possibility of longitudinal changes in local
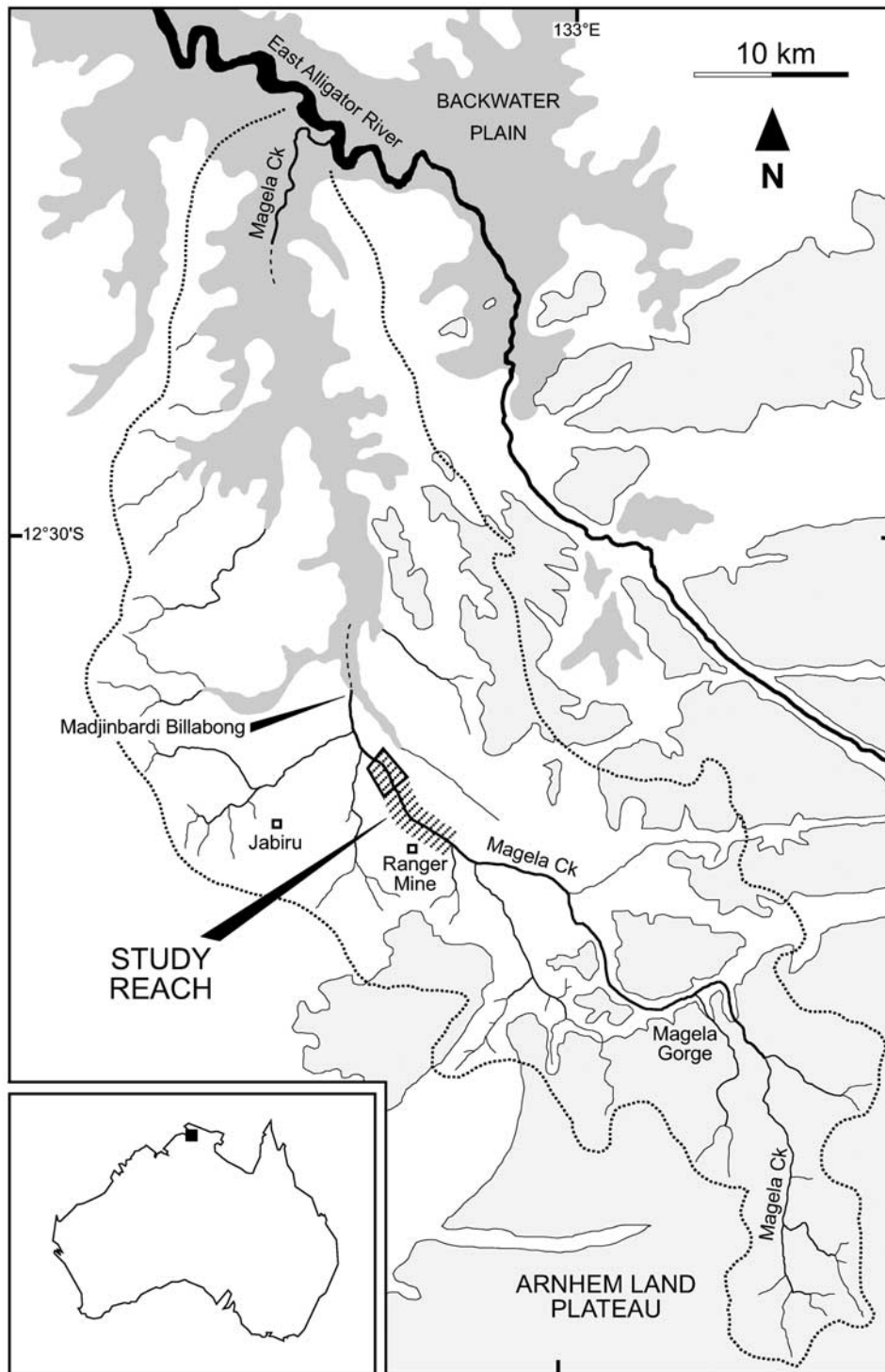
Figure 1. Magela Creek catchment setting and 8.5 km study reach (and 2 km subreach). The anabranching Magela Creek extends 24 km from the gorge exit to Madjinbardi Billabong. The inset map highlights the Alligator Rivers region of monsoonal northern Australia.

boundary conditions controlling planform (Figure 2). About 60% of the 8.5 km surveyed reach is island dominated and 35% is ridge dominated. Anabranching reaches comprise up to 5 independent channels. Convergence into a single channel is rare, only 4 examples (in total, 7% by length) occur in the 8.5 km reach, and flow redivides in each case within about 150 m of converging. Figure 3 shows these

short segments of single channel have comparatively high width/depth ratio, which tends to decline as the number of channels increases.

[13] Peaks in valley width correspond closely with tributary flood basins, and these zones of flow expansion tend to host maximum island-ridge width development (Figure 2). The number of channels varies between 1 and 5, with just 1
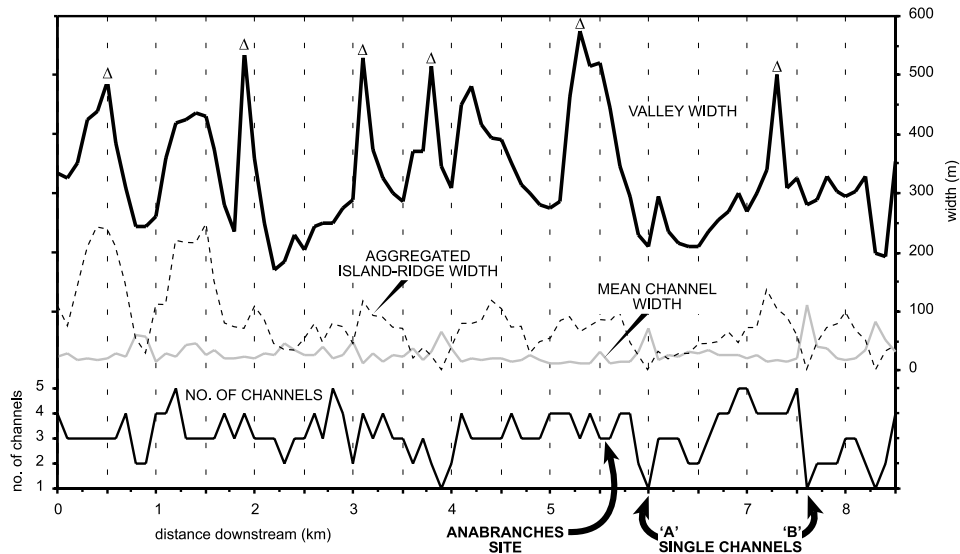
Figure 2. Longitudinal interrelationships along the 8.5 km study reach. Note that single channels correspond to valley constrictions 200–350 m in width, and triangles mark tributary flood basins adjoining valley expansions. "Mean channel width" is the mean width of anabranches present in a valley transect.

or 2 wider-than-average channels developed at valley constrictions signifying that island-ridge and floodplain development tends to minimize variance in mean channel width (Figure 2).

