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Tropical rivers

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Abstract

This paper presents an overview of tropical river systems around the world and identifies major knowledge gaps. We focus particularly on the rivers draining the wet and wet–dry tropics with annual rainfall of more than 700 mm/year. The size of the analyzed river basins varies from 10^4 to 6×10^6 km^2. The tropical rivers across the globe drain a variety of geologic–geomorphologic settings: (a) orogenic mountains belts, (b) sedimentary and basaltic plateau/platforms, (c) cratonic areas, (d) lowland plains in sedimentary basins and (e) mixed terrain. All of them show clearly high but variable peak discharges during the rainy season and a period of low flow when rainfall decreases. Some tropical rivers show two flood peaks, a principal and a secondary one, during the year. We computed the intensity of floods and discharge variability in tropical rivers. The relationship between sediment yield and average water discharge for orogenic continental rivers of South America and Asia was also plotted. Insular Asian rivers show lower values of sediment yield related to mean annual discharge than continental orogenic rivers of Asia and South America. Rivers draining platforms or cratonic areas in savanna and wet tropical climates are characterized by low sediment yields. Tropical rivers exhibit a large variety of channel form. In most cases, and particularly in large basins, rivers exhibit a transition from one form to another so that traditional definitions of straight, meandering and braided may be difficult to apply. In general, it is more useful to apply the terminology of single and multi-channel systems or complex anabranching systems at least for selected regional segments.

Present-day knowledge of tropical systems and its potential application to improve interpretation of older alluvial sequences and facies models are briefly discussed. Human impact and river management issues including land use changes, mining, dams, interbasin water transference as well as flood hazards are some of the daunting problems in tropical river basins today.

Keywords: Tropical rivers; Channel patterns; Sediment transport; River management; Hydrology

1. Introduction

An enormous growth has occurred in fluvial geomorphology during the recent decades. River systems in northern and southern hemispheres have been

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studied in a variety of climatic settings ranging from temperate, glacial and humid tropical areas to semi-arid and arid regions. Large tropical rivers in different parts of the world have attracted particular attention and a range of subjects have been investigated including geomorphology (e.g. Coleman, 1969; Sabat, 1975; Tricart, 1977; Baker, 1978; Pickup, 1984; Pickup and Warner, 1984; Tricart et al., 1984; Iriondo, 1987, 1993; Drago, 1990; Thorne et al., 1993; Mertes, 1994; Winkley et al., 1994; Mertes et al., 1996; Sinha, 1996; Stevaux, 1994; Dunne et al., 1998; Goswamy, 1998; Gupta et al., 1998, 2002; de Souza et al., 2002; Dietrich et al., 1999; Latrubesse and Franzinelli, 2002; Latrubesse and Stevaux, 2002; Ramonell et al., 2002), sedimentological and hydro-sedimentological processes (Smith, 1986; Bristow, 1987; Nordin and Perez Hernandez, 1989; Santos and Stevaux, 2000; Vital and Stattegger, 2000; Warne et al., 2002), flood and paleoflood hydrology (Ely et al., 1996; Sinha and Jain, 1998; Baker, 1998; Dhar and Nandargi, 2000; Kale, 1998; Paoli and Schreider, 2000; Latrubesse et al., 2002) and tectonic/fluvial processes relationships (Sternberg, 1950; Iriondo and Suguio, 1981; Dumont, 1993; Dumont and Fournier, 1994; Franzinelli and Igreja, 2002; Latrubesse and Rancy, 2000). Bearing in mind the large extent of the tropical regions and the size of the rivers themselves, however, the knowledge base of the tropical rivers is still limited. The aim of this paper is to present an overview of tropical systems around the world and identify the major knowledge gaps. We focus particularly on the rivers draining the wet and wet–dry tropics with rainfall more than 700 mm/year. The size of the river basins considered in the paper varies from 10^4 to 6×10^6 km^2. Hydrological data were obtained from internet data bases as for example www.gdrc.sr.unh.edu and from National Agencies such as ANA (National Agency of Water, Brazil) and CWC (Central Water Commission) India.

2. The wet and wet–dry tropics

Geographically, the tropical regions are roughly bounded by the Tropics of Cancer (23°27′N) and Capricorn (23°27′S) (Fig. 1). A great amount of solar energy in this region creates a climate without strong winters. The sun is at high angles, and therefore, only a minor diurnal variability exists from 12 to 13 h. Temperature shows a consistent variation from day to night and from summer to winter across the tropical region. Some dry areas have higher temperatures as a result of intense surface radiation. Annual temperature ranges depend upon the duration of the dry season: where no dry season occurs, the mean monthly temperature can vary within 1–2 °C. Solar energy influences the hydrological cycle more directly in the tropics than in other regions of the

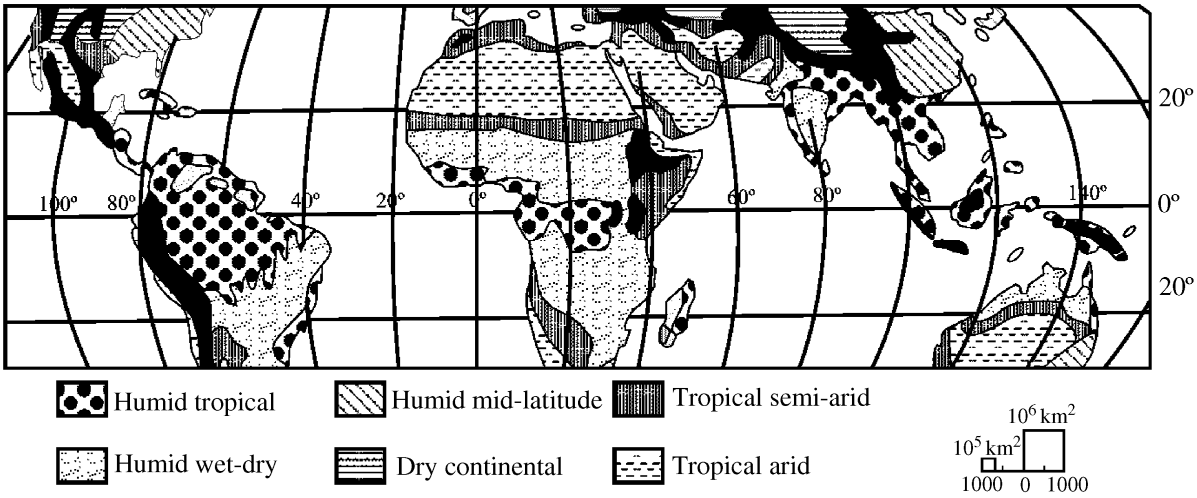

Fig. 1. Climatic zones in the tropics.

planet. In tropical areas, rainfall is the main factor that determines the seasons, and therefore, the quantity and temporal distribution of rainfall are important criteria to distinguish sub-climatic zones viz. wet (>1800 mm), wet–dry (700–1800 mm) and dry (<700 mm).The focus of this paper is on the rivers flowing through wet and wet–dry climatic zones, including those in a monsoonal regime.

The convergence of airflows into the Equatorial trough is called the Intertropical Convergence Zone (ITCZ). The ITCZ is characterized by the cancellation of the opposite effects in the wind patterns known as easterlies (Balek, 1983). Typical of both sides of ITCZ is the reversal of the wind direction and changes in temperature and humidity. The annual movement of the overhead sun produces migration of the ITCZ during the year from north to south which in turn affects tropical wet climates (Mc Gregor and Nieuwolt, 1998). During summer in the northern hemisphere, the center of the ITCZ moves to a position 10–20°N of the Equator. The greatest movement is over Africa and the Eastern part of the Indian Ocean (Fig. 1) where it moves between the Tropic of Cancer in July and the Tropic of Capricorn in January.

Probably the most variable element of tropical climate is rainfall (Mc Gregor and Nieuwolt, 1998). Three types of rainfall are identified in the tropics: convectional, cyclonic and orographic. Wet tropical climates are characterized by temperatures ranging from 24 to 30 °C with an annual oscillation of about 3 °C. In general, total rainfall fluctuations from year to year in tropical lowlands are relatively small compared with monsoonal regions and those areas dominated by orographic conditions. Typical annual rainfall in the wet tropics is close to 2000 mm/year. In some areas, however, it can reach 14,500 mm/year as recorded in Mount Cameroon in West Africa (Hidore and Oliver, 1993) and 10,000 mm/year in the Chocó forest of Colombia. Rainfall frequency and intensity in tropical regions are also quite variable. For example, Duitenzorg in Java has 322 days per year with intense and brief thunderstorms, while Rio Branco in Southwestern Brazilian Amazonia has a total rainfall of only ~100 mm spread over three months from June to August.

