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Patterns of anabranching channels: The ultimate end-member adjustment of mega rivers

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ABSTRACT

Large fluvial systems adjust to a combination of controls to form distinctive channels, which represent a dominant factor in the evolution of floodplain geomorphology and sedimentology. Fluvial geomorphology has commonly classified river channels into meandering, straight and braiding patterns, which are seen to represent a continuum of channel geometry. Anabranching patterns, rivers with multiple channels, however, are characteristic of many rivers. The identification of a combination of variables that discriminates specific channel patterns has been a significant focus of research in fluvial geomorphology. The development of this body of knowledge, however, has been established from medium and small rivers, and laboratory flume studies. Very few of these research ideas developed from analysis of large fluvial systems.

This paper assesses the pattern of channel adjustment of large fluvial systems by employing hydraulic geometry, discharge, *w*/*d*, slope, grain size, stream power, specific stream power, and Froude number (Q_{mean} > 1000 m^3/s). The study demonstrates that methods currently used to discriminate channel patterns are not useful when applied to very large rivers. Further, with the exception of the Lower Mississippi, alluvial rivers with mean annual discharges greater than ~17,000 m^3/s, here classified as mega rivers, do not generate single thread meandering or typical braided patterns. These mega rivers develop anabranching patterns.

1. Introduction

Fluvial systems adjust the floodplain and channels to a combination of controls, and a strong correlation exists between river channel patterns and floodplain sedimentology (Nanson and Croke, 1992; Bridge, 2003). Over small time-scales floodplain conditions affect channel patterns by influencing local bank resistance, flow transmission and sediment load. Over longer time-scales, however, the patterns of river channels are seen as the driver for floodplain styles (Nanson and Croke, 1992), and models of alluvial architecture and depositional environments are dependent upon the dynamics of channel patterns (Miall, 1996; Bridge, 2003).

Fluvial geomorphology has commonly categorized river channels as meandering, straight and braiding patterns, which are seen to represent end-member patterns (Leopold and Wolman, 1957, Knighton, 1998). The identification of a combination of variables that discriminates specific channel patterns has been a significant focus of research in fluvial geomorphology. The development of this body of knowledge, however, has been established from small and medium sized rivers, and laboratory flume studies.

This paper examines the adjustment of channel patterns for the largest fluvial systems on Earth, with the idea of being able to identify a threshold for what may be considered a large river. Simple definitions such as straight, meandering and braided are difficult to apply in large rivers (Latrubesse et al., 2005). In a recent paper, Jansen and Nanson (2004) indicate that the largest rivers are dominated by anabranching patterns, an observation made by Latrubesse (1992) a decade earlier. Anabranching channel patterns represent an additional planform geometry (e.g. Nanson and Knighton, 1996), and agreement exists among researchers that the physical causes for anabranching channels should be identified (Nanson and Huang, 1999; Huang and Nanson, 2007).

As addressed by several authors (Nanson and Croke, 1992; Knighton 1998, Miall, 1996; Fielding, 2007) a close association occurs between the type of channel pattern and the characteristics of floodplain development. The distinctive aggradation morphologies and the sedimentary architecture that characterize a floodplain can be related to the hydro-geomorphologic dynamics of the associated channel pattern. Nanson and Croke (1992), for example, quantitatively identified several types of floodplains and channel patterns as a function of specific stream power at bankfull discharge and sediment texture. The largest rivers, however, exhibited a variety of channel styles, and anabranching pattern were common. Considering the existing lack of knowledge on anabranching rivers on the varieties of sub-patterns or planforms as well physical causes for anabranching, understanding floodplain evolution generated by anabranching patterns remains incomplete.

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Table 1
Largest rivers of the world

River	Country to the mouth	Mean annual discharge (m^3/s)	Drainage area (103 km^2)	Annual Q_s (Mt/year)	Sediment yield (t/km^2 year)	Dominant channel pattern
Amazon	Brazil	209,000[a]	6100	~1000[e]	167	Anabranching
Congo	Zaire	40,900	3700	32.8	9	Anabranching
Orinoco	Venezuela	35,000[d]	950	150[d]	157.8	Anabranching
Yangtze	China	32,000	1943	970[e]	499	Anabranching-occasional complex and geologically controlled sinuous reaches
Madeira	Brazil	32,000[a]	1360	450[c]	330	Anabranching
Negro	Brazil	28,400[a]	696	8[b]	11.5	Anabranching
Brahmaputra	Bangladesh	20,000	610	520[e]	852.4	Anabranching
Japura	Brazil	18,600[a]	248	33[b]	133	Anabranching
Parana	Argentina	18,000	2600	112[g]	43	Anabranching
Mississippi	USA	17,000	3200	330[e]	102	Meandering

Data sources: [(a)] data estimated from the Brazilian National Agency of Water-ANA, [(b)]Filizola (1999), [(c)]Martinelli et al. (1993), [(d)]Meade et al. (1983), [(e)]Meade (1996), [(g)]Amsler and Prendes (2000).

While the basis of knowledge in fluvial geomorphology continues to stem from studies of smaller rivers, a greater recognition exists that large rivers are unique fluvial systems, in terms of the controls, processes, and from the standpoint of management (Potter, 1978; Junk et al., 1989; Latrubesse et al., 2005; Gupta, 2007). Geomorphologists, however, have neither agreed upon how large a river needs to be to be considered "large", or have identified objective criteria to categorize such rivers. Indeed, commonly a great range in the size of rivers is considered "large". Kellerhalls and Church (1990) identified large rivers as having a bankfull discharge exceeding 20 m^3/s and channel width of greater than 20 m, which is too small to be classified a large river by most categories (e.g., Potter, 1978; Latrubesse et al., 2005; Wohl, 2007). Nevertheless, this implies that the channel would be unlikely to be significantly influenced by local factors, such as a landslide blockage or fallen trees, providing some distinction from smaller rivers in terms of the controls on channel morphology. Other authors suggest that the scale of large fluvial systems creates distinctive types of channel and floodplain hydrologic connectivity (Junk et al., 1989; Mertes et al., 1996; Mertes, 1997) which also suggests floodplain/channel style and scale-dependence in hydro-ecological process (Latrubesse et al., 2005, Latrubesse, in press). Other studies, however, have noted that large rivers generally require extensive geologic control by structure or tectonics (Potter, 1978; Latrubesse et al., 2005; Miall 2006; Tandon and Sinha, 2007). Indeed, this has emerged as the main criteria for identifying large rivers, which results in very long channels, a large drainage basin, and a high mean annual

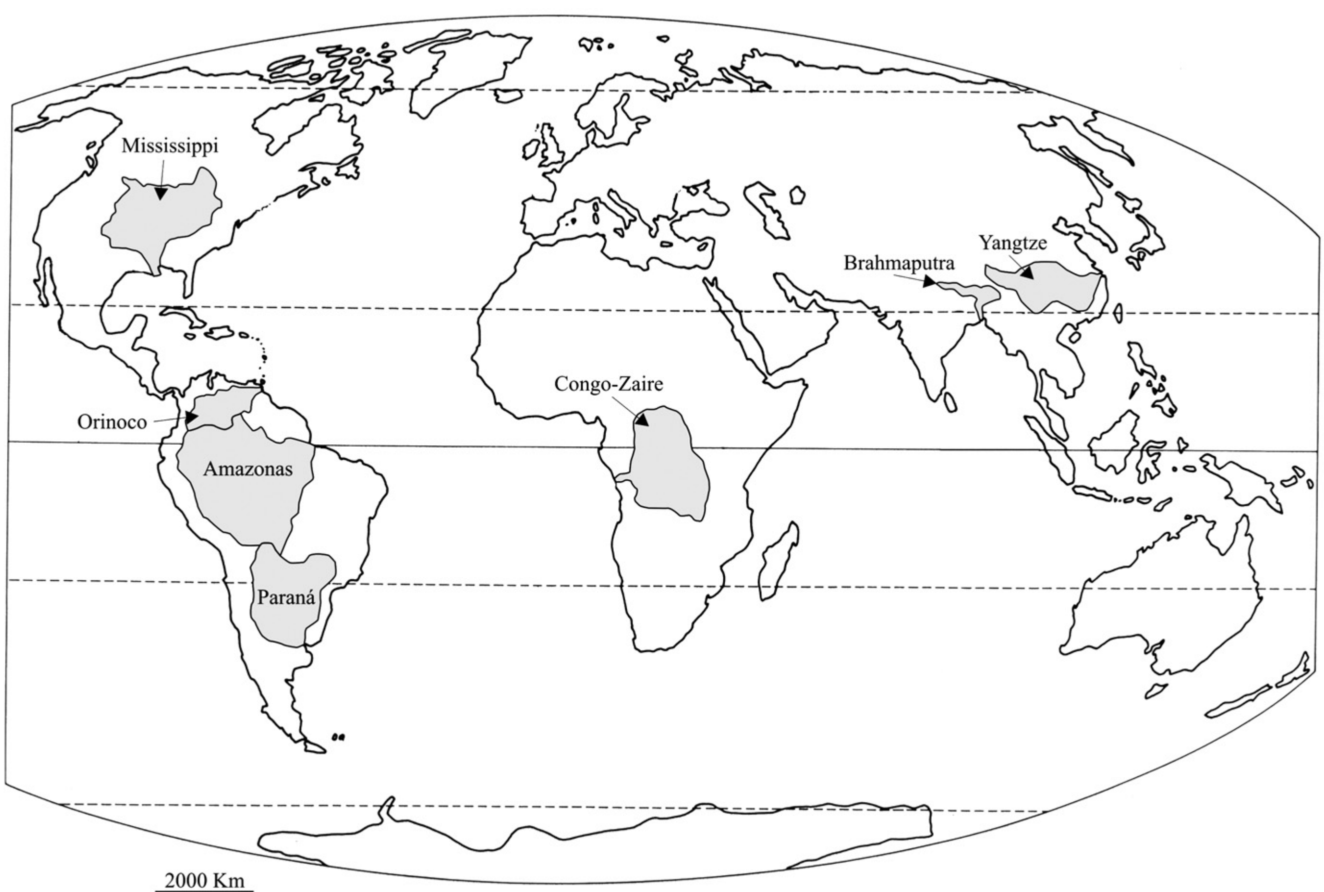

Fig. 1. Location of the ten largest river basins based on discharge.

discharge (Gupta, 2007). While it is probably reasonable to avoid too strict of a threshold, such a broad categorization results in even the latest treaties on the subject including rivers that span an incredible range of drainage area, length, and discharge. Obviously drainage area is a helpful parameter to define large rivers. To study modern geomorphic processes, however, discharge is a key variable because channel and floodplain processes are strongly related to fluvial processes. Several fluvial systems with extensive drainage areas, for example, are located in dry regions and, thus, are often not considered large rivers. The Global Commission on Continental Paleohydrology (GLOCOPH) Large Rivers Working Group, for example generally considers large rivers to have a mean annual discharge (Q_{mean})>1000 m^3/s).