4. Field Methods

[14] Our field objective was to compare detailed hydraulic and sediment transport measurements in single channel and anabranching sites. Figures 4 and 5 show selected sites within the 8.5 km reach. The anabranching site was monitored by *Roberts* [1991] in a study involving detailed measurement of flow hydraulics and sediment flux over 3 wet seasons: 1987–1989. The three well-defined anabranches have bed widths of 16.4 m, 12.0 m, and 6.3 m in the left (Lb), middle (Mb), and right (Rb) channels, respectively, and all are active during low flows. Both Roberts' and our study used a rod-mounted Helley-Smith pressure-difference sampler with a 76.2 mm inlet [*Helley and Smith*, 1971]. Roberts measured bed material discharge at 4 to 8 stations, 3 stations, and 2 stations in Lb, Mb and Rb, respectively, taking a total of 671 samples under known conditions of discharge, water slope, and velocity over 22 flood events. Field observations, aerial photograph analysis, and resurveying of cross sections confirm that negligible channel change has occurred at the anabranching site since *Roberts*' [1991] study.

[15] A reliable stage-discharge relationship exists for GS-8210009 (single channel "A") based on 176 flow ratings up to 540 m^3/s (nearly 14 times Q_{bf}). Stage at single-channel "B" and the anabranching site was related to the known discharge at the gauge via a series of stage boards; these were installed in pairs at single channel sites "A" and "B" and in each of the three anabranches, providing a detailed picture of actual water slopes generated at different discharges. Discharge calculated in this way is subject to uncertainty of ±5%.

[16] Sampling at single-channel "B" was conducted during the 2001–2002 wet season at flows up to nearly 4 times bank-full discharge: water slopes were measured for 18 separate floods; velocity was measured for 8 floods (5–150 m^3/s), and bed material discharge for 5 floods (39–150 m^3/s). This compares with 7, 7, and 8 floods measured in Lb, Mb and Rb anabranches, respectively, ranging over flows of 14–340 m^3/s [*Roberts*, 1991].

[17] A steel cable was erected spanning single-channel "B" and velocity and bed material discharge were measured at 5 m intervals from a small punt secured to the cable, yielding 22 stations consistent with *Emmett's* [1980] recommendations for a channel of this size. The Helley-Smith sampler was held on the bed for 3–5 min in accordance with the USGS single equal-width-increment method [*Emmett*, 1980; *Edwards and Glysson*, 1998]. A double
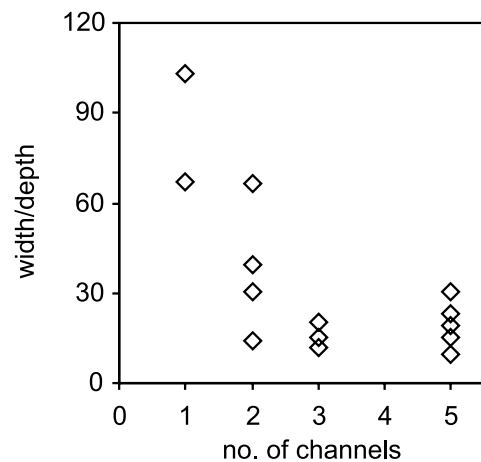
Figure 3. Width/depth ratio relative to the number of channels at selected cross sections in Magela Creek.
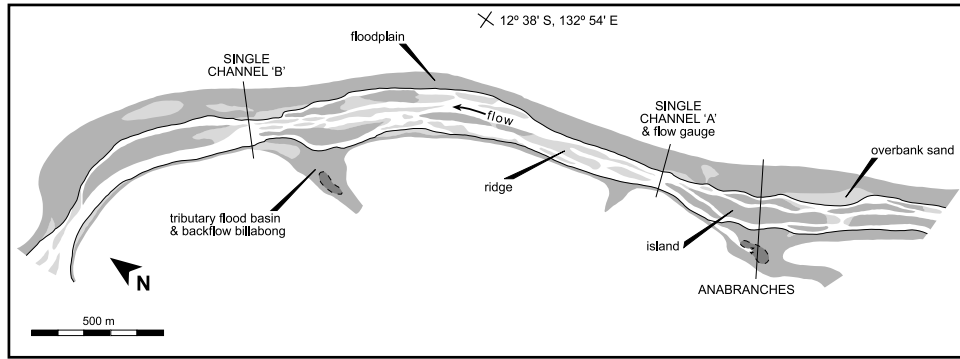
Figure 4. Planform map of the 2 km study subreach in Magela Creek (indicated by the small box in Figure 1), with the anabranching site, single-channel sites "B" and "A," and the flow gauge (GS-8210009). The tributaries shown extend for a few hundred meters upstream only and therefore contribute negligible discharge.

traverse yielded two samples from each of the 22 stations; these were pooled and subjected to particle size analysis. Differences in bed material caliber across the single channel and among the three anabranches [*Roberts*, 1991] were not statistically significant. Consistent with *Roberts* [1991], velocity was measured with a rod-mounted Ott C31 impeller-type current meter (rms error = 0.01 m/s) and mean velocity at each station was taken as the average of four measurements over 40-s intervals at 0.2, 0.4, 0.6, and 0.8 of flow depth. Water temperature was recorded together with stage and water slope before and after each sampling session.

5. Field Results

[18] Magela Creek offers an excellent opportunity to investigate the dynamics of floods well above bank-full discharge. We report here hydraulic information on floods up to 14 times bank-full, with bed material flux and flow measurements up to 4 times bank-full discharge.