The typical vegetation of tropical wet climate areas is evergreen rainforest. Forest distribution is also regulated by the shift of the ITCZ; where the ITCZ shift is maximum, the rainforest is less high and other types of transitional vegetation units appear. Altitude also is an important factor controlling the distribution of the rainforest because temperature decreases with altitude. Rainforests generally develop at altitudes of up to~1000 m above which highland vegetation is represented by shorter trees and fewer species.

Wet–dry climates are characterized by very pronounced rhythmic seasonal moisture patterns. Tropical wet–dry climates occur peripheral to tropical rainforest environments. The Cerrado, Llanos and Chaco are typical wet–dry climatic areas of South America. In areas north and south of the Congo basin and in much of southeast Asia and part of the Pacific Islands, large and extensive belts of tropical wet–dry climate occur. The alternation of marine tropical and continental air masses dominates the seasons in these climates, where average annual precipitation varies from place to place with a general increase seasonally away from the equator, with the maxima occurring in monsoonal regimes. In Rangoon, Burma, average precipitation during the three months of the winter is 25 mm compared with a summer rainfall average of 1800 mm. The extreme values of seasonality come from Cherrapunji, NE India, with 4050 mm of precipitation in 5 days and a total winter precipitation of 25 mm (Hidore and Oliver, 1993). Monsoonal rain affects most of India, Thailand, Vietnam, southwestern Sri Lanka, west coast of Burma, Malaysia, north Australia and Sierra Leone (Balek, 1983).

3. Geologic and geomorphologic setting of tropical river basins

The tropical rivers across the globe drain a variety of geologic–geomorphologic settings namely (a) orogenic mountains belts, (b) sedimentary and basaltic plateau/platforms, (c) cratonic areas, (d) lowland plains in sedimentary basins and (e) mixed terrain (Table 1 and Fig. 2).

Orogenic mountain belts are linear features generated mainly in the Cenozoic by plate convergence tectonics. They are characterized by high relief, intensive seismic activity and, in some cases, igneous activity (volcanism and plutonism). Such regions comprise part of the Andean Chain in South

Table 1
Geologic and geomorphic setting of tropical rivers of the world

Category/description	Examples
A. Orogenic belts–linear fluvial belts: rivers with headwaters in active orogenic belts, basin linear in shape	
(a) Encased in rocky terrain but poorly developed alluvial plain (only in lower reaches)	Mekong, Irrawady, Fly
(b) Wide and extensive alluvial plains after debouching from the mountain front	Ganga, Yamuna
(c) Subsidence foreland areas, anastomosing pattern, high vertical aggradation systems	Magdalena
(d) Avulsive systems: highly dynamic rivers, very unstable channels, normally meandering, high in suspended load, muddy banks?	Baghmati, Beni
B. Alluvial fans: rivers forming large fans in the alluvial plain	
(a) Foreland setting: most parts lying in foreland	Kosi, Gandak, Pastaza
(b) Intracratonic: most parts lying in the intracratonic basin	Pantanal (Taquari, Cuiaba, etc.)
(c) Complex: fan spreading into different settings such as foreland and lowland plains	Pilcomayo
C. Platforms/plateau: river draining dominantly platform areas, bedrock channels, with incised valleys and rapids, bed-load dominant	Decan Plateau rivers, Uruguay
D. Cratonic areas: headwaters in low relief areas of stable Precambrian crystalline basement	
(a) Bedrock channels, with incised valleys and rapids, bed-load dominant, v. low suspended load, fragmented, narrow alluvial plain in lower reaches	Zambese, Betwa, Chambal
(b) Blocked valley, flooded . . . . bed-load dominant, v. low suspended load	Tapajos, Xingu
(c) Wide valleys with islands alternating with narrow reaches with rapids or nodal points, bed-load dominant, v. low suspended load	Congo, Negro
E. Lowland plains: single channel, non-harmonic meanders, muddy banks, high suspended load	Purus, Jurua, Baghmati, Burhi Gandak
F. Mixed: rivers draining mixed terrain	
(a) Platforms + cratons: mainly braided alternating with incised valleys, bed load dominant	Araguaia
(b) Orogenic + platforms + cratons: complex systems, mainly braided, low anabranching, rapids alternating with wide alluvial reaches, high sediment load (bed load + suspended load)	Orinoco, Madeira
(c) Orogenic + lowlands: well-defined headwater areas in orogenic belts and narrow alluvial plains, mixed morphologies (braided/meandering)	Japura, Ica, Mamore

America, the Himalaya and the island arcs of Sunda and New Guinea. Reactivated older Mesozoic and Paleozoic belts of southwestern Asia, South America and northwest Australia are also included in this category.

Plateau and platforms include the Paleozoic and Mesozoic sedimentary basins of central and northern Brazil, the Decan Plateau in India and central Africa. Plateaus are relatively stable areas that experienced some uplift during the Cenozoic and some were formed mainly by sub-horizontal sedimentary rocks and extensive basaltic lava flows.

Cratons or continental shields are areas of moderate to low elevation formed by Precambrian plutonic and metamorphic rocks, characterized by absence of any sedimentary cover. This group includes the Brazilian and Guyana shields in South America, the crystalline basement of Peninsular India, the African Shield and part of northern Australia.

Lowland plains of Cenozoic sedimentary basins include foreland active basins associated with orogenic belts such as in parts of the South American, Andean basins and in the Indo-Gangetic plains. The flat areas of sedimentary basins occur in the Western Amazon Depression, Eastern Amazon Plateau and Central African plateau in the Congo Basin. Large rivers, however, cross forelands and intracratonic or platform basins as in the case of the Amazon system or the Chaco plains. Rivers that drain different types of terrain are included in the 'mixed' category.

4. Hydrology of tropical rivers

Among the 10 largest rivers in the world[1] in terms of water discharge, eight of them are tropical rivers viz. the Amazon, Congo, Orinoco, Brahmaputra,

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[1] Amazon, Congo, Orinoco, Yang Tse, Madeira, Negro, Brahamaputra, Japura, Paraná, Mississippi.

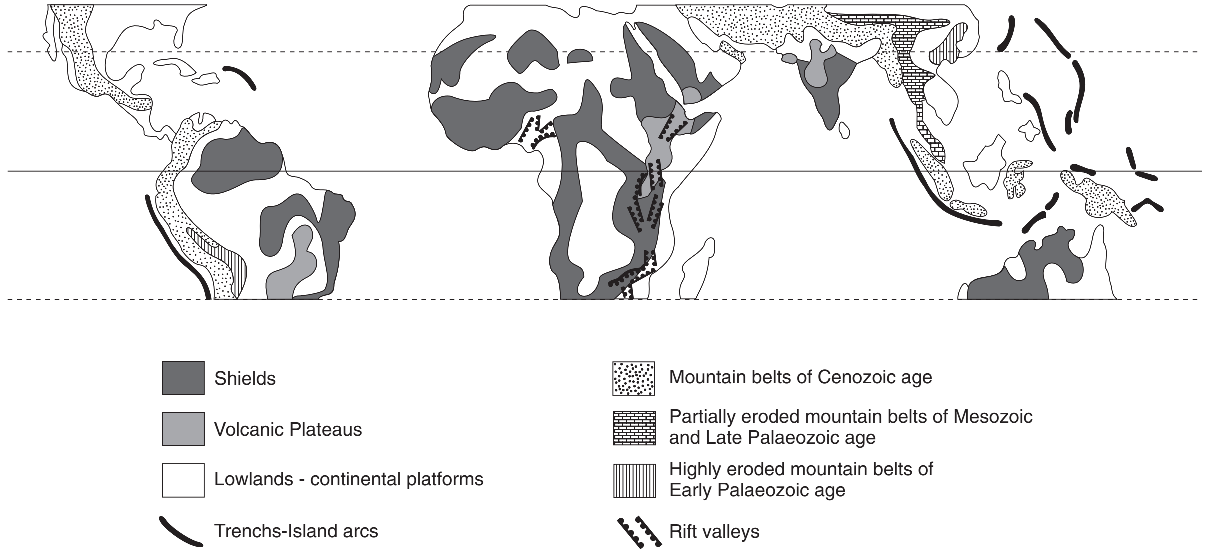

Fig. 2. Main geotectonic domains. Dotted lines indicated the localization of Tropics of Cancer and Capricorn.