Thus, in this study a large river is defined as having a mean annual discharge (Q_{mean})>1000 m^3/s, with the majority of case studies including rivers>5000 m^3/s Q_{mean}. The objective is to emphasize rivers with a Q_{mean} greater than 1000 m^3/s, which are infrequently studied and are seldom included in studies used to quantitatively discriminate channel pattern. "Flashy" rivers with high peak events were not included. Additionally, a new category of "very large" rivers is proposed: *mega rivers*, which are those rivers with a Q_{mean}> ~17,000 m^3/s and include the nine largest rivers on Earth. These rivers include the Amazon, Congo, Orinoco, Yangtze, Madeira, Negro, Brahmaputra, Japura, Parana. Additionally, the tenth largest river, the Mississippi, will be also discussed (Table 1, Figs. 1 and 2). This study aims to improve the understanding of why the largest rivers differ from smaller rivers, and how this response is observed in the planform channel geometry. The decoupling of knowledge between large and smaller fluvial systems represents a tremendous problem in fluvial geomorphology. Considering the importance of large rivers and river floodplains to a range of global-scale ecological issues, such as sediment flux, carbon sequestration, and water resources, this represents a significant problem for river management. Indeed, most of the runoff on Earth is transported by a few very large rivers, with ~16 to 20% of the runoff discharge by the Amazon. In this regard, this study identifies new research directions for large rivers.

2. Data, methods, and approach

To situate the findings from this study within the body of knowledge on the topic, it is critical to utilize methods that are consistent with the published literature. Thus, this study utilizes techniques which have influenced the current geomorphological thinking on channel patterns and predictions of channel planform morphology. Data from large rivers were obtained from gauging station records in several countries (Table 2 and Fig. 3). The data include records as well as measurements of bankfull discharge (Q_{bf}) and mean annual flooding (Q_{maf}) for time-series, hydraulic geometry (w, d and v), median grain size (D_{50}), slope, Froude number, stream power, and percent of suspended or bed load in relation to total load. Channel patterns were characterized by using topographic maps, hydrographic surveys, and satellite imagery from several sources, including Landsat 5 TM and Landsat 7 ETM+, CBERS (Chinese–Brazilian Satellite), Google Earth, Geocover, and JERS 1 (Synthetic Aperture Radar—SAR). Further description and referencing of these data sources are included below.

In addition to the author's original data obtained from government agencies, field work, and analysis of remote sensing imagery, data sets available from published articles were included in the analysis, which includes data from Franzinelli and Potter (1983), Mertes and Meade

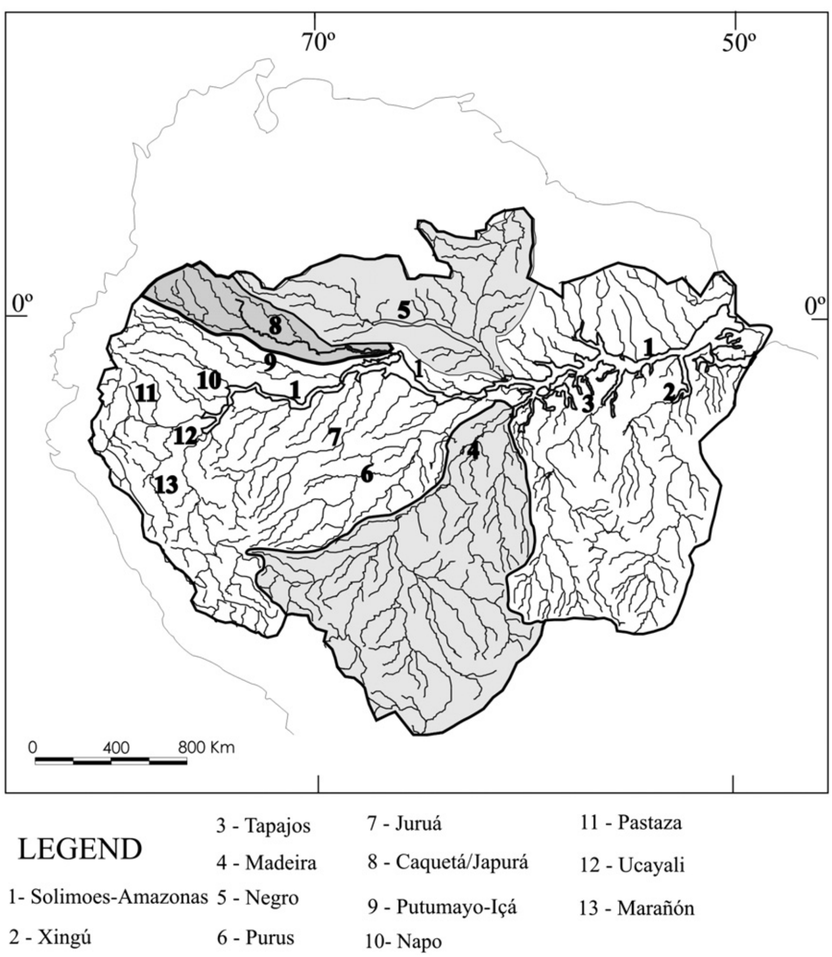

Fig. 2. Main sub-basins of the Amazon drainage basin. The Madeira River, Negro River and Japura River basins (dashed areas) complete the list of the ten largest rivers (Fig. 1).

Table 2

Number in Fig. 2	River	Gauge station	Channel pattern	Drainage area (km^2)	Mean annual discharge Q_m (m^3/s)	Bankfull discharge Q_b (m^3/s)	Slope — S (cm/km)	Stream power (J s^{-1})	Specific stream power (W/m^2)	w/d	Median bed-size — D_{50} (m)
1	Juruá	Eurinepê	Tortuous meandering	77,136	1783	3000	7.2	2118	9.76	18	0.0003
2	Juruá	Santos Dumont	Tortuous meandering	142,234	3980	7700	8	6041	16.7	24	0.0003
3	Purus	Beaba (Cariuacanga)	Tortuous meandering	347,147	9564	16,711	3.2	5244	7.6	35	0.0003
4	Purus	Valparaíso	Tortuous meandering	103,285	2088	6000	9.3	5472	18.8	24	0.0003
5	Purus	Lábrea	Tortuous meandering	220,351	5521	10,550	6.5	6725	14.7	27	0.0003
–	Fly	Kuambjt gauging station	Tortuous meandering	18,400	2355	3018	5	5001	15	26	0.0002
–	Mississippi	Viscksburg	Meandering	2,964,252	16,600	25,000	8	19,614	14.3	70	0.0004
6	Iça	Ipiranga	Meandering	108,362	7188	10,213	8.2	8213	10.2	75	0.0003
7	Paraguay	Porto Murtinho	Meandering	474,500	2376	3333	4	1111	3.8	20	0.0003
–	Yangtze	From Chijiang to Ouchi	Anabranching with sinuous branches	1,010,000	14,500	45,600	4.4	17,887	13.3	102	0.00025
8	Mamoré	Guajará–Mirim	Meandering upstream Guajara	589,497	8154	14,700	9	12,974	15.2	75	0.0003
9	Madeira	Abunã	Anabranching	1,532,002	18,630	25,000	6	14,710	23	30	0.0003
10	Madeira	Porto Velho	Anabranching	954,285	19,039	30,000	4.3	12,651	17	33	0.0002
11	Madeira	Manicoré	Anabranching	1,157,516	25,538	42,000	4.1	16,887	19	35	0.0002
12	Madeira	Fazenda Vista Alegre	Anabranching	1,586,000	31,003	57,000	5.7	31,862	23.1	64	0.0002
13	Japura	Acanauí	Anabranching	242,259	14,333	21,000	3.6	8041	7.7	65	0.0004
14	Japura	Vila Bittencourt	Anabranching	197,136	13,758	20,000	4.1	8041	7,8	68	0.0004
15	Solimões	Teresina	Anabranching	983,157	45,366	60,000	3.8	22,359	10.35	127	0.0003
16	Solimões	Santo Antonio do Içá	Anabranching	1,134,540	55,538	70,000	3.4	23,340	10.9	110	0.0003
17	Solimões (Amazon)	Itapeua	Anabranching	1,769,000	82,069	90,000	1.6	14,112	13.6	24	0.0002
18	Solimões (Amazon)	Manacapuru	Anabranching	2,147,736	101,218	120,000	1.8	21,183	6.6	120	0.00025
19	Amazon	Jatuarana	Anabranching	2,854,286	123,680	161,330	2.1	33,219	12.2	72	0.00025
20	Upper Parana	Porto Rico	Anabranching	670,500	9700	12,300	11	13,268	11.5	68	0.0003
21	Parana	Corrientes	Anabranching-	1,950,000	19,170	27,330	4.9	13,123	8.81	110	0.0004
22	Parana	Curtiembre	Anabranching-	2,300,000	19,500	20,500	4.8	9643	7.25	111	0.0003
23	Parana	Villa Urquiza	Anabranching-	2,173,000	16,460	17,140	4.4	7390	5.6	112	0.0003
–	Brahmaputra	Bahadurabad area	Anabranching-	636,130	21,261	60,000	6.8	33,343	9.8	200	0.00025
24	Araguaia	Luis Alves	Anabranching-	117,580	1621	3700	10	3628	7	76	0.0003
25	Araguaia	Aruana	Anabranching-	76,964	1200	3200	15	4707	12.2	64	0.0004
26	Araguaia	São Felix	Anabranching-	193,923	2700	6000	9.8	5766	9.2	83	0.0003
27	Orinoco	Musinacio	Anabranching-	1,705,383	28,723	64,600	6	34,763	19.6	101	0.0004
–	Yangtze	Datong	Anabranching-sinuous	1,705,000	25,023	87,204	9.3	79,477	26.4	130	0.00013

(1985), Nordin and Perez Hernandez (1989), Thorne et al. (1993), Biedenharn and Thorne (1994), Dietrich et al. (1999), Guyot et al. (1999), Amsler and Prendes (2000), Paoli and Schreider (2000), Orfeo and Stevaux (2002), Ramonell et al. (2002) and Rocha and Souza Filho (2005). ANA (National Agency of Water) provided historical series and other hydrologic data from Brazilian rivers.