[19] Figures 6a, 6b, and 6c show how three in-channel hydraulic variables (velocity, depth, and water slope) vary with total discharge in the anabranches and single-channel "B." In Figure 6c a linear regression of water slope data for single-channel "B" yields the best fit (standard error: 3.5 ×

10^{-5}), whereas power functions best describe water slope behavior in the anabranches (mean standard error: 4.1 × 10^{-6}).

[20] In-channel velocity in each of the anabranches peaks over discharges ranging 50–135 m^3/s, with Lb featuring notably higher velocities due to that channel's deeper flows. The variable trends in water slope exemplify the hydraulic independence of these channels. Slopes are generally steeper in the anabranches over a wide range of flows and it was observed in the field that slopes decline slightly where multiple channels converge at single channels "A" and "B." All anabranches show a decline in channel velocity at high-stage, and this is largely responsible for rising in-channel Darcy-Weisbach friction factor (*ff*) relative to total discharge (Figure 6d). Although single channel "B" velocity does not show the same tendency to decline, much larger rated flows at single channel "A" reveal that velocity levels out between 250 and 500 m^3/s. Flow drag-effects of the dense bank vegetation are clearly shown by the sharp transitions in point-velocity separating in-channel and overbank domains.

5.1. In-Channel Discharge (Q_c)

[21] Total discharge during each sampling session was determined from the flow rating curve at GS-8210009. As
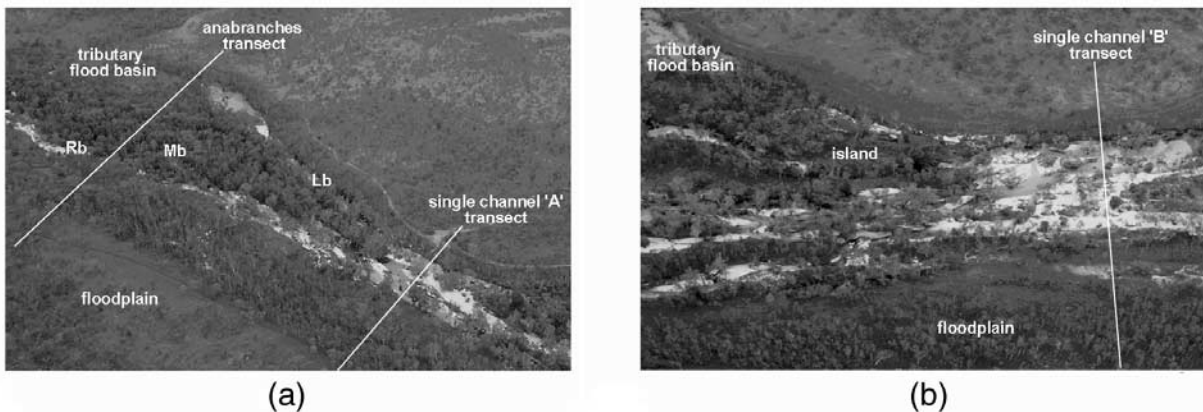
Figure 5. (a) Oblique aerial photograph of single-channel "A," and the anabranching site; flow from left to right. (b) Oblique aerial photograph of single-channel "B"; flow from left to right. (Photographs: M. J. Saynor).
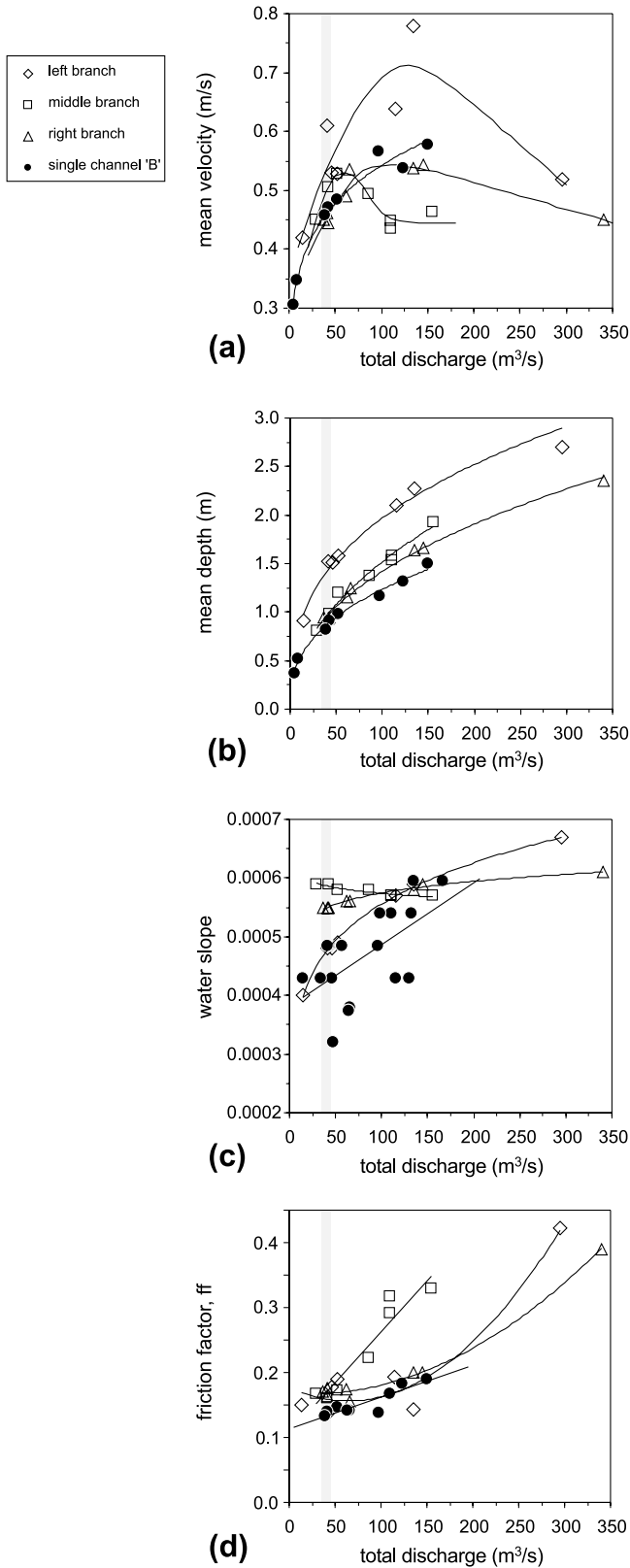
Figure 6. In-channel hydraulic variables relative to total discharge at single channel "B" and the anabranching site, with Q_{bf} marked by a shaded band (40 ± 5 m^3/s): (a) mean velocity, (b) mean depth, (c) water slope, and (d) Darcy-Weisbach friction factor. Trends shown here from single channel "B" are representative also of single-channel "A."

bed material transport primarily occurs within the channel, we restrict our analysis to in-channel discharge (Q_c) defined as the discharge conveyed between banks. In-channel discharge was calculated using the mean section method: a standard method described by *Gregory and Walling* [1973, p. 132]. Zero velocity was assumed at channel banks with a plane extending vertically for overbank flow; a reasonable assumption given the marked transition from in-channel to overbank velocities.