Parana and three tributaries of the Amazon River system: Negro, Madeira and Japura rivers. For this paper, we have considered mainly tropical rivers with a catchment area of more than 10,000 km^2 and with a precipitation of more than 700 mm/year (Table 2). Therefore, some of the large river systems like the Niger and São Francisco, which cross dry tropical areas, are not included in this study. Nevertheless, the focus is on medium to large size basins, but some minor basins were also included mainly for the analysis of water discharge/sedimentary load.

Because of the great complexity of tropical climates and the large extent of tropical river basins, it is impossible to establish a unique regime for tropical rivers. Many authors have proposed different regime classifications for tropical rivers on the basis of rainfall distribution (rivers fed in summer or autumn) such as pluvial, glacial and mixed regimes. In general, rivers draining tropical rainforest, such as Purus, Madeira, Negro, Mekong and Irrawaddy, have more or less similar behavior compared to rivers draining tropical dry–wet savanna or monsoonal areas. All rainforest rivers show high but variable peak discharges during the rainy season and a period of low flow when rainfall decreases. Some tropical rivers, such as the Congo, Ogooue or Magdalena, show two flood peaks during the year, one principal and other secondary. Fig. 3 shows mean monthly discharge for some large tropical systems. Mean monthly discharges were normalized in relation to Q_{mean} (mean annual discharge) to facilitate comparison of different systems. In general, we can group the rivers in two main types: (a) rivers with well-defined high and low discharges in agreement with unimodal rainy periods, e.g. Godavari, Mekong, Ganges, Purus; and (b) rivers with two flood peaks per year, in agreement with bimodal rainy periods in summer (main) and fall (secondary), e.g. Magdalena, Congo.

We characterized the discharge variability of the river systems using the ratio between the maximum and minimum daily discharges ($Q_{\mathrm{max}}/Q_{\mathrm{min}}$) based on the available historical record. The monsoonal climate in India is characterized by high discharge variability with a period of high flood peaks during the summer monsoon and very low discharge during the remaining months. Many of the rivers in the Gangetic plains in India show discharges 40–50 times greater during the monsoons than those of the non-monsoon months (Sinha and Friend, 1994; Sinha and Jain, 1998). Extreme values can be found in rivers in central India.

Contrary to general belief, some rivers draining the tropical rainforest also show a marked variability,

Table 2

River	Country to the mouth	Mean annual discharge (m^3/s)	Drainage area (10^3 km^2)	Annual Q_s (Mt/year)	Sediment yield (tons/km^2 year)
Amazon[a]	Brazil	209 000[b]	6000	1000[c]	167
Congo[d]	Zaire	40 900	3700	32.8[e]	9
Orinoco[f]	Venezuela	35 000[c]	950	150[c]	157.8
Madeira[a]	Brazil	32 000[b]	1360	450[g]	330
Negro[a]	Brazil	28 400[b]	696	8[b]	11.5
Brahmaputra	Bangladesh	20 000	610	520	852.4
Japura[a]	Brazil	18 600[b]	248	33[b]	133
Paraná	Argentina	18 000[h]	2600	112[h]	43
Mekong	Vietnam	14 900	810	160[e]	197.5
Irrawady	Myammar	13 600	410	260[e]	634
Tapajos[a]	Brazil	13 500[b]	490	6[b]	12.2
Ganges	Índia	11 600	980	524	534.7
Tocantins[i]	Brazil	11 800	757	58	76.6
Kasai[d]	Zaire	11 500	861.8	–	–
Purus[a]	Brazil	11 000[b]	370	30[b]	81
Marañón[a]	Peru	10 876[j]	407	102.4[j]	251.6
Oubangui[d]	Congo	9900[k]	550.7	–	–
Xingu[a]	Brazil	9700[b]	504	9[b]	17.8
Ucayali[a]	Peru	9544[j]	406	124.6[j]	306.9
Salween	Myanmar	9510	325	100[e]	307.7
Madre de Dios/Beni[a]	Brazil/Bolivia	8920	282.5	165	584
Ica[a]	Brazil	8800[b]	143.7	19	132.2
Jurua[a]	Brazil	8440[b]	185	35[b]	189.2
Mamore[a]	Brazil/Bolivia	8255[b]	589.5	80[b]	135.7
Guaviare[f]	Venezuela	8200[l]	114.2	30[l]	678.3
Magdalena	Colombia	7200[m]	257	144[m]	544.7
Zambezi	Mozambique	6980	1400	48	34.3
Araguaia[i]	Brazil	6100	377	18	
Caroní[f]	Venezuela	5000[l]	93.5	2[l]	21.3
Fly	New Guinea	4760	64.4	70[k]	1087
Uruguay	Argentina/Uruguay	4660	365	6	16.4
Meta[f]	Venezuela	4600[l]	105.4	80[l]	759
Napo[a]	Peru	4595	122	22.4[j]	183.6
Caura[f]	Venezuela	4000[l]	47.3	2[l]	42.2

[a] Rivers of the Amazon basin.
[b] Filizola (1999).
[c] Meade et al. (1983).
[d] Rivers of the Congo basin.
[e] Meade (1996).
[f] Rivers of the Orinoco basin.
[g] Martinelli et al. (1993).
[h] Amsler and Prendes (2000).
[i] Rivers of the Tocantins basin.
[j] Gibss (1967).
[k] Milliman et al. (1999).
[l] Nordin et al. (1994).
[m] Restrepo and Kjerfve (2000).

similar to some of the savanna environments. Some tropical rainforest rivers, such as the Purus and Juruá, show similar values of discharge variability or more than rivers draining savannas, such as Tocantins, or mixed environments, such as Magdalena, or Paraná.