2.1. Bed material size

The median particle size (D_{50}, mm) of bed material was obtained from field work on Brazilian rivers, and for other rivers was obtained from the previously cited peer reviewed published literature (above). The D_{50} of large rivers is medium or fine sand with values varying between 0.13 and 0.5 mm.

2.2. Data on bankfull discharge (Q_{bf})

Bankfull discharge was estimated using standard procedures (e.g., Dunne and Leopold, 1998; Knighton, 1998), and was estimated for cross-sections at hydrologic gauging stations. This procedure was applied in all the Brazilian gauging stations where mean daily discharges are in general available from about 1970. The observed level was also compared with the discharge recurrence interval data obtained from the hydrological series at each station and the stage level compared to a distribution of peak daily discharges for each recorded year. Field survey was carried out in Manacapuru (Solimões River), Guajara (Mamoré River), Aruana and Luiz Alves (Araguaia River), Porto Velho and Abuna (Madeira River) and Porto Rico (Upper Parana River) gauge stations. The average of the mean annual floods was also used for comparison and calibration. Additionally, the estimated bankfull data were compared with estimates of recurrence intervals from a Gumbell distribution. Bankfull data from Brahmaputra, Yangtze, Fly, Mississippi, Orinoco and Parana were obtained from the literature mentioned above.

2.3. Hydraulic geometry

The at-a-station hydraulic geometry data were analyzed using the method proposed by Leopold and Maddock (1953), with width, depth and velocity expressed below as:

$$w = aQ^b;\ d = cQ^f;\ u = kQ^m \qquad (1)$$

where w = width; d = depth and u = mean velocity.

Data were calculated for twenty-three Brazilian gauging stations. Data from the Orinoco, Fly and additional data from the Parana were obtained from Nordin and Perez Hernandez (1989), Dietrich et al. (1999) and Rocha and Souza Filho (2005), respectively.

2.4. Slope

Slope is the most problematic variable to accurately estimate for large rivers. Estimates of slope at bankfull stage were provided from published literature or calculated from hydraulic data using standard procedures. The water-surface gradient of the Solimões–Amazon River has been estimated by using remote sensing data from the Seasat mission (Guzkowska et al., 1990) and TOPEX/POSEIDON (Birket et al., 2002), as well as water velocity profiles at specific locations (Dunne et al, 1998). The values are available for Santo Antonio do Iça, Itapeua and Manacapuru gauging stations from field work by government agencies. Slope is not available, however, for other gauging stations along the Amazon. In such cases, slope was estimated

Fig. 3. Location of the South American gauging stations. Numbers are in agreement with the numbered gauging stations in Table 2.

by using the Manning technique, as adopted from the method used by Dietrich et al., (1999) for the Fly River:

$$u = d^{0.67} S^{0.5} / n. \quad (2)$$

Solving for the slope, (S), and replacing the mean velocity, u, and the average depth (d), and width (w) obtained from the hydraulic geometry relationships

$u = kQ^m$ and $d = cQ^f$

gives

$$S = (kQ^m)^2 n^2 / \left(cQ^f\right)^{1.33}$$

or

$$S = k^2 c^{-1.33} Q^{(2m-1.33f)} n^2. \quad (3)$$

Applying Eq. (3) the slope was estimated for bankfull stage at the twenty-three stations in Brazil, and, when possible, compared with data obtained from other methods, such as recorded from the literature or from personal field measurements.

A Manning's n of 0.03 was proposed for all the rivers with exception of the Amazon where an n value of 0.025 was used. For large alluvial rivers as those of our data set, n values at bankfull are highly consistent with dominant narrow range that oscillates from 0.02 to 0.035. The suggested roughness values (n) are inside the range of estimates obtained in the Amazon River (Itacoatiara and Obidos) and Madeira River (Fazenda Vista Alegre) by Strasser et al., (2005).

The data obtained by this method at Manacapuru, Itapeua and Santo Antonio do Içа are inside the range of water gradient values estimated by the TOPEX POSEIDON satellite radar altimetry (Birket et al., 2002), and calculation from water velocity profiles (Dunne et al, 1998). This comparison was used as a validation of the method to obtain slopes for other stations of the Amazon basin.

Hydraulic geometry estimations of slope were additionally compared with direct slope measures available on upper Parana and Araguaia by the author and collaborators and on the Orinoco River (Nordin and Perez Hernandez, 1989). Slope estimates for the Mississippi, middle-lower Parana, Fly and Yangtze Rivers were available from the published literature.

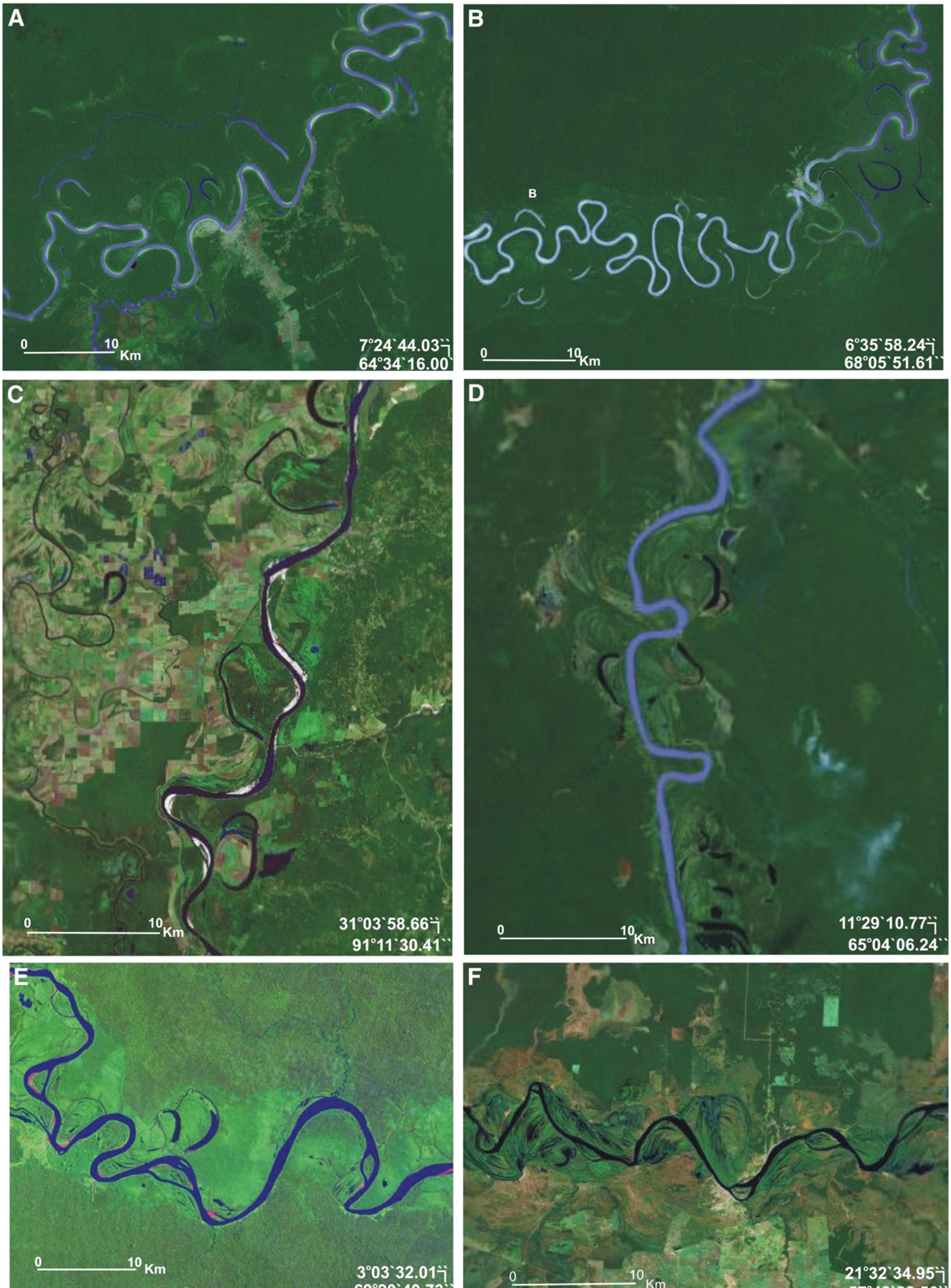

Fig. 4. Meandering rivers. A) Purus River at Labrea (Q_{mean} = 5521 m^3/s); B) Jurua River at Santo Dumont (Q_{mean} = 3980 m^3/s); C) Mississippi at Vicksburg (Q_{mean} = 16,660 m^3/s); D) Mamoré River upstream of Guajara Mirim (Q_{mean} = 8154 m^3/s); E) Içа River at Ipiranga Novo (Q_{mean} = 7188 m^3/s); F) Paraguay River at Porto Murtinho (Q_{mean} = 2376 m^3/s.