[22] Figure 7a shows in-channel discharge conveyed at single channel sites "A" and "B" and the sum of the anabranches, as a function of total discharge. Overbank flow is initiated at a lower discharge in the anabranches: about 20 m^3/s, compared with 40 m^3/s in single channel sites "A" and "B". Thus overbank flow occurs more frequently from the anabranches (80 days/yr compared with 40 days/yr at the single channels), and for flows over 20 m^3/s the anabranches convey a rapidly declining proportion of total discharge. While the inception of overbank flow ranges between 20 and 40 m^3/s along the study reach, for simplicity, "bank-full discharge" in this paper refers to 40 m^3/s, as this is the point of spillage from the single channels.
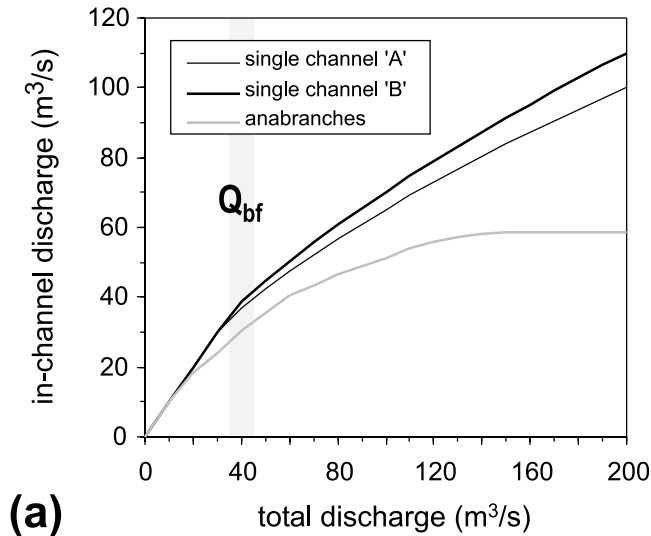
5.2. In-Channel Power (Ω_c)

[23] Total stream power calculations are generally applied to individual channel reaches, but such calculations are ill suited to anabranching river systems. For this reason, we do not consider total stream power across the entire flow, but rather "in-channel power", as this contributes directly to bed material transport and thus channel morphology. In-channel power (Ω_c) is thus

$$\Omega_c = \gamma Q_c\, S \qquad (1)$$

where γ is the specific weight of water; Q_c is in-channel discharge; and S is the energy grade line, which is approximated by the water slope. A comparison of in-channel power for single channel sites "A" and "B" and combined anabranches shows equivalence up to about 60 m^3/s, but power becomes progressively greater in the single channel at higher discharges (Figure 7b; stream power uncertainties are 10% and 12% for the single channel and anabranch data, respectively).

5.3. Bed Material Discharge

[24] Bed material discharge (kg/s) was calculated using the mean-section method [*Edwards and Glysson*, 1998]. In Figure 8a a simple power function describes the trend in single channel "B." Peak bed material discharge through individual anabranches occurs over a narrow range of flows, 0.23–0.44 kg/s at 40–65 m^3/s. In terms of combined instantaneous bed material flux, the three anabranches peak with 0.98 kg/s at just over bank-full flow. On the basis of curve extrapolation through the origin, bed material flux appears approximately equivalent in the anabranches and single channel up to about half bank-full; the anabranches then transport bed material faster up to about 65 m^3/s, above which the single channel becomes dominant. Figure 8b reveals a similar trend with bed material discharge per unit in-channel

(a)
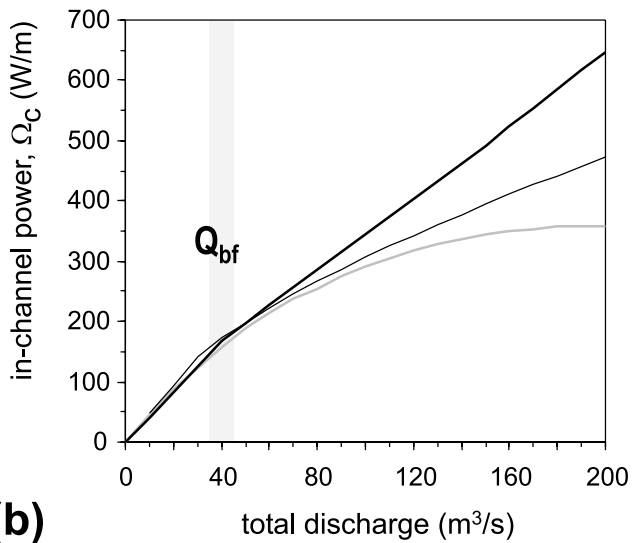
(b)

Figure 7. (a) In-channel discharge relative to total discharge in the anabranches and single channels "A" and "B" and (b) in-channel power (Ω_c) relative to total discharge. In-channel discharge was calculated as the velocity-area product using the mean section method, total discharge was calculated from the GS-8210009 rating curve, and power was calculated from equation (1) using field-measured water slopes.

power (i.e., flow efficiency) varying with total discharge. The same threshold, about 65 m³/s, marks where the higher flow efficiency of the anabranches is surpassed by the single channel.