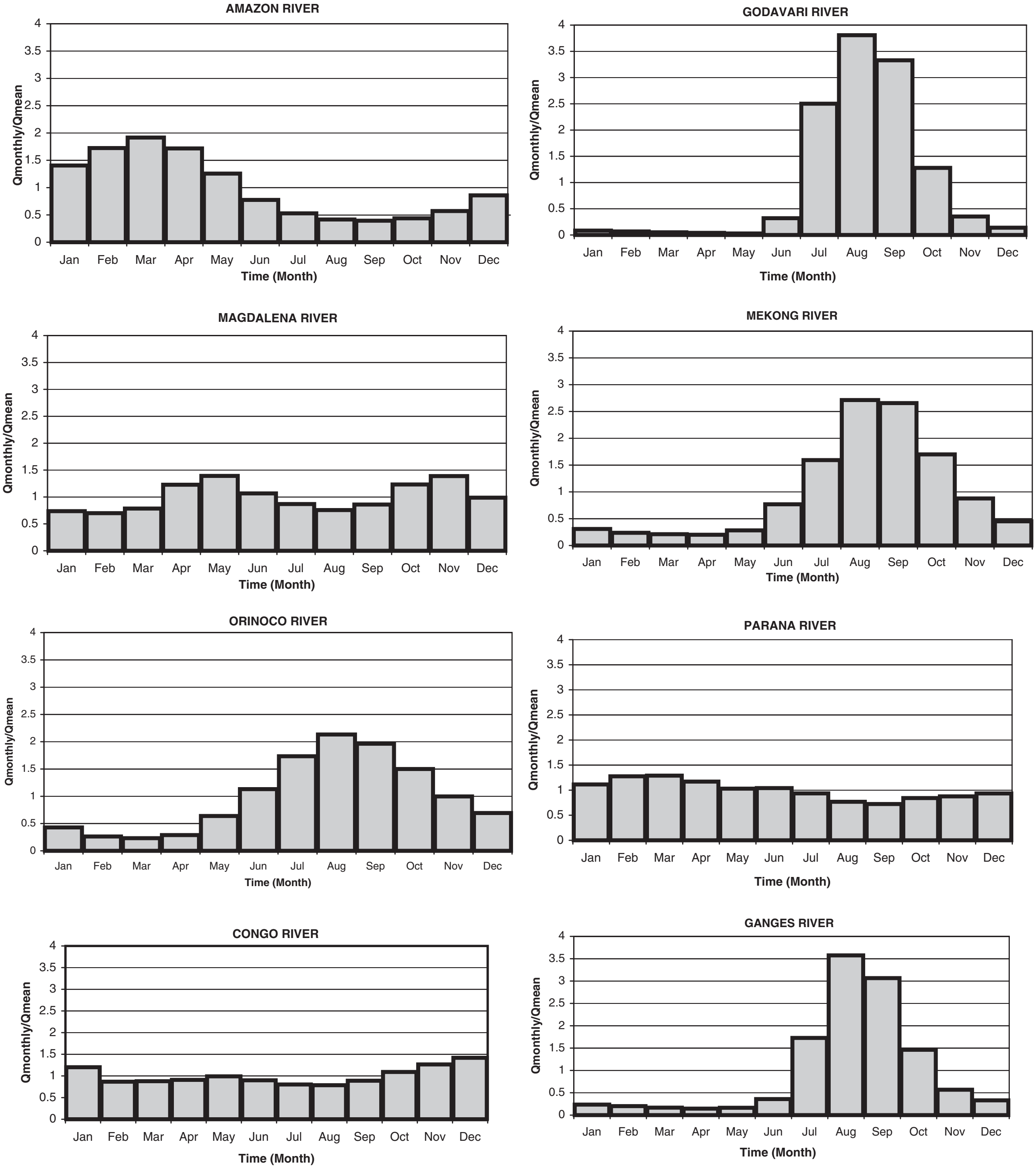

Fig. 3. Normalized mean monthly discharge in relation to mean annual discharge ($Q_{\mathrm{monthly}}/Q_{\mathrm{annual}}$ mean) for selected large tropical rivers.

We also computed the ratio between the highest daily and mean annual discharges ($Q_{\max}/Q_{\mathrm{mean}}$) to indicate the intensity of floods in tropical rivers in different regimes. Although the ratio of maximum discharge to mean annual flood ($Q_{\max}/Q_{\mathrm{maf}}$) is more commonly used to characterize flood regimes, we have used Q_{max}/Q_{mean} because of the easy availability of such data. Fig. 4 plots Q_{max}/Q_{mean} versus the Q_{max}/Q_{min} ratio and some interesting observations emerge from this plot:

1. The rivers with high discharge variability (Q_{max}/Q_{min}) also correspond to high flood regime characterized by high Q_{max}/Q_{mean} ratios. Considering that river systems with drainage areas larger than 10,000 km^2 have been included in this data set, drainage area is not a primary factor controlling extreme flows and flood variability.
2. Further, the river basins from rainforest basins generally show low values of Q_{max}/Q_{mean} and Q_{max}/Q_{min} ratios with a marked increase for rivers draining savanna-dominated environments. The intermediate group also includes large complex tropical basins draining areas with more than one climatic zone, e.g. Orinoco, Madeira, Tocantins, Brahmaputra. They show a trend similar to basins that cross more than one climatic belt in temperate areas of western Europe, Siberia and the northern systems of North America (Canada and Alaska).
3. More irregular discharge variability is shown for semiarid to arid systems as reflected in high values of Q_{max}/Q_{min} (Fig. 4). Extremely arid systems are not included in this comparison because the minimum value of discharge in such cases is zero.
4. Tropical perennial rivers, such as the rivers draining from the Andes to the Chaco plain, show high variability, attaining values of Q_{max}/Q_{mean} as high as 150 (e.g. the Pilcomayo) and 190 (e.g. the Bermejo). In reality, these rivers cross mountain forest areas with orographic rainfall in the sub-Andean zone and the semiarid Chaco plain. This results in high discharge variability.
5. More extreme regimes are recorded in the monsoonal systems of Peninsular India. During the summer monsoon, the Peninsular Indian rivers show extreme high peak discharges when compared to the extreme

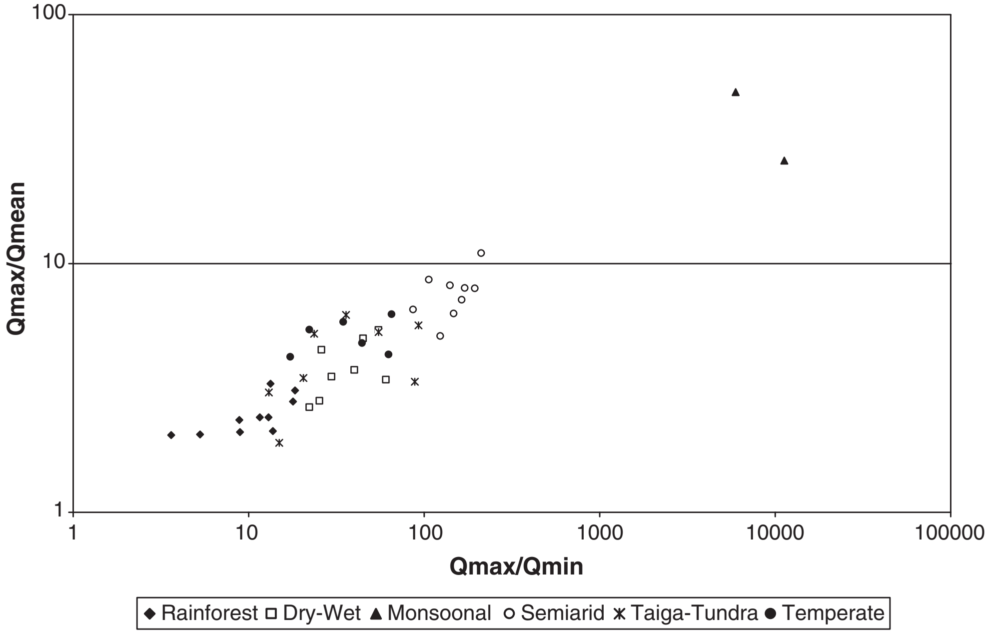

Fig. 4. Discharge variability for rivers in different hydrologic/morphoclimatic zones (for large basins was considered the dominant climate). In the abscise (x) was plotted the Q_{max}/Q_{min} ratio (ratio of maximum and minimum daily discharge values for the historical available series) and in the ordinates (y) was plotted the Q_{max}/Q_{mean} ratio (the ratio between maximum daily discharge and mean annual discharge for the historical available series). (◆) Rainforest = Congo, Juruá, Madeira, Purus, Magdalena, Upper Paraná, Ogooue, Irrawady, Brahmaputra. (□) Dry wet=Mamoré, Orinoco, Tocantins, Sanaga, Uruguay, Upper Xingu, Araguaia, Ganges. (▲) Monsoonal of Peninsular India = Narmada, Godavari. (○) Semiarid = Douro, Colorado (Texas), Ebro, Colorado (Arizona), Pilcomayo, Trinity, Murray, Bermejo, Grande Santiago. (∗) Taiga/Tundra = Obi, Columbia, Mc Kenzie, Nelson, Yenisei, Pékora, Amur, Lena. (●) Temperate = Dnepr, Seine, loire, Vistula, Dvina, Volga.

low flows for the rest of the year. Peninsular Indian rivers plot very far from any other fluvial system, having extreme variability.

Tropical fluvial regimes are also affected by the 2–7 years of recurrence the El Niño-Southern Oscillation (ENSO). Recent studies have demonstrated that annual discharge of the Amazon (Molion and de Moraes, 1987; Richey et al., 1989) and Congo Rivers are weakly and negative correlated with the equatorial Pacific SST (sea surface temperature) anomalies with 10% of the variance in annual discharge produced by ENSO (Amarasekera et al., 1997). On the other hand, in the Parana basin, river discharge shows a positive relation (Amarasekera et al., 1997), which can increase flood size as well as increase flood duration (Depetris and Kempe, 1990; Paoli and Cacic, 2000). The Asian monsoon system is also closely linked to ENSO events. Many of the large floods in Peninsular India have been related to increased monsoonal rainfall and cold ENSO events (Kale, 1999; Hire, 2000).