2.5. Width and depth

Values for width and depth were measured and estimated in several ways. Direct field measures are available at surveyed gauging stations for all South American rivers reported in this study. As an additional control, however, width measurements were obtained from navigation charts and topographic maps to compare with direct measurement at gauging stations (in the Amazon basin). For additional comparison, the width data were estimated by applying the hydraulic geometry relations to bankfull discharges. This procedure

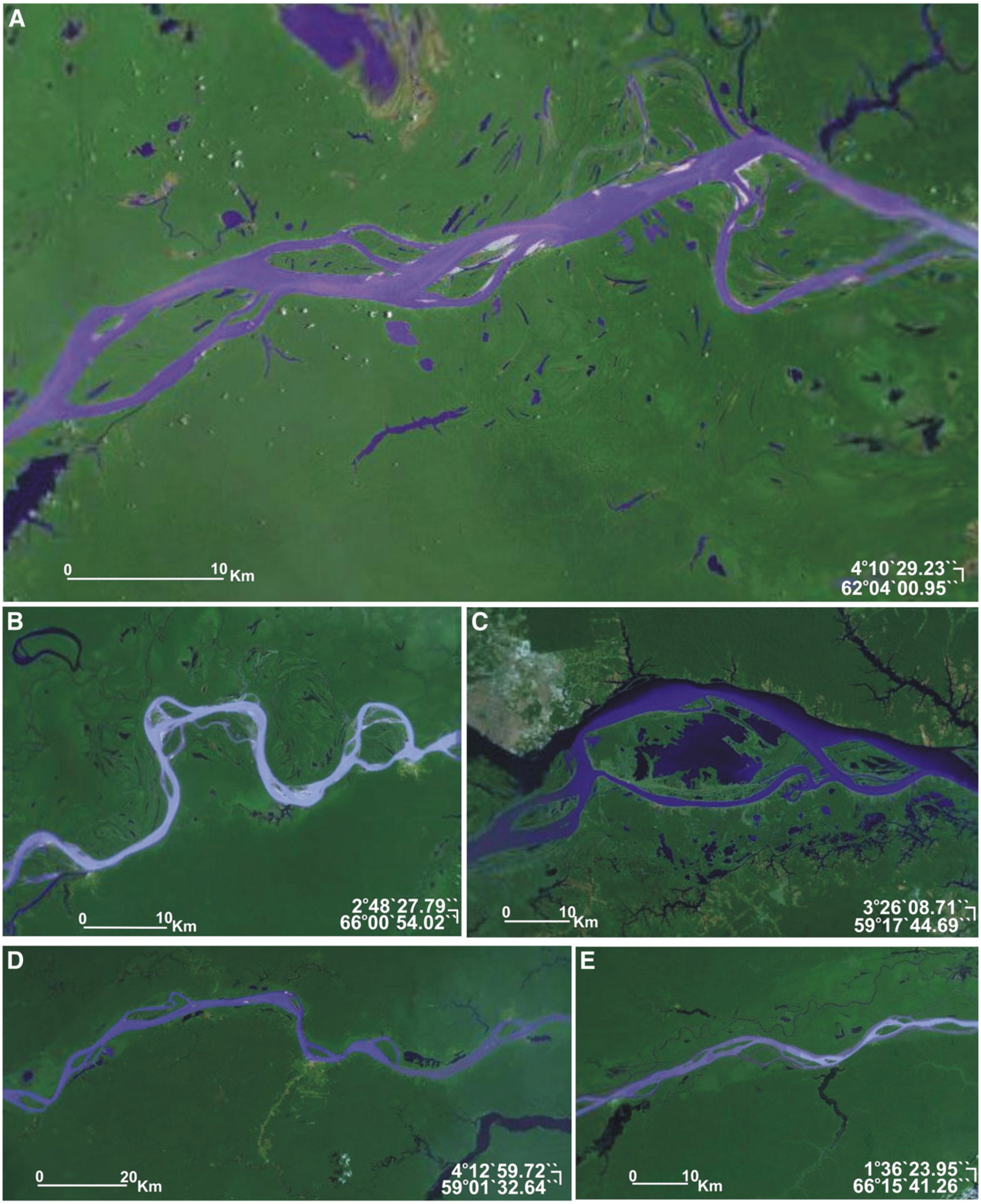

Fig. 5. Low sinuosity anabranching patterns. A) Solimões–Amazon immediately downstream of Itapeua; B) Solimões–Amazon at Fonte Boa downstream of Santo Antonio do Içа (Q_{mean} ~ 55,600 m^3/s); C) Amazon at Careiro Island, Jatuarana station (Q_{mean} = 123,680 m^3/s); D) Madeira River at Fazenda Vista Alegre (Q_{mean} = 31,000 m^3/s); E) Japura River at Acanaui (Q_{mean} = 14,333 m^3/s).

was applied to all the rivers in the Amazon basin and to the upper Parana, the Paraguay, the Araguaia, and the Orinoco Rivers (Fig. 3).

For the Mississippi, Yangtze, Brahmaputra, and Parana, such data were obtained from the published literature. In the lower Brahmaputra (downstream of Bahadurabad) and Mississippi Rivers the available channel width data were compared with measurements obtained from analysis of Landsat 5 TM and Landsat 7 ETM+ satellite imagery. Considering the scale of the rivers and image resolution (15 m for Landsat 7 ETM+), the amount of error should be negligible. Indeed, satellite imagery is increasingly useful for such measurements of large rivers (Latrubesse et al., in press), and a more recent study has used the widely available public satellite imagery data source *Google Earth®* (Constantine and Dunne, 2008).

Depth values where obtained from the published literature (Yangtze, Brahmaputra, Mississippi) and from cross-section measurements at gauging stations for the South American rivers. Additionally, hydraulic geometry relations were used to estimate mean depth from bankfull discharge data and navigation charts, where available.

2.6. Stream power

Total stream power is an expression of the rate of potential energy expenditure per unit length of channel, and is defined as

$$\Omega = \gamma Q s \tag{4}$$

where γ is the specific weight of the water, Q discharge and s is slope, whereas specific stream power is stream power per unit of channel width.

$$(\omega = \Omega / w) \tag{5}$$

Because it is a direct product of discharge and slope, stream power is closely related to sediment transport, bank erosion and rates of lateral migration (Nanson and Hickin, 1986; Knighton, 1998).

Ω and ω were calculated for all rivers at bankfull discharge (Table 2).

3. "Mega" rivers and anabranching channel patterns

The characteristics of the ten largest rivers are provided in Table 1. Mean annual discharge (Q_{mean}) for each river was obtained from the lower-most gauging station. The data used to characterize the rivers at individual gauging stations are reported in Table 2.

Of the ten largest rivers only the Mississippi, the smallest, has a single-thread meandering channel (Fig. 4C). Rivers with Q_{mean} slightly higher, such as the Parana and Japura rivers, clearly anabranch (Figs 5E and 6A).

In the lower Mississippi w/d ratios can be ~70–90 (from Vicksburg to Natchez) (Fig. 4C) but before human modifications were as high as 200 in some places (Schumm et al., 1994). In the Mississippi, "natural" sinuosity up to 1915 varied mainly from 1.3 to 2 (Schumm et al., 1994, from Fisk, 1944). Historic maps indicate that, prior to human modifications, the lower Mississippi had a substantial number of small channel islands, especially in meander bends. This was particularly common in the middle reaches of the alluvial valley (Schumm et al., 1994), which underwent high rates of meander bend migration (Hudson and Kessel, 2000). Nearly all bends included an island or channel bar.

The Yangtze River at Yichang gauging station has a Q_{mean} of ~14,200 m^3/s, and displays a complex multi-channel sinuous pattern where it crosses a tectonically active basin, as can be observed downstream from Chijiang (Wang et al., 2005). Several branches are individually sinuous, but the overall pattern is multi-channel. In others downstream reaches the sinuosity of the Yangtze River increases. But the pattern, however, is related to geologic (bedrock and structural) controls, confining the channel to a narrow valley, which does not permit the river to develop typical meanders and an anabranching pattern with sporadic islands prevail. Furthermore, the upper Solimões–Amazon at Fonte Boa has a complex multi-channel

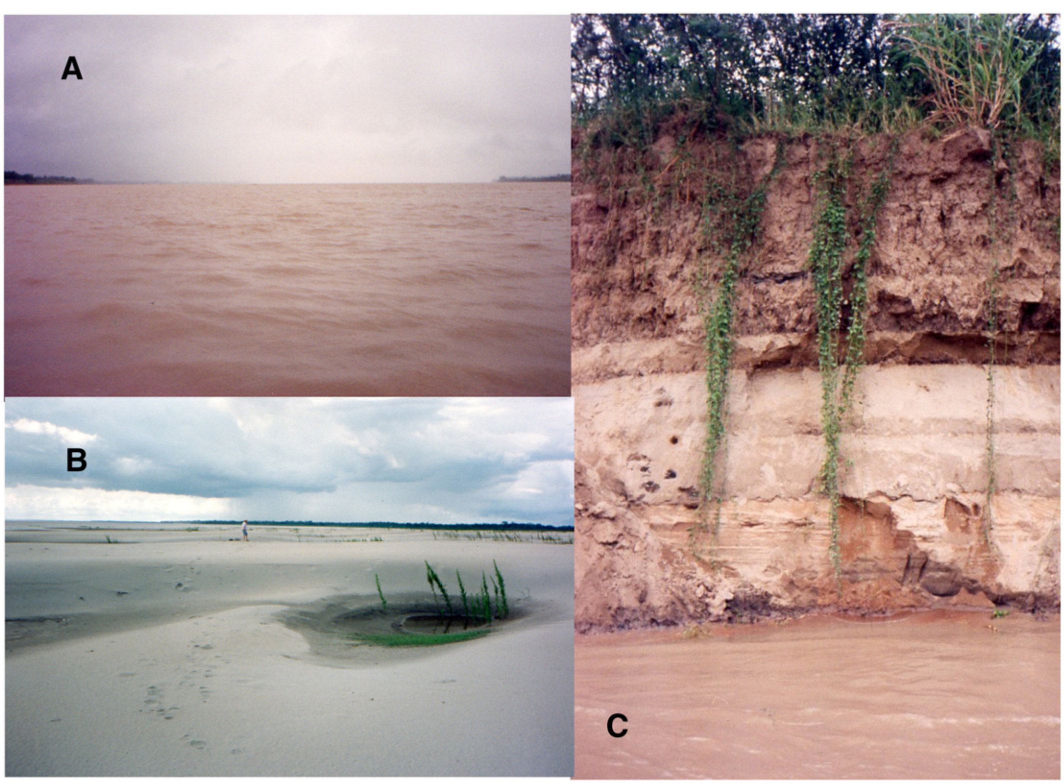

Fig. 6. The Solimões River at Manacapuru area. A) The main channel, B) large sand bar at low water stage, C) exposure of channel cutbank, ~7 m high, at the head of Marchantaria Island.

sinuous pattern rather than a single meanders-thread, with a Q_{mean} of 55,000 m^3/s and a Q_{bf} of 70,000 m^3/s (Fig. 5B).