5.4. Maximum Flow Efficiency and Effective Discharge

[25] Relative flow efficiency varies with discharge; the anabranches attaining peak efficiency at 30–40 m³/s, or around bank-full discharge. Stage-dependent variables relating to flow efficiency are summarized in Table 1. The bed material discharge data were integrated with flow duration data for GS-8210009 (1971–2002) to determine the discharges responsible for transporting most of the bed material, that is, the "effective discharge" (in the sense of *Andrews* [1980]). The peak interval 40–45 m³/s in Magela Creek (Figure 9) supports the notion that effective discharge usually approximates bank-full in sand and gravel bed rivers [*Wolman and Miller*, 1960; *Pickup and Warner*, 1976; *Andrews*, 1980; *Batalla and Sala*, 1995; *Emmett and Wolman*, 2001].

[26] Additional flow resistance imposed by the more numerous anabranch banks does not fully offset their flow efficiency advantage at bank-full discharge (Figure 6d). Thus caution is necessary when equating higher *ff* with hydraulic inefficiency [cf. *Tabata and Hickin*, 2003], as MFE need not connote minimum *ff*.

6. Flume Experiments

[27] The flume experiments were conducted at the University of Wollongong using a 10 m long, 0.45 m wide, and 0.3 m deep flume, with transparent walls and adjustable slope that recirculates both water and sediment. Baffles located at the head box of the flume reduced turbulence and fostered uniform flow. Bedload measurements were taken using a trap comprising 1 cm² compartmented aluminum mesh fitted into the bed of the flume once stable conditions were attained. Medium to coarse quartz sand ($d_{50} = 0.47$ mm; $d_{90} = 0.67$ mm) was used for all experiments.

[28] Rather than attempt a scaled, generic simulation, we aimed to model qualitatively similar circumstances to that in the field (where the ratio of single channel "A" and "B" width versus the anabranches' aggregated width is 1.5 and 2.1, respectively). Three experiments were conducted using different channel configurations: (1) a single-channel 45 cm wide, (2) a multichannel system of 3 parallel channels, each 10 cm wide, and (3) a single-channel 30 cm wide. Recognizing that the flume simulates bank-full conditions only and does not account for the effects of flow conveyed overbank the exclusion of such effects from the experiments enabled us to separate any associated flow efficiency gains.

[29] The results are summarized in Table 2. Experiments 1 and 2 featured equivalent total wetted perimeter, and channel configurations were comparable with those in Magela Creek. Under near-constant discharge and total stream power conditions, the multichannels maintained deeper and faster flows. Thus flow efficiency was considerably greater (about 60%) in the divided flows. These results prompted us to examine the relative efficiency of a single narrow channel.

[30] In experiment 3, we retained a single channel, but halved the width/depth ratio of experiment 1 with the aim of comparing a narrow (30 cm) single-channel with the multichannels (3 × 10 cm) at near-constant "in-channel" discharge (i.e., in the absence of overbank flow). Such a comparison was not possible in the field, because single channel width invariably exceeds the aggregated bed width of adjacent anabranches (see also Figure 3), and bank-full capacity of the single channels is roughly twice that of the anabranches combined. With lower water slopes and wetted perimeter but essentially constant velocity and depth, the narrow channel transported bed load at a higher rate with less available power: relative to the multichannels, about
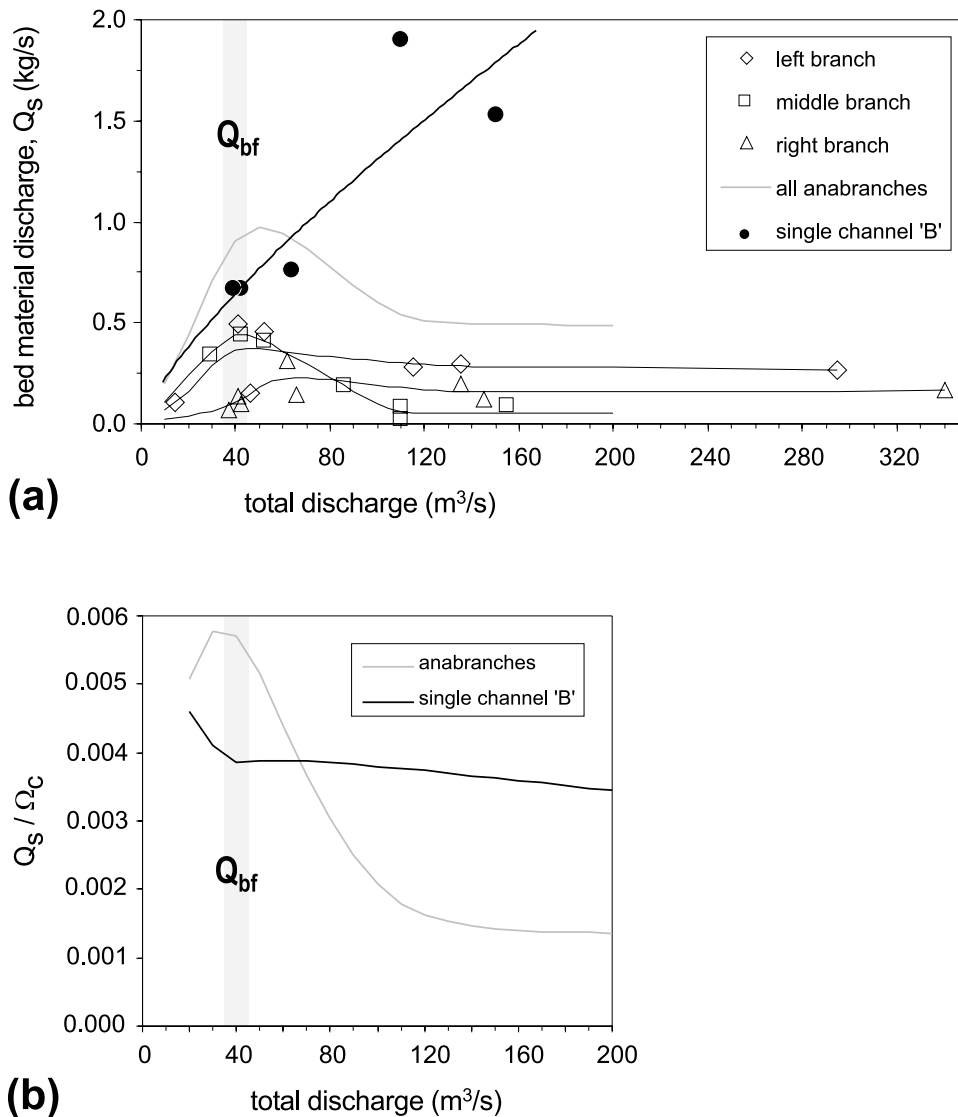
Figure 8. Bed material discharge and flow efficiency relative to total discharge in the anabranches and single channel "B": (a) bed material discharge (Q_s), single channel "B" $Q_s = 0.04Q^{0.77}$ ($r^2 = 0.84$); (b) flow efficiency (Q_s/Ω_c).