5. Sediment transport

Basins situated in high relief, active orogenic belts have very high sediment production (Fig. 5). Rivers draining the orogenic belts of southern Asia and high elevation islands in the East Indies are responsible for more than 70% of the sediment load entering the oceans (Milliman and Meade, 1983). The relatively small drainage basins of the East Indies (Sumatra, Java, Borneo, Celebes and Timor), representing about 2% of the land area draining into the ocean, with high topographic relief, relatively young and erodible rocks and tropical wet climates, discharge about 4200 million tons of sediment annually (Milliman et al., 1999). This is equivalent to 20–25% of the global sediment transfer to the oceans. The Himalayan rivers also transport a large quantity of sediments: major basins, such as the Brahmaputra and the Ganges, are the largest sediment producing basins and annually transport 900–1200 million tons of sediment. Smaller basins, such as the Kosi and Gandak for example,

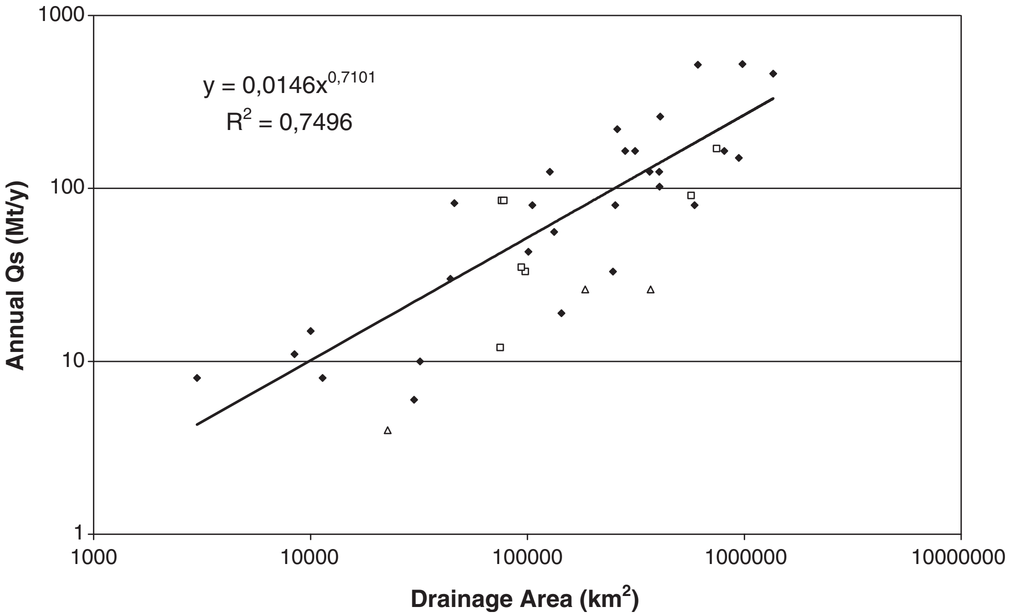

Fig. 5. Annual suspended sediment load (Q_s) versus drainage area. The correlation is indicated for orogenic continental rivers. Many orogenic continental rivers plot above Insular Asia Rivers (which is considered a highly productive area of sediments) and lowlands rivers of southwestern Amazonia drain sedimentary lowlands totally covered by rainforest and also produce abundant sediment load. Orogenic continental rivers: (◆)=Ganges, Brahmaputra, Buhri Gandak, Kamla-balam, Mahakam, Yamuna, Gomti, Ramganga, Gandak, Kosi, Baghmati, Gahghra, Mekong, Irrawady, Madeira, Mamoré, Beni-Madre de Dios, Japurá, Içá, Ucayali, Marañón, Orinoco, Meta, Guaviare, Bermejo and Magdalena. Insular Asia rivers: (□)=Fly, Mahakam, Sepik, Java, Borneo, Celebes and New Guinea (sum per island). Southwestern Amazon lowland meandering rivers: (△)=Purus, Juruá and Acre.

have a sediment production of 190 and 80 million tons/year, respectively.

Production of sediments is also very high in the Andes of South America: with a drainage area of 257,000 km^2, the Magdalena, which drains the Colombian Andes, contributes 144 to 220 million tons of suspended sediment to the Caribbean sea (Milliman and Meade, 1983; Restrepo and Kjerfve, 2000). The Madeira basin contributes around 50% of the total suspended load transported by the Amazon river (estimated values ranging between 600 and 248 million tons/year) (Meade, 1994; Martinelli et al., 1993; Filizola, 1999). The Madeira tributaries, draining the Bolivian and Peruvian Andes, are also characterized by high suspended load and high sediment yields. The sediment load of the Beni basin was estimated at 165 million tons/year, while the Mamoré river contributes 64 to 80 million tons annually (Filizola, 1999; Guyot et al., 1999). More than 90% of the total suspended load of the Amazon system, estimated to be close to 1000 million tons/year, comes from the Andean tributaries.

Fig. 5 shows the relationship between sediment load and drainage area for orogenic continental rivers of South America and Asia. Insular Asian rivers (Java, Borneo, Celebes and New Guinea) show similar to lower values of sediment yield related to mean annual discharge than continental orogenic rivers of Asia and South America. Some lower values of insular rivers could be related to lower relief of the area in contrast to the Himalayan and Andes chain. The available data, however, are in agreement with results obtained by Milliman et al. (1999), which established a good consistency between the values of sediment yield of insular rivers with South Eastern Continental Asian rivers.

The Andean tributaries of the Paraná river also carry high amounts of suspended sediment. With a mean annual discharge of 145 m^3/s, the Bermejo river contributes ~50% (48 million tons/year) of the total suspended sediment transported by the Paraná river ($Q_{\mathrm{mean}} = 18{,}000$ m^3/s). The Pilcomayo River, another tributary of the Paraná with a mean annual discharge of ~300 m^3/s, carries more than 140 millions tons/year of fine sediments but a large quantity of sediments is stored in the Chaco plain before it meets the Parana river. The main difference between insular southeastern Asia systems and Himalayan/Andes tributaries is that the former are short, steep gradient rivers draining directly to the ocean, while the latter are part of larger fluvial networks, such as those of the Amazon, Paraná, Orinoco Magdalena, Ganges and Brahmaputra basins. In large basins, a part of the sediment load is stored in alluvial plains and the rest is transported to the ocean. Further, a number of tributaries from lowland or cratonic/platform areas have much lower sediment discharges for the amount of water discharged. High sediment production in the Himalayan region is favored by monsoonal rains in the source areas. Heavy and intense rainfall, up to 11,000 mm/year, triggers extensive catchment erosion, thereby introducing high amounts of sediments (Froehlich and Starkel, 1993). In South America, the Andes act as an orographic barrier to the incoming air masses from the east, thereby increasing rainfall along the Eastern Andes slope from Venezuela to Argentina. High relief and heavy concentrated precipitation produce high sediment yield in mountainous basins: rainfall can reach more than 6000 mm/year in some parts of the subandean zones of Equator, Peru and Bolivia.

Rivers draining lowland tropical areas totally covered by rainforest can carry also abundant sediment load for example, the Purus, Jurua and Acre rivers that drain the tertiary sedimentary lowlands of southwestern Amazonia (see Fig. 5).

Rivers draining platforms or cratonic areas in savanna and wet tropical climates are characterized by low sediment yield (Fig. 6). Major rainforest fluvial systems, like the Congo, Negro, Tapajos and Xingú, transport rather insignificant amounts of suspended sediment for their large drainage areas and enormous water discharges. For example, with a drainage area of 659,000 km^2 and a mean annual discharge of 29,000 m^3/s, the Negro carries just 8 million tons of suspended load annually (Filizola, 1999) of which large part could be organic matter. The Congo, the second largest river in terms of water discharge ($Q_{\mathrm{mean}} = 40{,}000$ m^3/s), carries approximately 40 million tons of sediments per year (Meade, 1996). Large cratonic Amazon tributaries like the Tapajos, Xingú and Trombetas also carry relatively small quantities of suspended sediments.