As with meandering, braided rivers are not represented in mega rivers. Islands are a characteristic element of large rivers but these divide the flow at discharges up to bankfull. This suggests that individual channels act as anabranches, as defined by Nanson and Knighton (1996), rather as channel bars within the same channel cross-section.

In general terms, the channel belt of anabranching rivers such as Amazon, Japura and Madeira, are relatively straight and have a sinuosity for main and major secondary channels of <1.3 (Fig. 5). The Amazon–Solimões River generally does not divide in more than two or three branches at the same location, flowing in between strongly vegetated islands and generating episodic and large sand bars (Figs. 5A, B and 6). In some specific places secondary branches can be relatively sinuous but are restricted to short lateral reaches (Mertes et al, 1996; Latrubesse and Franzinelli, 2002). The Madeira River (Q_{mean}=32,000 m^3/s at the mouth), the main tributary of the Amazon as well as the Japura River (Q_{mean}=18,600 m^3/s at the mouth) mentioned above, show a few branches with relatively straight channels with sinuosity of less and characteristic w/d ratios oscillate between 30 and 70 (Fig. 5D).

Numerous sand bars, however, can also be characteristic of some anabranching rivers, such as the Brahmaputra and Orinoco, where extensive channel bars form and result in local channel braiding. Nevertheless, the overall pattern is anabranching, with large stable vegetated islands that do not seasonally adjust with annual flow variability, as with unconsolidated sediments comprising bars in a braided river. Examples of anabranching patterns with large islands and sand bars resembling braiding patterns are shown in Fig. 7. Several reaches of the Brahmaputra River (Fig. 7B) (Bristow, 1987, Sarma, 2005) as well as the Middle Parana River in Argentina (Figs. 7A and 8) are in this category, which includes very high w/d ratios which exceed frequently 200. Bed load represent approximately 15% of the total load in Brahmaputra (Goswamy, 1989, Sarma 2005) and 17% in the middle Parana (Ramonell et al., 2002).

The Orinoco River shows a less complex pattern with a few islands and several sand bars as can be observed at Musinacio area (Fig. 7C)

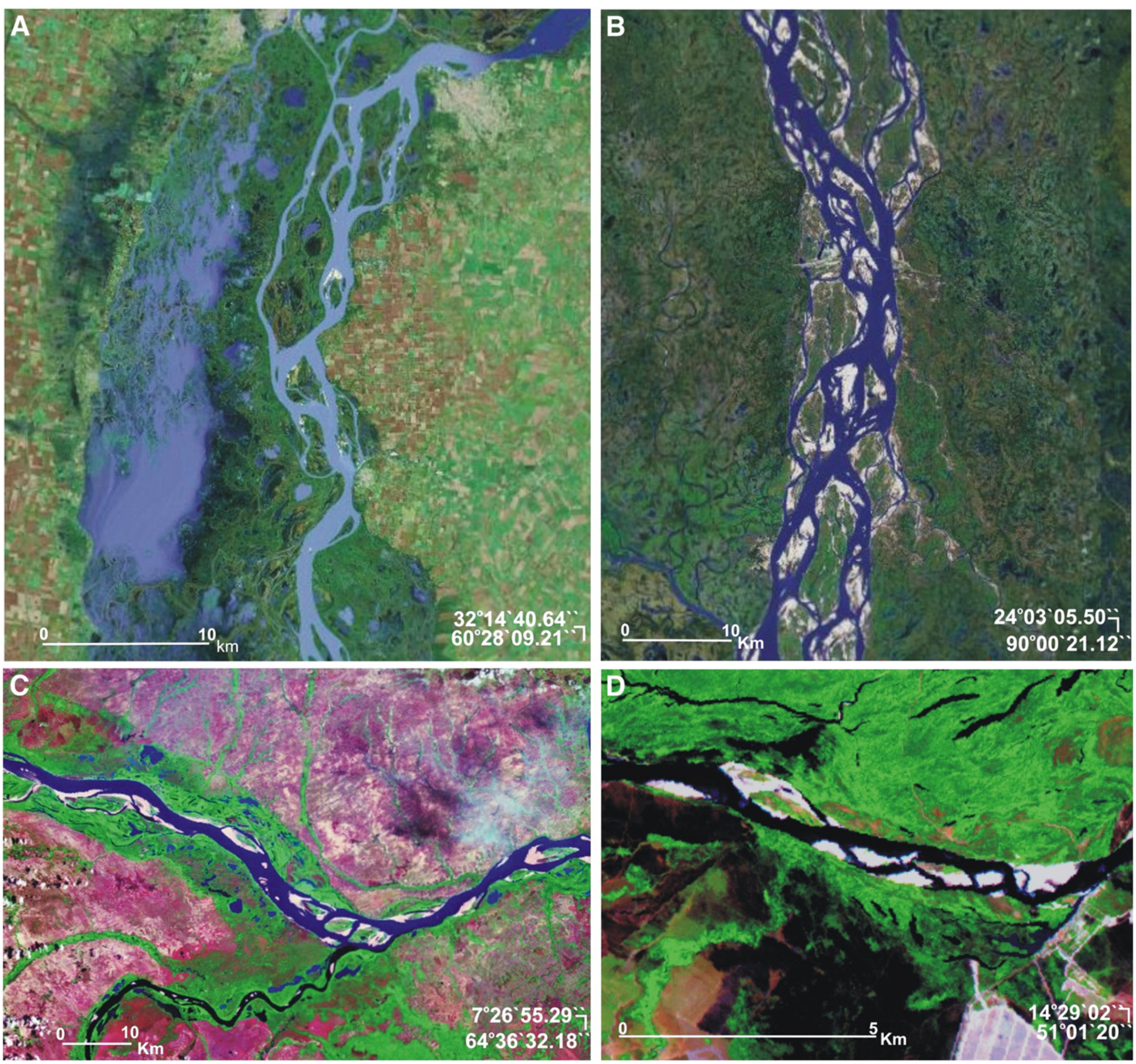

Fig. 7. Anabranching rivers with tendency towards braided pattern. A) lower Parana River downstream of Santa Fe (downstream Villa Urquiza gauge station) (Q_{mean}=16,400 m^3/s); B) Brahmaputra at Baharudabad (Q_{mean}=21,261 m^3/s); C) Orinoco River at Musinacio (Q_{mean}= 28,723 m^3/s); D) Araguaia River at Luiz Alves (Q_{mean}=3700 m^3/s).

Fig. 8. The anabranching pattern of the Middle Parana River near Santa Fe (downstream Villa Urquiza gauging station).

where the Q_{mean} is ~28,700 m^3/s. The two largest rivers draining dominantly Precambrian rocks in tropical rainforest, the Congo in Africa and the Negro in South America, generate substantial fluvial archipelagos (Fig. 9). Nevertheless, these rivers display an intricate multi-channel pattern and complex floodplains that have low suspended sediment loads relative to the very large discharge values (Table 1). A substantial part of these river channels are controlled by geology (structures and bedrock) and do not generate broad floodplains. As noted above, however, tectonic blocks permit the development of impressive fluvial archipelagos that exceed 15 km in width and extend for hundreds of kilometers. These rivers were not included in the database because of the lack of hydrologic and hydraulic data for multi-channel reaches, and because a considerable amount of the floodplain, representing the older Quaternary floodplain geomorphology, is unrepresentative of the modern system (Latrubesse and Franzineli, 2005). Briefly, these rivers have a broad range of w/d ratios, ranging from 400 in large channels to 20 in secondary channels.

4. Discriminating channel patterns

4.1. The discharge/slope approach

The most commonly accepted approaches to discriminate channel patterns include discharge (Q) and slope (S) (Leopold and Wolman, 1957, Lane 1957).

Leopold and Wolman (1957) proposed that:

$$S = 0.013Q_{bf}^{-0.44}$$

where

Q_{bf} is the bankfull discharge and S is the channel slope.

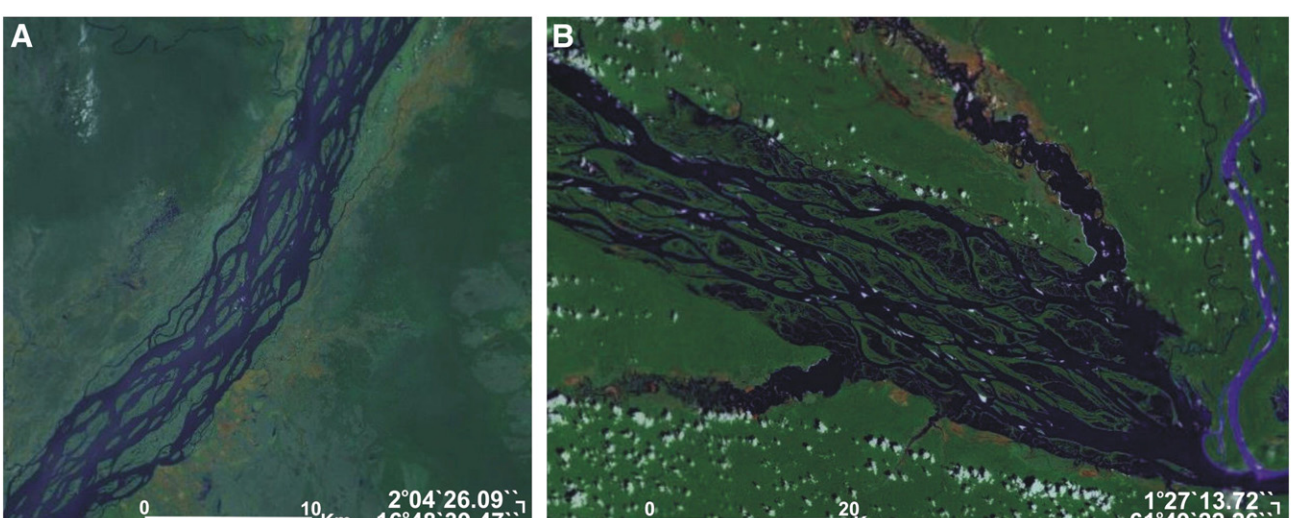

Fig. 9. Mega complex anabranching rivers. A) the Congo River between Mobenga and Mokangamoi B) the Negro river at Barcelos, Mariuá archipelago (no gauging stations available at these reaches, however taking account data from gauging station located upstream and downstream, the river reaches are inside the classification of mega rivers with Q_{mean} > 17,000 m^3/s).