32% greater flow efficiency in the absence of overbank flow.

7. Discussion

7.1. Flow Efficiency in Magela Creek

[31] The observation that anabranching commonly develops in environments where sediment flux is maintained with little or no recourse to increasing energy slope first prompted *Nanson and Knighton*'s [1996] hypothesis that rivers may, under certain conditions, adopt multiple channels in order to reduce total flow width and raise mean flow depth, thereby maximizing sediment transport per unit area of the channel bed. They suggest that, by anabranching, rivers might maintain or enhance sediment throughput where they cannot otherwise increase slope by decreasing sinuosity. Two recent field studies of the anastomosing upper Columbia River [e.g., *Abaddo et al.*, 2003; *Tabata and Hickin*,

2003] find no apparent flow efficiency advantage with a multichannel network [cf. *Makaske*, 2001].

[32] We present field evidence from Magela Creek corroborating the hypothesis that anabranching channels at near-bank-full flow can convey sediment more efficiently, that is, at a faster rate per unit available stream power, relative to naturally wide, single-channel counterparts (Figure 8). Moreover, faster, steeper and deeper flows (40–45 m³/s) through the anabranches are responsible for transporting the largest proportion of the annual bed material yield and so equate with the most effective discharge (Figure 9). A corollary of anabranch efficiency at near-bank-full flows is that sediment accumulates temporarily at single channel sites around bars associated with in-channel trees. Yet, as Figure 9 shows, circumstances reverse in larger, overbank flows (>65 m³/s) when higher bed material discharge through the single channel is associated with flushing of the temporarily stored sediment. Bed

Table 1. Summary Hydraulic and Sediment Flux Relationships at Bank-Full and Greater Than Bank-Full Discharge

| Flow Variable	Q_{bf} ($\sim$40 m^3/s)	>1.6 Q_{bf} (>65 m^3/s)
In-channel discharge Qc	$Qc_{single} > Qc_{multi}$	$Qc_{single} > Qc_{multi}$
Water slope S	$S_{single} < S_{multi}$	$S_{single} \sim S_{multi}$
In-channel stream power Ωc	$\Omega c_{single} \sim \Omega c_{multi}$	$\Omega c_{single} > \Omega c_{multi}$
Bed material discharge Qs	$Qs_{single} < Qs_{multi}$	$Qs_{single} > Qs_{multi}$
Flow efficiency $Qs/\Omega c$	$Qs_{single}/\Omega c_{single} < Qs_{multi}/\Omega c_{multi}$	$Qs_{single}/\Omega c_{single} > Qs_{multi}/\Omega c_{multi}$

material yield is balanced overall through the sum of the anabranches and the single channel, and dynamic equilibrium is maintained in Magela Creek. It appears that approximate mass flux balance prevails over time frames of 1 to 10^2 years, as shown by the lack of detectable channel change over the past 50 years.

[33] Evidently, Magela Creek reflects a range of formative discharges rather than a single dominant discharge [*Pickup and Rieger*, 1979], and the relationship between in-channel and overbank flow is key to the system's flow efficiency. At the effective discharge (40–45 m^3/s), the single channels run bank-full while, concurrently, the anabranches convey 25% of total flow overbank (Figure 7a); yet, at this discharge the anabranches transport 37% higher bed material yield (Figure 9). Wetted perimeter increases dramatically when floodwaters begin spilling from the anabranches at 20 m^3/s; however, our field observations and the delayed effect on flow efficiency suggest that minimal mixing occurs between in-channel and overbank flows up to 40–50 m^3/s (Figure 8b). At higher discharges, overbank floodwaters are brought to a near standstill by dense vegetation covering the islands, and we predict that eddies shed from anabranches into these stalled water bodies dissipate energy via momentum transfer, thereby diminishing flow efficiency at high stage (Figure 8b).

[34] The flume results confirm the flow efficiency gains in dividing flow according to the Magela Creek field configuration (experiments 1 and 2, see Table 2). Experiment 3 corroborates field studies of the anabranching style found in upper Columbia River [see *Abaddo et al.*, 2003; *Tabata and Hickin*, 2003], which show that no flow efficiency advantage derives from anabranching if aggregated bed width of the anabranches equals that where flows

converge into a single channel. Clearly, two types of anabranching are possible: one efficient and the other less so [*Nanson and Knighton*, 1996]. The flume results suggest a critical role for overbank flow in the flow efficiency process; without it, a narrow single channel may be more efficient than anabranches. The presence of anabranching probably reflects historical contingencies inherent to the sedimentary style and vegetative environment. In Magela Creek, for instance, bars may coalesce as they become progressively stabilized by vegetation thereby forming islands, which then separate anabranches that iteratively attain MFE. Although not developing a single channel, one or two anabranches may become dominant consistent with the flume results indicating a narrow single-channel of high flow efficiency. Figure 3 reveals some spread in width/depth ratios among anabranches in a single cross section that presumably also indicates variable flow efficiency.