Rivers draining platforms, cratonic areas or a combination of different geological domains in savannas or mixed savanna/forest environments, for

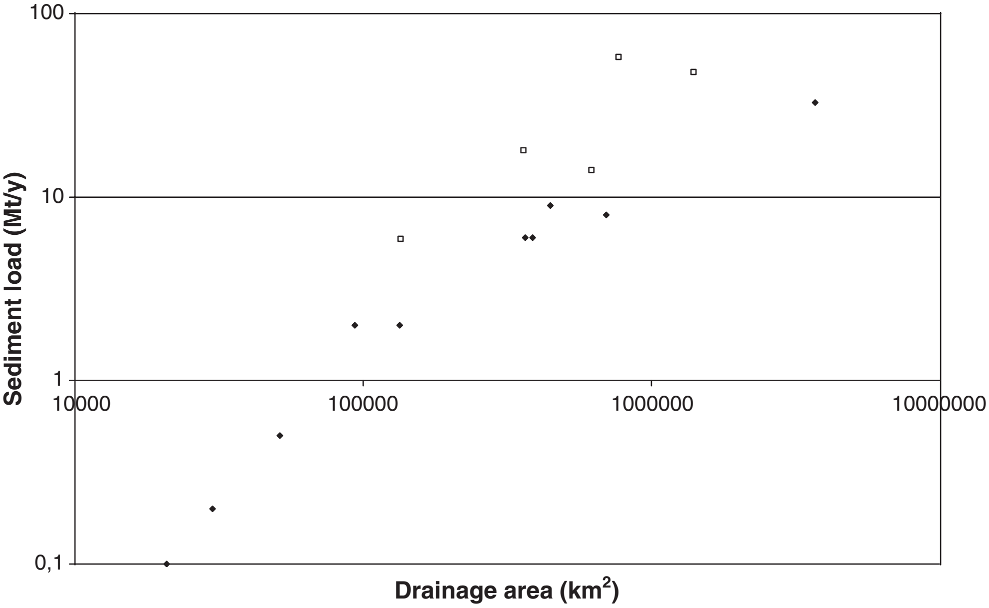

Fig. 6. Wet–dry and rainforest plateau/cratonic rivers: annual suspended sedimentary load (Q_s) versus drainage area. (◆) Rainforest regime dominant = Congo, Tapajós, Trombetas, Negro, Purus Jarí, Purua, Uruguay. (□) Wet–dry regime dominant (mixed vegetation mainly savanna) = Araguaia,, Paraná, Sanaga, Zambese, Tocantins, Xingu.

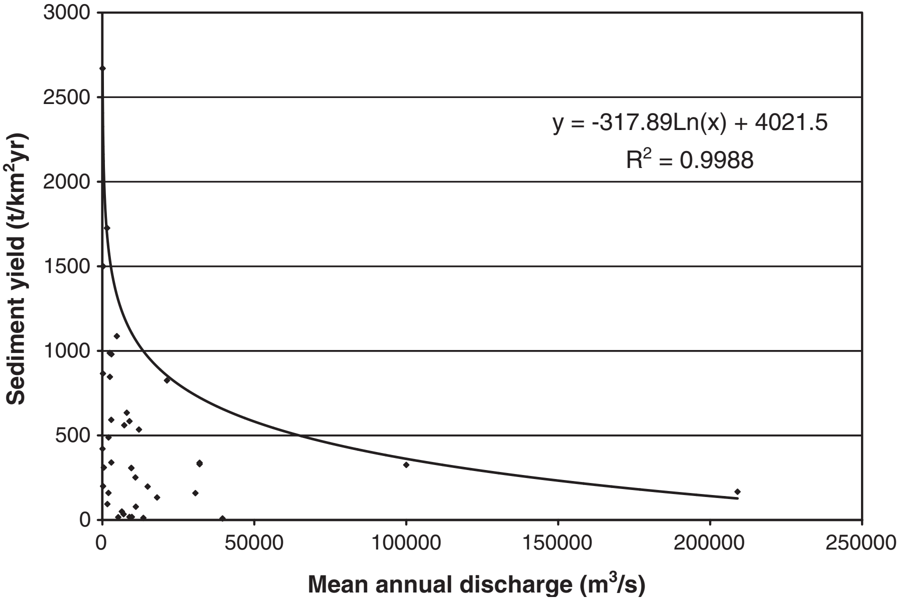

Fig. 7. Sediment yield (tons/km^2 year) versus mean annual discharge (Q_{mean}) for tropical rivers. The envelope curve could indicate a natural threshold of sediment yield in relation to Q_{mean} for present-day rivers. Considering that some of the basins with the highest sedimentary yield were included, probably this envelope curve can be used like a good approximation of universal validity. (◆) = Japurá, Madeira, Purus, Araguaia, Magdalena, Orinoco, Paraná, Bermejo, Uruguay, Sanaga, Amazon (mouth), Congo, Irrawady, Amazon (Manacapurú), Ganges, Brahmaputra, Mekong, Sepik, Fly, Mahakan, Godavari, Buhri Gandak, Kamla-balam, Yamuna, Gomti, Ramganga, Krishna, Gandak, Kosi, Baghmati, Ghaghra.

example the Araguaia-Tocantins, Paraná and Orinoco rivers, show lower sediment yields when compared to tropical mountain rivers but higher values when compared with rainforest cratonic/plateau rivers. Sediment yield versus Q_{mean} are plotted for several tropical rivers across the world (Fig. 7). The logarithmic trend shows that sediment yield is quite variable for medium size basins but decreases sharply for large rivers. Considering that water discharge is related to drainage area, the logarithmic relationship is an indicator of the influence of a natural threshold of sediment yield for fluvial systems.

6. Channel morphology

Tropical rivers exhibit a large variety of channel form. In most cases, and particularly in large basins, rivers exhibit a transition from one morphological form to another so that traditional definitions of straight, meandering and braided may be difficult to apply. The use of empirical equations relating channel morphology to sediment load and morphometric parameters to predict the incidence of channel patterns frequently do not work in tropical rivers (Baker, 1978; Pickup and Warner, 1984). It may be more useful to apply the terminology of single and multi-thread channel systems (Schumm, 1985; Friend and Sinha, 1993) or complex anabranching systems (Nanson and Knighton, 1996) at least for selected regional segments.

Rivers originating in orogenic belts and characterized by very high suspended load (>80%) and much smaller bed load (2–15%) have sinuous channels that are frequent in small to medium size rivers, frequently alternating with straight reaches. In lowland rainforest environments, asymmetric and non-harmonic meanders are typical and indicate a tendency to incise during part of the Holocene: good examples are the rivers draining southwestern Amazonia such as the Purus and Juruá (Latrubesse and Kalicki, 2002) (Fig. 8) and the Fly river in New Guinea (Dietrich et al., 1999). Harmonic meanders, indicating relatively mixed load transport, are more typical of some rivers draining a plateau, such as the Mortes river (a large tributary of the Araguaia river) and the Paraguay river, a tributary of the Paraná. This type of pattern is also exhibited in selected reaches of the Iça river (also called Putumayo), a northern tributary of the Amazon. Alternating single and multi-channel morphologies have been reported from the Ucayali river in Perú (Rasanen, 1993). Both the Yamuna and Ganga rivers in India show isolated meanders in some reaches in between multi-channel reaches (Sinha et al., 2002). The Brahmaputra is a multi-channel system, with moderate sinuosity in selected reaches (Bristow, 1987; Coleman, 1969). Some smaller river systems in the Gangetic plains, such as the Baghmati in north Bihar, have also been described as anabranching systems because of the hyperavulsive behavior even though they are dominantly suspended load rivers (Jain and Sinha, 2003a,b).

Rivers draining plateaus and cratonic areas, such as the Paraná, Araguaia and others, have a lower proportion of suspended sediment in relation to bed load, and they, therefore, develop low sinuosity channels. For example, the Parana upstream of the Paraguay confluence exhibits an anabranching pattern with a tendency to develop islands (Fig. 8). It transports 25% of the total load as bed load (Orfeo and Stevaux, 2002). Two large rivers draining rainforest, namely the Congo and the Negro, display an intricate multi-channel pattern and complex fluvial archipelagoes although transport they a small quantity of sedimentary load (Fig. 8).

Apart from the hydrological controls on channel morphology, two additional factors govern morphological variation in space and time in many rivers at least locally. Neotectonics, often cited as one of the important controls on the geomorphology of fluvial belts, affects channel patterns of large systems around the world. Several studies have utilized the forms of river channels as geomorphic indicators of active tectonics in large rivers (see Schumm et al., 2000 for a synthesis). The Amazon, the Brahmaputra, the Paraná and many other tropical rivers show clear examples of tectonically controlled reaches (Latrubesse and Franzinelli, 2002; Fortes et al., 2005; C. Ramonell, pers. com.). In the Brahmaputra, earthquakes introduce large quantities of sediments, which, consequently, affect the channel morphology (Goswamy, 1998; Bristow, 1987). Many of the smaller rivers in the Gangetic plains have also responded to Himalayan tectonics. Very subtle movements in the Baghmati river plains in north Bihar India have been manifested in frequent avulsion events, with the development of compressed meanders and local slope changes (Jain and Sinha, 2005).