Fig. 10-A shows the data plotted by Leopold and Wolman (1957) with additional data on anastomosing rivers (Knighton and Nanson 1993), which plot well below the original curve.

Several criticisms have risen on the validity of this approach, as for example:

- The braiding meander transition should be less dependent of bankfull discharge than suggested in the original diagram and grain size also could depend on median grain size, D_{50} (Carson 1984, Ferguson, 1987).
- In sinuous rivers, valley slope should be used rather than channel slope because the latter is directly influenced by sinuosity and, thus, does not represent a true independent variable (Carson, 1984, Van den Berg, 1995, Bridge, 2003).
- Empirical data from anastomosing rivers plot below the trend line (Knighton and Nanson, 1993), with the implication that bank sediments are as important as slope in producing changes in channel pattern (Schumm, 1977; Simpson and Smith, 2001).

The concentration of data in the Leopold and Wolman diagram is for small rivers less than 400 m^3/s to bankfull. The data set of Leopold and Wolman (1957) only include a few data points representing large rivers with a Q_{bf} > 5000 m^3/s (Fig. 10A). Only three points are plotted in the original figure for rivers with a Q_{bf} of more than 10,000 m^3/s, which plot below the trend line (two are meandering and one braided). The three points plotting above the trend line are for the Kosi River in India, which generates a fluvial mega fan in the Himalayan piedmont. The large "bankfull" discharge of the Kosi River is not characteristic of a large river because it is a product of the monsoonal effect (see discussion of effective discharge, Section 7) in an active and avulsive alluvial fan. The other three points below the trend line plotted by Leopold and Wolman (1957) are for the Ganges River near Patna, the Mississippi near Blytheville, and the Yukon River near Holy Cross, Alaska. Thus, the original relation developed by Leopold and Wolman (1957) is not sensitive enough to discriminate channel patterns for large rivers. Fig. 10B shows an enlargement of this figure for rivers of more than 1500 m^3/s, with the majority of data for rivers with a Q_{bf} that exceeds 5000 m^3/s. The revised values of sinuous rivers are plotted as values corrected to valley slope (Sv).

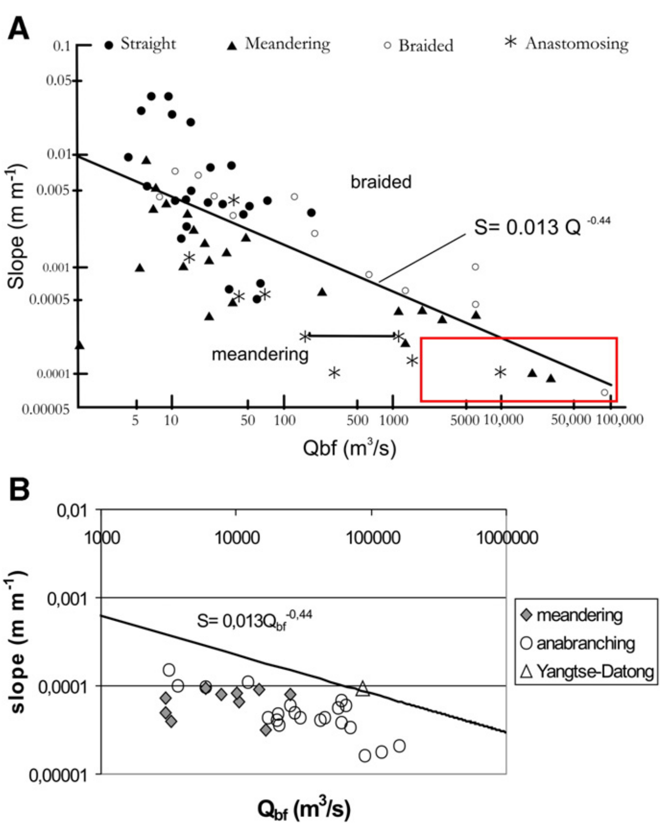

Fig. 10. A) The Leopold and Wolman (1957) slope/bankfull discharge diagram to discriminate channel patterns, including the plot of anabranching rivers by Knighton and Nanson (1993). The squared area indicates the location of the large rivers plotted in Fig. 5B. B) enlarged area of the diagram of Leopold and Wolman.

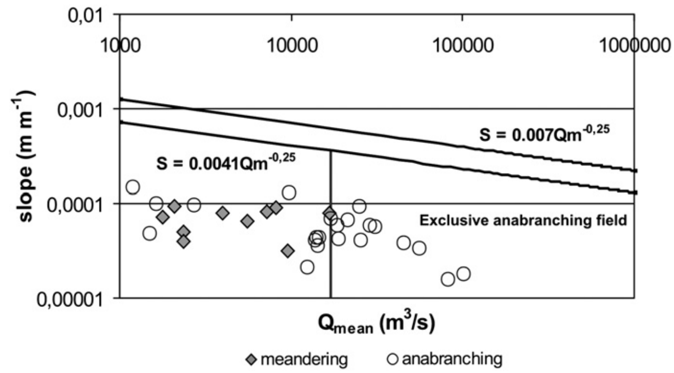

Fig. 11. Lane (1957) slope/mean annual discharge diagram to discriminate channel patterns. The figure shows an enlarged area where large rivers plot.

Despite the slope correction, the entire group of large rivers plot below the Leopold and Wolman trend line (1957), and cannot be discriminated in relation to channel pattern. The tendency is that slope (s) decrease as discharge increases, but it is not possible to distinguish channel styles.

Large rivers have very low slopes, <0.0002, and the largest rivers have slopes <0.0001. The only large river plotted close to the discriminating curve is the Yangtze River at Datong, where, as explained above, geological control causes the slope to be near 0.0001 at bankfull discharge.

Fig. 11 shows the trend line produced by Lane (1957) to discriminate channel patterns relating Q_{mean} and slope, where:

$$S<0.007Q_m^{-0.25} \text{ for meandering, sand – bed channels}$$

$$0.0041Q_m^{-0.25}>S<0.007Q_m^{-0.25} \text{ meandering–braiding transition}$$

$$S>0.0041Q_m^{-0.25} \text{ braided, sand – bed channels.}$$

To summarise, the trend lines utilized for the analysis of channel patterns are not useful (Fig. 11) to discriminate channel patterns for very large rivers. All rivers with a Q_{mean} discharge higher than ~17,000 m^3/s are anabranching systems. These "mega" rivers plot in an exclusive "anabranching field" and have channel slopes less 0.00007 (Fig. 11).

4.2. The sediment load approach

Schumm (1977, 1985) suggested that the type of sediment load is a major control of channel pattern because it controls w/d and sinuosity (Table 3). Bed load rivers are generally characterized as highly active and low sinuosity channels that exhibit a braided channel pattern. Suspended sediment load dominated rivers are characterized by a single channel with a higher sinuosity, and stable banks because of cohesive fine-grained deposits. Mixed load rivers exhibit intermediate properties. Criticisms of the Schumm (1977, 1985) approach were made because it was noted that sinuous single thread river channels can be generated for sandy or gravely systems (Van den Berg, 1995, Lewin and Brewer, 2001, Bridge, 2003), and because it is also not clear

Table 3

Type of channel			Sedimentary load and bed load as % of total load	w/d ratio	Sinuosity	Slope	Characteristic rivers
Meandering	Sinuous–tortuous		Suspended load dominant, bed load <2% of total load	~15–30	Usually >2	Always Very gentle	Jurua, Purus and Fly
	Meandering with tendency to anabranching and others		Suspended load variable and bed load dominated by sand which can be up to 10% of total load	Variable and can be up to more than 200	Usually <2..3		Mississippi, Içá, lower Paraguay, lower Mamoré, l ower Ucayali
Anabranching	Low to moderate anabranching-low sinuosity	Simples to moderate anabranching-low sinuosity	Suspended load dominant, <5% of bed load	From 20 to generally >100	<1,5, occasional secondary branches sinuous or not		Madeira, Japura Amazon
		Anabranching with tendency to Braided	Significant bed load >10 % and up to 35% of total load	Generally more than 100	Some branches can be sinuous		Brahmaputra, Orinoc, Parana and Araguaia
	Complex anabranching archipelagos		Insignificant amount of suspended load. Relatively high bed load when compared with the low suspended load amounts they carried	Generally more than 100	Not relevant		Negro, Congo

what criteria the methods were used to define the percentages of bed load in relation to the total load to discriminate channel patterns. For example, Baker (1978) studying rivers in the Amazon basin and Pickup (1984) studying the Fly River demonstrated that the empirical equations proposed by Schumm (1977, 1985) were not adequate to characterize those systems.

Schumm's classification does not apply well to large rivers (Tables 3 and 4). For example, rivers in Schumm's (1977, 1985) classification would be defined as "suspended load rivers" and have a high sinuosity and tortuous and complex meanders, as those in South-western Amazon lowland (Purus, Jurua) transport ~98% of wash load have w/d ratios between 18 and 35 (Fig. 4A and B). Additionally, the Amazon, and several large tributaries, such as the Madeira and Japura, transport ~95% wash load and 2 to 5% sandy bed load (Gibbs, 1967, Mertes and Meade, 1985) and would be classified as suspended or mixed load rivers. These rivers, however, are anabranching (Fig. 5) with low sinuosity values, and the w/d values exceed 20, with several greater than 100. The classification also does not consider large complex anabranching rivers with very low sediment loads (suspended or bed load), such as the Congo or Negro Rivers (Fig. 9) where w/d can range from 20 to 400. Further, rivers such as Parana, Brahmaputra, and Orinoco as well as minor rivers such as the Araguaia would be categorized as bed load rivers by Schumm's (1977, 1985) criteria because the rivers transport greater than 11% of the total load as bed load. These systems, however, are anabranching with multiple islands and bars and do not generate typical braided patterns (Figs. 7 and 8).