[35] Remarkably, Magela Creek's anabranches attain peak flow efficiency while conveying 25% of total discharge overbank; an attribute linking anabranching to the floodplain's capacity to carry overbank flow. Frequent and/or prolonged overbank flooding is characteristic of many anabranching systems [*Makaske*, 2001]. *Rutherfurd* [1991] notes that anabranching reaches of the Murray River spill overbank more frequently than single-channel reaches, just as we observe in Magela Creek where the duration of overbank flooding from the anabranches is double that of single channel "A." Greater sediment delivery to the floodplains and islands-ridges flanking the anabranches is consistent with maintenance of dynamic equilibrium, because single-channels generally correspond to valley constrictions, which have less overbank accommodation space (Figure 2). The frequency and duration of overbank flow
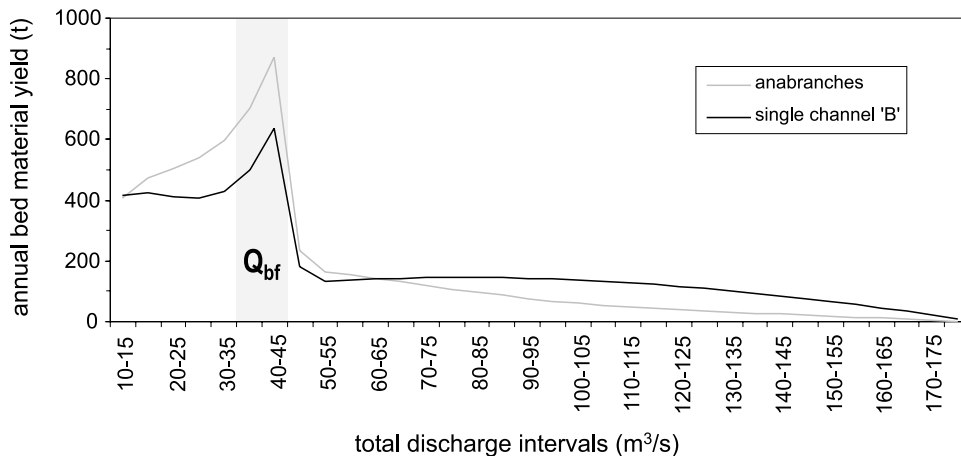
Figure 9. Magnitude-frequency effective discharge analysis based on bed material yield time integrated with flow duration data; note that bed material yield (the area under each curve) is essentially equivalent, indicating mass flux balance.

Table 2. Summary Results of the Flume Experiments

Variable	Experiment 1, Wide Single Channel	Experiment 2, Multichannels[a]			Experiment 3, Narrow Single Channel
		a	b	c	
Bed width, cm	45	10	10	10	30
Mean depth, cm	2.7	2.8	3.5	3.2	3.3
Width/depth ratio	17	3.6	2.9	3.1	9.1
Hydraulic radius, cm	2.4	1.8	2.0	2.0	2.7
Mean water slope($\times 10^4$)	45−50	45−50	45−50	45−50	35−40
Mean velocity, cm/s	32.5	42.5	47.5	40.0	43.5
Darcy-Weisbach friction factor ff	0.081−0.090	0.035−0.038	0.032−0.035	0.043−0.048	0.039−0.045
Time taken to attain equilibrium, h	40	22	22	22	22
Bed material measurement time, h	3.8	3.8	3.8	3.8	4.5
Wetted perimeter, cm	50.4	48.8	48.8	48.8	36.6
Flow discharge Q, L/s	3.95	4.09	4.09	4.09	4.31
Bedload discharge Q_s, g/s	0.93	1.54	1.54	1.54	1.69
Sediment concentration Q_s/Q, g/L	0.24	0.38	0.38	0.38	0.39
Total stream power Ω, W/m	0.174−0.194	0.180−0.201	0.180−0.201	0.180−0.201	0.148−0.169
Flow efficiency Q_s/Ω	4.79−5.34	7.66−8.56	7.66−8.56	7.66−8.56	10.00−11.42

[a]The three multichannels are denoted by a, b, and c.

may be expressed by the ratio $Q_{2.3}/Q_{bf}$, which in Magela Creek is a very high 13 to 26 due to the small bank-full capacity. The low w/d of the sandy anabranches signifies high bank strength imparted by reinforcing vegetation [*Erskine*, 2002]. Current anabranch w/d ratios appear to reflect a stable optimum struck between channel bank stability and maximum water and sediment flux over a mobile bed. Why single channels coexist with anabranches, and why they are consistently wider than the sum of the anabranches in Magela Creek remains an intriguing question. Equivalence between single-channel Q_{bf} and the effective discharge suggests that the anabranches' low w/d ratios are not simply the result of higher bank strength. We note that at high-stage bank shear and stream power are greater at the single channel relative to the anabranches. In-channel deposition at the single channel sites may also encourage bank erosion and channel-widening much as in braiding rivers [*Leopold and Wolman*, 1957].

7.2. Flow Efficiency Continuum and Fundamental Causes of Anabranching

[36] As originally proposed by *Nanson and Knighton* [1996] and analytically examined by *Nanson and Huang* [1999], the adoption of multiple channels may serve to enhance flow efficiency in some rivers, but not all anabranching systems are adjusted for maximum efficiency. Clearly, MFE does not extend throughout the drainage network of Magela Creek. Madjinbardi delta has functioned as a bed material sink for the past 4−3 ka [*Roberts*, 1991; *Nanson et al.*, 1993]. Approaching the delta, fading sediment transport capacity is associated with declining slope, numerous bars and in-channel trees along with the increased number and w/d ratio of the anabranches, quite the opposite to the study reach where anabranches retain low w/d ratios, and few bars or in-channel trees exist (Figure 3).

[37] In some cases, anabranching appears to be a temporary response to changing sediment supply or transport capacity [e.g., *Smith et al.*, 1989; *Brizga and Finlayson*, 1990]. Elsewhere, rapidly aggrading anabranching systems feature splays, channel avulsion and ultimately channel abandonment, processes active in anabranching rivers that apparently do not manifest MFE [e.g., *Smith and Smith*,

1980; *Smith*, 1983, 1986; *Schumann*, 1989; *Makaske*, 1998, 2001; *Abaddo et al.*, 2003; *Tabata and Hickin*, 2003]. The anabranching upper Columbia River, for instance, sequesters 66% of bed material supplied from upstream [*Locking*, 1983], and in the Ovens and King Rivers, southeastern Australia, anabranches stemming from new avulsions become more sinuous with time and eventually cease to function [*Schumm et al.*, 1996].

[38] Anabranching rivers apparently share remarkably little in common [*Nanson and Knighton*, 1996]; they develop in widely divergent climatic and hydrologic environments in alluvium ranging from clay to boulders with specific stream powers spanning two orders of magnitude. Recognition of coexisting efficient and less-efficient anabranching behavior introduces considerable subtlety to arguments concerning the stability of this river pattern. These rivers span a continuum of flow efficiency and therefore may constitute a dynamic equilibrium or disequilibrium state, as do other river patterns such as braiding or meandering.