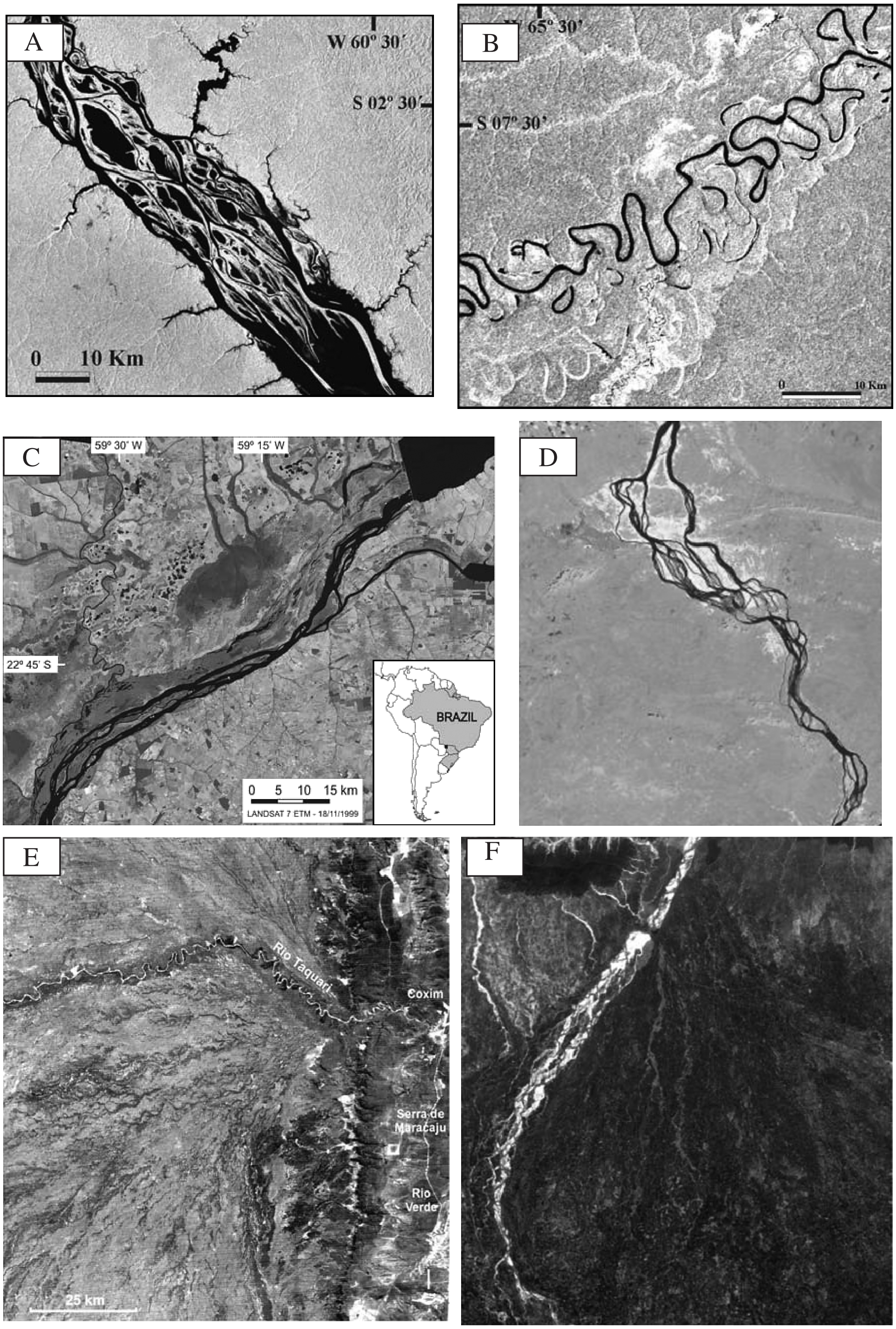

Fig. 8. Channel patterns in tropical rivers: (A) Negro, (B) Purus, (C) Parana, (D) Mekong, (E) Taquari fan, (F) Kosi fan.

Another important control is the basement topography. Many rivers with a relatively thin alluvial cover often cut through to the bedrock in selected reaches which affects the channel morphology. Basement rocks constrain or divide the channels and the alluvial plain, and affect the longitudinal profile of the river. The complex four thousand archipelago in the Mekong basin can be used as a fascinating example of bedrock control on channel pattern (Fig. 8). In the southern Gangetic plains, minor rivers such as Ken and Son also provide clear examples of bedrock control in selected reaches due to isolated exposures of bedrock within the alluvial plains; rock control in between alluvial reaches also characterizes the large Orinoco river.

7. Fluvial processes, landforms and stratigraphy

One of the main problems confronting an understanding of widespread old sequences in sedimentary basins is to find some analogue model facies in recent systems. During recent decades, facies models were built on the basis of a few active fluvial systems and in many cases from small to medium sized basins. Today, a general agreement exists that the conceptual framework is still incomplete. Present-day analogue fluvial models used for understanding ancient sedimentary sequences are poor and incomplete (Miall, 1996). To improve this, more detailed research in tropical fluvial systems is needed.

Recent discoveries, deriving mainly from geomorphologic studies in tropical areas, are opening a new horizon for the interpretation of the sedimentary record of widespread alluvial sequences in the past. Channel patterns, as discussed above, can offer some assistance. When related to the interpretation and record of old sequences, however, avulsion and mega fan generation are some of the major fluvial processes operating in the tropical rivers that require attention.

Typical avulsions of fluvial channels, affecting some specific reaches/segments of large rivers and mainly related to neotectonic activity, have been described in the Amazon basin rivers, as the Solimões, Moa, Ipixuna systems and Ucamara depression (Latrubesse and Franzinelli, 2002; Latrubesse and Rancy, 2000; Mertes et al., 1996; Dumont, 1993) and in the Beni basin (Dumont and Fournier, 1994; Parssinen et al., 1996). More impressive, however, are large depositional megafans that are characteristic landforms of tropical systems. In orogenic active belts and foreland settings, some of the largest megafans extending for thousands of squared kilometers have developed including the Kosi and Gandak megafans (Fig. 8) in the Gangetic plain of India and the Parapetí, Pilcomayo and Bermejo fans in the Chaco plains. It is widely recognized that frequent avulsion and availability of large amounts of bed load grade sediments are the main factors controlling the development of such fans. In the Chaco fans, however, very gentle slopes, extreme suspended loads during floods, high discharge variability and logs acting as obstacles could favor avulsion mechanisms.

The Pilcomayo megafan extends for about 210,000 km^2 and several generations of paleochannels and swampy areas, occupying more than 125,000 km^2, have been mapped (Iriondo, 1993). Megafans are also associated with active subsidence basins in platform/plateau areas, such as the Taquari river megafan in the Pantanal wetlands of Brazil spreading for more than 50,000 km^2 (Fig. 8). This fan has formed by repeated avulsion and its distal lobes are frequently flooded and marked by numerous small lakes (de Souza et al., 2002; see paper of Assine, 2005).

The megafans of the Indo-Gangetic plain are relatively well known (Wells and Dorr, 1987; Jain and Sinha, 2003a). Mountain-fed rivers, such as the Gandak and Kosi, transfer a great quantity of sediments from the high relief source area to the piedmont and have formed large depositional fans. A number of studies are available on the sedimentation record and facies distribution of megafan deposits of the Gangetic plain. A dominance of sandy facies in the plains with a very narrow zone of gravel, restricted to the reaches close to mountain front (10–20 km downstream of mountain front), is the main feature in the Kosi megan deposits. In a more recent work, Shukla et al. (2001) recognized four zones in the Ganga megafan from upstream to downstream namely, gravelly braided zone, sandy braid plain, anastomosing channel plain and meandering channel zone.

The rivers draining the Indo-Gangetic plains are some of the most dynamic rivers in terms of rapid and frequent avulsions. The Kosi river has migrated about 100 km westward in the last 200 years (Mookerjea, 1961; Gole and Chitale, 1966; Arogyaswamy, 1971; Wells and Dorr, 1987; Agarwal and Bhoj, 1992). The migration along the Gandak river has been slow but significant, about 80 km eastward in the last 5000 years (Mohindra et al., 1992). The smaller interfan rivers in the north Bihar plains, eastern India such as Burhi Gandak, Baghmati and Kamla-Balan also show instability through avulsion and cut off process (Phillip et al., 1989, 1991; Sinha, 1996). In a more recent work, one of the most comprehensive reconstructions of fluvial dynamics in this region has been documented by Jain and Sinha (2003b) demonstrating decadal scale avulsions in the Baghmati river over the last 250 years. Major controlling factors for such avulsions are local sedimentological adjustments as well as neotectonics. Further west in the Indo-Gangetic plains, the rivers are not as dynamic as in the north of Bihar. Channel movements, however, have been recorded in the Ganga river around Kanpur (Hegde et al., 1989), and Ghaghra Sarda and Rapti rivers around Bahraich (Tangri, 1986; Chandra, 1993).