Alternatively, Schumm's classification assumes that slope is related to the type of sediment transport. For instance, channel patterns should be related to the calibre of the bed sediments. Large rivers with similar slopes and similar grain sizes, however, generate a variety of channel patterns from meandering to a set of anabranching patterns. Table 4 presents a synthesis of main characteristics of the large rivers analyzed in this paper.

4.3. Stream power and grain size

Van den Berg (1995) postulated that the threshold slope for braiding also depends on the grain size of the bed material and plotted specific stream power against median grain size (Fig. 12A).

The study was based on an analysis of 228 data points obtained from rivers spanning a diversity of climatic and physical settings. The study employed valley slope as an alternative to channel slope, a regime-based estimate of channel width, and bankfull discharge. This generated the discriminating function of,

$$\omega = 900D_{50}^{0.42} \quad (6)$$

where ω is specific stream power at the transition between single-thread and multi-thread channels and D_{50} = median diameter of the bed material.

While the approach has been widely utilized, it has been criticized (Lewin and Brewer, 2001, 2003) based on the notion that regime-based estimates of channel width result in exaggerated values of specific stream power (Lewin and Brewer, 2001, 2003).

Of note is that the data set concentrates on rivers with more than 25 W/m^2, and values of D_{50}>0.5 mm. In contrast, large rivers have a D_{50}<0.5 mm, and specific stream power<25 W/m^2. Only 19 of the 228 data points of Van den Berg (1995) are for rivers with D_{50} less than 0.5 mm. Thus, the Van den Berg (1995) equation is not suitable for discriminating channel patterns in large systems (Fig. 12B). For large rivers, single and anabranching patterns plot on a very restricted area because large alluvial rivers have a narrow range of grain sizes with D_{50} mainly between 0.1 and 0.5 mm, and specific stream power is characteristically <25 W/m^2. As observed in Table 2, all large alluvial rivers have medium to low values of stream power that range from ~3 to 25 W/m^2. A similar approach to the Van den Berg (1995) study was taken by Bledsoe and Watson (2001) by plotting $SvQ^{0.5}0$ against D_{50}.

Table 4

Type of channel	Bed load as% total load	w/d ratio	Sinuosity	Slope	Channel pattern	Some main problems for large river
Suspended load	<3	<10	Usually >2	Relatively gentle gradient	Meandering-tortuous	Rivers considered suspended load with tortuous meander have w/d ratios varying from 18 to 35. River with <3% of bed load can generate low anabranching-low sinuosity patterns with very gentle slopes
Mixed load	3–11	10–40	1.3–2	Moderate gradient	Meandering-harmonic	Rivers with up to 11% of bed load can generate a variety of anabranching patterns to slopes as lower as "suspended load" rivers. w/d ratio can reach values as higher as more than 100. Rivers generating harmonic meanders can have w/d ratios as high as 200.
Bed load	>11	>40	<1.3	Relatively steep gradient	Braided	Anabranching rivers with tendency to braided have very gentle slopes. No pure braided patterns are founded in large rivers.

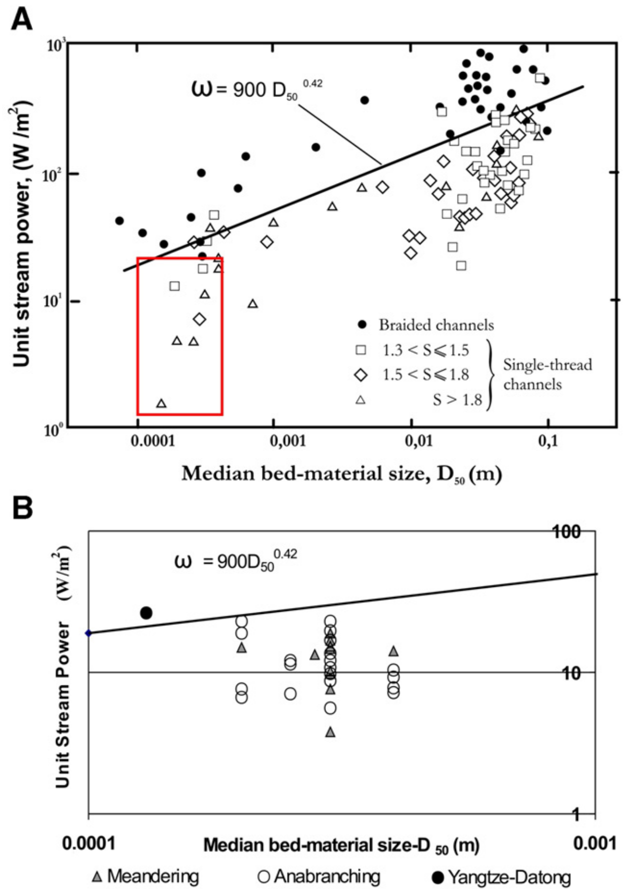

Fig. 12. A) Van den Berg (1995) diagram of channel pattern in relation to grain size and specific stream power. The square identifies the large rivers. B) Enlarged area of Fig. 5A.

Because the low D_{50} variability, however, this function was not suitable for discriminating the channel patterns of large rivers.

4.4. Theoretical analysis of channel stability

Several authors proposed that channel pattern is controlled by a combination of width, depth, slope and Froude number (*Fr*), with Parker (1976) suggesting discrimination on the basis of on $w/d \approx Fr/S$. Bridge (1993) observed that the braiding criterion of Parker does not agree well with field data. The data show that large rivers plot in the Parker diagram in the restricted region relating to meandering and transitional to straight (Fig. 13). For large rivers d/w oscillated mainly between 0.05 and 0.007, and the values of the relation Slope/Froude numbers are very low, restricted between 0.00012 and 0.0014. Mean velocity for several cross-sections to bankfull varied between 1 and 2 m/s and slope was very low. Data obtained by Richardson and Thorne (2001) for the Brahmaputra River plot in a similar position.

The large w/d values greater than 20 for large rivers could promote flow separation and the generation of new channel branches. As indicated also by Fredsoe (1978) and Fukuoka (1989), w/d probably is a major control for braiding. The value of $w/d>50$ for braiding pattern generation as suggested by Fredsoe (1978), however, is too large. Alternatively, single meandering channels can be maintained with w/d ratios >50.

By employing the Fukuoka equation $S^{0.2}\ w/d \approx 10$–20 with original field data for the meandering–braided transition (S = slope), nearly all of the large rivers could have w/d estimated values of <13.

4.5. Predicting the bifurcation of single channels

The preceding analysis shows that anabranching patterns are more characteristic of large rivers, and particularly of mega rivers. In an attempt to identify the mechanisms in association with the formation of anabranches for the Brahmaputra River, Richardson and Thorne (2001) related specific energy (E) to depth/width ratio (d/w) for several cross-sections, where specific energy is defined as,

$$E = \left(v^2/2g\right) + d \tag{7}$$

and d = mean depth of water (m); v = mean velocity (m/s) and g = acceleration because gravity (m/s^2). The authors plotted two series of data, one from single-thread flows and the other second from multi-thread flows with the threshold between the two series defined by the power relation:

$$E = 46.6(d/w)^{0.39}. \tag{8}$$

They concluded that multi-thread channels have higher values of specific energy for a given d/w ratio. The problem is that, for large rivers, specific energy becomes almost entirely a surrogate for depth such that in the discriminating relationship d plotted against d/w becomes invalid (Fig. 14). Indeed, for the study data mean depth oscillates between 6 and ~43 m. For this reason the term $(v^2/2g)$ is irrelevant.

5. The hydraulic geometry of large rivers

At-a-station hydraulic geometry relates adjustments in cross-sectional alluvial channel morphology to changes in discharge

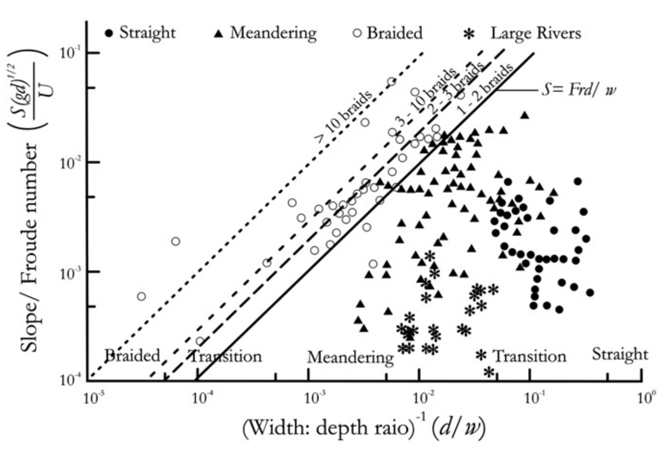

Fig. 13. Parker's (1976) diagram to discriminate straight, meandering, and braided rivers. The degree of braiding is defined in terms of slope/Froude number and d/w ratios.

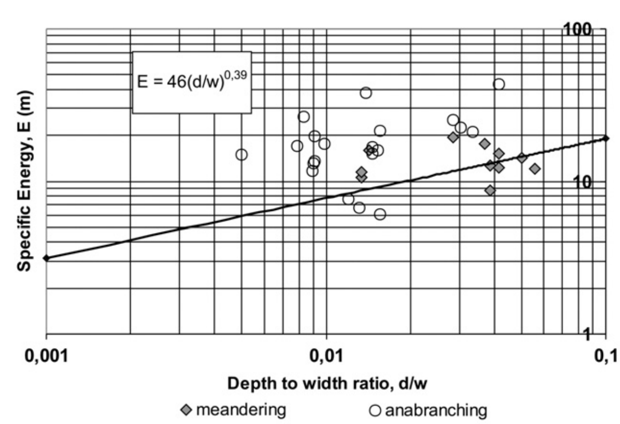

Fig. 14. Large rivers shown by plotting specific energy in relation to depth:width ratio as proposed by Richardson and Thorne (2001). The curve indicates the threshold between single-thread flows and multi-thread flows as found in the Brahmaputra River.