[39] According to minimum variance theory, alluvial channels maintain their dynamic stability by maximally dissipating any excess energy remaining after sediment transport [*Huang et al.*, 2004]. Energy dissipation might be accomplished, for instance, via deformation of the channel boundary to create braid bars or river meanders. *Bettess and White* [1983] propose a scheme in which river pattern and system adjustment is explained in terms of the available valley slope (S_v) relative to the dynamic equilibrium channel slope (S_r) necessary for the transport of a given sediment load. These same quantities might equally be viewed as energy available (E) and minimum energy necessary (E_{min}) to maintain mass flux balance [*Huang et al.*, 2004]. Three possible states exist: (1) $S_v > S_r$ *or* E > E_{min}, e.g., dynamic equilibrium is achieved through dissipation of excess energy via bed roughness in braiding rivers, or increased sinuosity, which reduces the energy slope in meandering rivers; (2) $S_v = S_r$ *or* E = E_{min}, e.g., a straight channel in dynamic equilibrium; and (3) $S_v < S_r$ *or* E < E_{min}, e.g., disequilibrium rivers (in the sense of *Renwick* [1992]).

[40] The disequilibrium rivers exhibiting the third state possess insufficient energy or sediment transport capacity to

meet sediment supply. This inherently unstable condition advances two possible options for the system to achieve dynamic equilibrium: maximize available energy by enhancing flow efficiency, or increase the absolute energy available. If the deficit in available energy is substantial, the latter option will prevail and aggradation will eventually increase S_v along with the energy necessary for potential attainment of dynamic equilibrium. This situation may apply in rapidly aggrading anabranching systems responding to a downstream base level control, such as those described from western Canada [e.g., *Smith and Smith*, 1980]. However, valley slope steepening via aggradation is a long-term process that becomes necessary only *after* shifts in river pattern, geometry and bed configuration fail to overcome the slope or energy deficit [cf. *Schumm et al.*, 1987]. Given that MFE is commensurate with dynamic equilibrium, it follows that $E = E_{min}$ in the Magela Creek study reach. We infer that Magela Creek would be unable to maintain transport of the sediment supplied with the energy available as a continuous single channel; disequilibrium would prevail. However, the available energy falls only slightly below that necessary to maintain dynamic equilibrium, and this deficit is met by the enhanced flow efficiency afforded by the anabranching river pattern. Anabranching channels in Magela Creek appear to be maximally efficient and dispose of excess energy at high stage by displacing flow overbank where it is met with high roughness across the islands and floodplain.

[41] Anabranching offers a versatile adjustment or stabilizing mechanism spanning two end points of system efficiency. First, where valley slope is only slightly less than the dynamic equilibrium valley slope ($S_v < S_r$), anabranching permits MFE ($E = E_{min}$) as modeled mathematically [*Nanson and Huang*, 1999] and demonstrated with field and laboratory data in this paper. Second, where valley slope is much less than the dynamic equilibrium slope ($S_v \ll S_r$), anabranching provides a mechanism for distributing excess sediment load across the valley floor promoting long-term sediment storage and aggradation that ultimately steepens the valley slope enabling attainment of dynamic equilibrium ($E = E_{min}$). We suggest that this versatility explains the existence of anabranching under aggradational, dynamic equilibrium and probably even erosional regimes, spanning diverse substrates and stream power conditions.

8. Conclusions

[42] We demonstrate that development of anabranching in Magela Creek increases conveyance of sediment compared with a single channel at the same total discharge while maintaining overall sediment flux balance. We supplement these results with simple flume experiments showing the flow efficiency advantages of divided flow when compared with field analogues in Magela Creek.

[43] Resistant vegetation is an essential requirement for anabranching rivers formed in uncohesive sediments [*Wende and Nanson*, 1998; *Tooth and Nanson*, 1999, 2000b]. The cause of anabranching in Magela Creek stems from the enhanced conveyance of sediment along its near-straight, low-gradient valley floor and we anticipate that this explanation applies equally to other sand-dominated, island

and ridge-forming anabranching rivers [e.g., *Nanson and Knighton*, 1996; *Wende and Nanson*, 1998; *Nanson and Huang*, 1999; *Tooth and Nanson*, 1999, 2000b].

[44] However, as previously emphasized by *Nanson and Knigthon* [1996] and *Nanson and Huang* [1999], not all anabranching rivers are adjusted to MFE. Adoption of multiple channels engages the fourth dimension of fluvial system adjustment: multiple independent channels that self-regulate slope, channel geometry and boundary resistance. Enhanced facility for adjustment is especially important when one or more options are limited, for instance, in straight rivers that cannot increase their slope by decreasing sinuosity. We suggest that the versatility stemming from such self-regulation may partly explain the diversity of anabranching rivers so far recognized [*Nanson and Knighton*, 1996]. Just as braiding, meandering and straight rivers manifest dynamic equilibrium, disequilibrium or nonequilibrium states varying spatially and temporally throughout the channel network, anabranching rivers host similarly diverse states of mass flux balance and hence may differ in their efficiency. It follows that the question of whether or not anabranching represents an dynamic equilibrium or transitional state [e.g., *Abaddo et al.*, 2003; *Tabata and Hickin*, 2003] presents a false dichotomy. Anabranching rivers like other rivers can be either dynamic equilibrium *or* transitional (disequilibrium) forms and, as in Magela Creek, these two states may even coexist in the same river.

[45] We propose that the anabranching river pattern spans two end points of a flow efficiency continuum: (1) MFE equating with dynamic equilibrium, as modeled mathematically [*Nanson and Huang*, 1999; *Huang and Nanson*, 2000] and demonstrated with field and laboratory data in this paper; and (2) a mechanism for distributing excess sediment load across the valley floor promoting aggradation and long-term sediment storage (i.e., disequilibrium) leading to eventual valley steepening and potential attainment of dynamic equilibrium. We recognize that the efficiency gains that anabranching can offer are modest relative to the energy gains involved in valley steepening, but if the available energy falls only slightly below that necessary to maintain dynamic equilibrium, we contend that this deficit can be met by adoption of a system of multiple channels. Accordingly, anabranching can constitute a stable river pattern in dynamic equilibrium under circumstances in which a single channel would be unable to maintain sediment conveyance, therefore becoming inherently unstable.

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