In general terms, three-dimensional architecture of megafan deposits consists of multi-storied sand-sheets (generally gravel in upper reaches), interbedded with overbank muddy layers. Thickness and facies distribution vary from upstream to downstream reaches. Information available on the stratigraphy of the interfan area is very limited. From the sedimentological point of view, the Indo-Gangetic fans are more well known than the Chaco fans. Shallow alluvial architectural studies in the Gandak-Kosi interfan showed that the top 2–3 m of the interfan area consist predominantly of muddy sequences, with narrow sand bodies defining former channel positions and very minor sandy layers defining crevasses. More detailed studies in the Baghmati river plains in north Bihar were carried out on the basis of subsurface records available from exposed sections and deep boreholes (Sinha et al., 2005). Borehole records in the midstream reaches of the Baghmati river down to about 300 m showed a 30–50 m thick mud rich unit including a very thin sand layer (2–4 m) that characterized a distal floodplain environment. In the Sharda-Gandak interfan area, the top 10–20 m of sediments are characterized by muddy sequences averaging thick medium sand layers (Chandra, 1993). The coarse sand layer was interpreted as a possible marker of the Rapti palaeochannel with a high-energy fluvial regime.

Considering that many tropical rivers form large depositional systems, in some areas the late Quaternary history shows a clear interaction of fluvial and aeolian landforms. In the Indo-Gangetic plain as well as in the Chaco and Amazonia, aeolian deposits can be identified in some areas through the late Quaternary. Aeolian activity related to large fluvial belts also can be identified in the Orinoco river system (Nordin and Perez Hernandez, 1989) and in the upper Paraná river (Stevaux, 2000).

8. Anthropogenic influences and human impacts

Large populations in developing economies, chaotic growth of urban areas and a sharp increase in water and power demands are some of the common problems in all tropical countries. The resources available and management strategies adopted to tackle river problems, however, may be entirely different from country to country. These differences eventually affect the overall economic growth of the country. For example, Brazil, with a total of 8 million km^2 of area and around 180 million people, is considered one of largest agricultural producer in the world because of a spread agricultural area and intensive water management. On the other hand, the Gangetic plain constitutes one of the largest alluvial tracts in the world, with an area of 374,400 km^2, where millions of people live using rather rudimentary agriculture and having scarce availability of ground and surface water. This has obviously resulted in a much lower rate of growth in the agricultural sector and has also affected the water and power demands in many parts of the country.

Another main concern for large rivers in Asia is the occurrence of floods. The Ganges, Brahmaputra and Megna/Barak rivers support more than 500 million people in Nepal, India, Bhutan and Bangladesh. The rivers are crucial for water supply for irrigation, domestic and industrial consumption but at the same time are responsible for heavy losses of life and property from floods. Bangladesh, for example, is considered to be the most-flooded country in the world followed by India. Flood damage has increased 40 times in India from the 1950s to the 1980s (Centre for Science and Environment—CSE, 1992) although a part of this assessment may be attributed to improved techniques for damage assessments and settlement expansion (Mirza et al., 2001).

Human interference with the river systems has affected the natural flow conditions of tropical rivers in many ways. Construction of dams and barrages on major rivers affects the entire river system manifested as aggradation or degradation in certain reaches and alteration of natural ecosystem because of changes in supply of nutrients and sediments. At the beginning of the 1960s, the total dammed area in the upper Paraná basin was just 1000 km^2. Recent data suggest that number of dams have increased dramatically and occupy an area of ~20,000 km^2 in 2000 (Agostinho et al., 1994). Large dams, apart from storing water, also trap a large quantity of sediment. In Brazil, it is estimated that about 80% of the total bed load is trapped in the Tocantins basin and about ~80% in the upper Paraná basin. Dams in Peninsular India rivers, like Narmada and Krishna, trap 75% of the sediment (Vorosmarty et al., 2003).

The Orinoco is not severely affected by dams. The large Guri dam was built on the cratonic southern tributary, the Caroní river. This river has a much smaller sediment load (Warne et al., 2002), and therefore, sediment discharge of the rivers and sediments and nutrients discharging to the Orinoco delta were not significantly affected. A similar situation exists in the Parana basin: all dams in this river basin have so far been constructed upstream of the confluence of the Paraguay River. The Paraguay is the main contributor of suspended load (>50%) to the Paraná river (Orfeo and Stevaux, 2002). As a result, the delta of the Parana has not been affected by dam construction.

The political boundaries of the river basins also affect river management issues. Many of the large river basins, such as Tocantins (757,000 km^2), Tapajos (490,000 km^2), Xingú (504,000 km^2) and São Francisco (640,000 km^2), are completely within Brazilian territory. New and large dams are also being planned in the Madeira, Araguaia, Xingú and others rivers, but relatively little discussion occurs about the environmental impacts of these dams. On one hand, it is easier to plan and implement river management programmes in large countries, but on the other hand, it also means that such countries may have the impunity to regulate the river systems without any obligation to the international community with reference to environmental impact. This situation is different in China, for example, where this situation results in intense international pressure on the proposal to construct the Three Gorges Dam on the Yangtze River. River basin management policy for river systems extending over different countries is usually governed by a multinational commission and the Mekong basin is a good example in the tropics. The Mekong Commission is composed of China, Laos, Thailand, Cambodia and Vietnam.

Another example of human interference with rivers arises from mining. In the Amazon basin, predatory gold extraction on the fluvial bed using dredgers and the exploitation of fluvial terraces by “garimpeiros” (informal gold extractors) was prevalent during the 1980s and beginning of the 1990s. Although the amount of sediment removed by mining was large, the large rivers were not significantly affected by introduction of sedimentary waste of mining. Water pollution, produced by the influx of large amounts of mercury in the rivers, however, was significant, particularly along the Tapajos river basin affecting mainly a few minor tributaries. At present, gold extraction by “garimpeiros” is scarce and declining. By contrast, the tropical rivers of New Guinea such as the Fly basin have been severely affected by mining extraction for decades. The Fly is a medium sized river and its sediment load was significantly altered by mining waste, increasing from 85 to more than 100 million tons/year (Milliman et al., 1999). Other estimations suggest annual additions of ~50 million tons of sediments through mining waste, out of which ~3% is transferred to the floodplain (Dietrich et al., 1999).

9. Summary and conclusions

Many of the largest rivers of the world are located in tropical areas together with some of the major areas of alluvial sedimentation by megafan systems. Large basins, such as the Amazon, Orinoco and Congo, include tributaries, which are some of the largest rivers of the world. Those complex and huge tributary systems need to be analyzed individually because the large variety of styles of geomorphologic and sedimentary processes acting in them are relatively unknown. The important role of tropical systems in sediment and nutrient transfer to the oceans and coastal areas, sediment storage in continental basins and in the global hydrological cycle, demonstrate that the geomorphology of tropical rivers has not received sufficient attention when compared to the advances realized by other disciplines in the tropics. Thus, no really sufficient agreement exists about the potentially useful information that geomorphology can make available to decision makers for water management and environmental planning. Ecological studies in tropical areas also lack a solid knowledge base. The ecology of aquatic tropical environments is being built on a poor or non-existing conceptual framework of the functioning of the physical hydrosystem. A deficiency of background information and understanding leads to engineers committing serious mistakes when managing tropical waters. This is leading to an uncertain future for the interbasin water transfer programs in India, the construction of huge dams on large Brazilian rivers and the questionable experience of high cost flood control systems implemented in a poor country like Bangladesh.

Geology, and in particular sedimentology, could make significant advances in the understanding of facies models, the reconstruction of paleoenvironments and the modeling of continental sedimentary basins, if new models were available from tropical systems.

The geomorphology of fluvial systems has advanced in the last decades and could further increase its conceptual framework on fluvial processes by obtaining proxy data from tropical systems. This could expose the weakness of some of the existing models and concepts created on the basis of northern Hemisphere systems, which have become established in what may eventually prove to be rather folkloric concepts.

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