Table 5
Hydraulic geometry exponents (*b.m.f*)

River	Gauge station	Width (b)	Depth (f)	Velocity (m)	Channel pattern
Amazon–Solimões	Teresina	0.0327	0.4674	0.4744	AN
Amazon–Solimões	Santo A. do Içá	0.0148	0.4929	0.492	AN
Amazon–Solimões	Itapeuá	0.0809	0.2072	0.7122	AN
Amazon–Solimões	Manacapuru	0.0269	0.4675	0.5031	AN
Amazon	Jatuarana	0.0491	0.3045	0.6489	AN
Madeira	Abunã	0.0388	0.2792	0.6821	AN
Madeira	Porto Velho	0.0387	0.2689	0.6925	AN
Madeira	Manicoré	0.0946	0.2631	0.6413	AN
Madeira	Fazenda Bela Vista	0.0225	0.3045	0.6489	AN
Japura	Vila Bittencourt	0.0454	0.3662	0.6103	AN
Japura	Acanauí	0.0182	0.4089	0.5727	AN
Parana	Puerto Rico	0.02	0.3	0.68	AN
Orinoco	Musinacio	0.04	0.63	0.33	AN
Araguaia	Aruana	0.05	0.42	0.52	AN
Araguaia	Luis Alves	0.048	0.65	0.3	AN
Araguaia	São Felix	0.041	0.41	0.54	AN
Mamoré	Guajará Mirim	0.015	0.2592	0.7387	M
Fly	Manda	0.04	0.37	0.59	M
Juruá	Cruzeiro do Sul	0.1131	0.5128	0.3746	M
Juruá	Eurinepê	0.2153	0.5171	0.2749	M
Juruá	Santos Dumont	0.1114	0.5472	0.344	M
Purus	Manoel Urbano	0.0634	0.524	0.4269	M
Purus	Valparaíso	0.1281	0.5174	0.3552	M
Purus	Lábrea	0.0901	0.5843	0.3244	M
Purus	Beaba (Cariuacanga)	0.058	0.22	0.71	M
Purus	Aruma-jusante	0.058	0.20	0.73	M

AN = anabranching. M = meandering.

(Leopold and Maddock, 1953). It is commonly expressed as power functions of the relationships between discharge and width, mean depth, and mean flow velocity at a particular cross-section.

Of course gauging stations are not always located at the most appropriate locations to examine these relationships in self adjusting alluvial channels, but they remain the primary source of data. The data sets in this study come from gauging stations where the channel was not influenced by resistant bedrock.

Following numerous studies of at-station hydraulic geometry at a wide range of alluvial channels, the average exponents obtained are $b=0.26$; $f=0.4$ and $m=0.34$ (Leopold, 1994). Bank composition (sediment), however, is known to influence the rate of channel adjustment. In general terms, cohesive bank material constrains lateral adjustment (width), causing exponent b to be low when compared to that for rivers with less-cohesive sandy banks.

The analysis of the hydraulic geometry data for large rivers (Table 5) permits several conclusions.

a) Exponent b is very low, in general less than or close to 0.1 and indicates only a slight increase in width with discharge.
b) The highly sinuous single-thread meandering rivers (Purus and Jurua) have high values of depth exponents (f), averaging 0.54, and indicating that these rivers increase significantly in depth with increasing discharge. The banks are formed mainly by cohesive sediments (clayey silty sediments dominants), and in some places include older resistant alluvium.
c) For meandering rivers that generate scrolled floodplains and arcuate meanders, such as Iça, Paraguay and Mamoré (Fig. 4D–F), a greater increase occurs in velocity m as discharge increases.
d) In low anabranching-low sinuosity rivers, exponent m reaches as high as 0.69 in the Madeira at Porto Velho, and for all the stations the average is 0.64. Depth increases more slowly in relation to velocity with values of f averaging 0.31.
e) The Amazon shows a more intermediate response for m and f. Three stations of the Amazon display a similar response (Santo Antonio do Iça, Teresina and Manacapuru), as velocity and depth similarly increase to approximately 0.47 and 0.49, respectively. Width remains nearly constant as water discharge increases. In the Amazon at Jatuarana, velocity increases to a rate of 0.65 while depth increases with an exponent of 0.3. At the Itapeua gauging station the velocity exponent m is as high as 0.71, while exponent f is only 0.2. This situation is likely influenced by the reach-scale specific geomorphic characteristics of these areas, where the channel is narrow and controlled by stable levees on the left bank and older alluvia on the right bank in the Itapeua area, as well as the large alluvial Careiro Island located at the confluence of the Solimões–Amazon with the Negro for example.

6. Effective discharge for sediment transport and channel geometry for large rivers

For many years bankfull discharge (Q_{bf}) has been considered the standard parameter to estimate effective or dominant flows that transport the most sediment, and thereby control the morphology of the channel. The return period for bankfull discharges has been observed in many rivers to average between 1 and 2 years, and mean annual floods (Q_{maf}) have been shown to occur with a return period of 2.33 years (Leopold et al., 1964).

Studies on large rivers, however, demonstrate that the effective (Q_{ef}) or synonymous dominant discharge occurs below bankfull stage, and that extremely large floods do not significantly change the channel or floodplain morphology. Details of the methodology to calculate effective discharge can be founded in Biedenharn et al., (1999). On the Brahmaputra (Thorne et al., 1993) and lower Mississippi (Biedenharn and Thorne, 1994) effective discharge (Q_{ef}) was shown to approximate a “bar full” stage that represents the elevation at the tops of channel bars and not bankfull stage. Additional results from Parana River (Amsler et al., 2005) and Araguaia River are in agreement and indicate that “bar full” stage or less than bankfull discharge is the most effective for the transport of bed sediments (Aquino, 2007).

Table 6 shows data from the Parana, Brahmaputra, Araguaia, and the Lower Mississippi Rivers. Effective discharges in these large rivers exceed Q_{mean} (mean annual discharge) and, in general, are less than bankfull discharge. It is interesting to note that the four rivers have different channel patterns, different hydrological regimes (monsoonal for the Brahmaputra, tropical dry–wet for the Araguaia, and a variety of environments for the Parana and Mississippi), as well as very different geology and topography.

Effective discharge relates well to channel morphology, but it is also associated with one of the more important and problematic aspects of large rivers: bed load. Channel processes that generate the most conspicuous channel changes are related to sand transported as bed load and suspended load. Large rivers can transport very large amounts of sand in suspension. For example, in the lower Mississippi River suspended sand was estimated to be 95% of the total transported “bed material load” (Biedenharn and Thorne, 1994), 91% in the Parana River (Amsler and Prendes, 2000) and 92% in the Araguaia River (Aquino, 2007).

7. Discussion

The preceding analysis illustrates that large rivers are unique, and many of them have anabranching channel patterns. Large rivers have very low slopes and relatively fine-grained sandy (medium to fine

Table 6

River	Q_{mean} (m^3/s)	Qeffective (m^3/s)	Qbankfull (m^3/s)
Lower Mississippi downstream Vicksburg	~17,000	~30,000	~35,000
Middle Parana at Corrientes	21,490	24,467	27,330
Brahmaputra at Bahadurabad	~21,200	38,000	~60,000
Middle Araguaia at Aruaná	1170	1700	3200

sand) bed load. As response to adjustments to changes in discharge at a cross-section, width remains remarkably constant in analysis of hydraulic geometry.

Large alluvial rivers have very low slopes, <0.00015, for greater than a thousand kilometers upstream of the ocean. To transport high discharge and sediment loads over such great distances with low gradients, the system maximizes efficiency by limiting channel width and maximizing flow depth and velocity. As proposed by Nanson and Huang (1999) and Huang and Nanson (2007), this can be achieved by the introduction of islands. Considering the limitations of slope adjustments, large rivers hydraulically force discharge and sediment transport.

Considering that hydraulic geometry is related to discharge some conclusions can be raised. The results illustrate that rivers with a Q_{mean} of ~17,000 m^3/s generate either single thread or anabranching channels. Beyond this threshold, only anabranching systems can achieve efficient ways to move water and sediment over exceptionally low gradients. In mega rivers with Q_{mean}>17,000 m^3/s, slope is typically less than 0.00007 and in many places less than 0.00003 to values close to 0 (zero). In this extreme condition, the rivers do not generate meanders.

If applying the concept of a channel pattern continuum, straight, meandering and braided, the end member pattern for large alluvial rivers is *anabranching*. Considering the Mississippi River as the ultimate meandering channel, no additional "pure" meandering single channel rivers exist with a mean annual discharge>~17,000 m^3 s^{-1}. These systems were classified in this paper as "mega" rivers, with a threshold Q_{mean}, available for all rivers.

When analyzing large rivers with >1000 m^3/s, several interesting conclusions can be raised.

Most current methods, proposed to discriminate channel pattern based on the analysis of variables such as slope, grain size, bankfull and others, are not useful when applied to large rivers.

The hydraulic geometry, very low slopes, and minor variability of grain size in large rivers indicates that, although meandering patterns are present, intrinsic characteristics of discharge and large *w*/*d* relationships favour the development of anabranching patterns. Additional research is needed, however, to discriminate the variables that control channel pattern. New and additional approaches are needed to classify and understand large anabranching rivers, and the response and mechanisms that control the generation of multiple river branches.

Considering that *w*/*d* ratios are high for the different channels patterns, additional methodological alternatives to this parameter should be developed. In particular it would be useful to relate this approach with effective discharge, taking account of the geomorphologic importance of bar full and bankfull discharges, and channel–floodplain interactions.

8. Final comments

Because of the close association between channel style, floodplain morphology, and alluvial architecture, it is important to understand the mechanisms that generate floodplains in large rivers. During recent decades, facies models were built on the basis of a few active fluvial systems, and in many cases from small to medium size rivers. Present-day analogues of fluvial models used for understanding ancient sedimentary sequences remain poorly developed and are incomplete (Miall, 1996, Latrubesse et al., 2005). Nevertheless, one of the implications of this study concerns modeling. The results from this analysis clearly suggest that it is not yet possible to "scale up" from data sets developed on small rivers or laboratory flumes to the extensive "mega" rivers considered in this study. Indeed, a major constraint to understanding older fluvial sequences is that the theoretical and empirical base of knowledge of fluvial geomorphology was built on extensive data sets of much smaller rivers, and a poor set of geomorphologic information exists for large rivers. It is fundamentally important that conceptual and quantitative models be developed for large river systems from field based data sets.

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