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How do big rivers come to be different?

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ABSTRACT

Big rivers dominate the world's continental surface, yet we are still learning about how they operate and whether they are explicably different, not only from each other, but also from smaller rivers. This paper uses global satellite imagery and ground field-experience to explain and illustrate why and how big rivers are strongly differentiated.

At the largest scale, trans-continent sized rivers do not possess unified valley systems created by fluvial erosion but instead involve chains of interlinked domains with contrasted fluvial functions. Alluvial settings are dependent on mainstream and tributary inputs of water and sediment, but big river channel pattern variety is determined by contrasts in sediment feed-rates and differences in the rates and routes of sediment exchange. Four modes of alluvial exchange are recognised: (i) deposition on the floodplain (e.g., levees, infilled palaeochannels, floodbasins), (ii) exchanges involving main channels (e.g., bank erosion and accretion), (iii) deposition within main channels (e.g. bedforms from metres to 10s of kilometres in size), and (iv) material input from tributaries (sediment-rich or sediment-poor). Different combinations of sedimentation activity lead to floodplain morphologies for big rivers that can be classified into four types: (i) lacustrine-dominated, (ii) mainstream-dominated, (iii) tributary or accessory-stream dominated, and (iv) confined or bedrock-dominated.

Channel patterning involves a range of main-channel, branch and floodplain styles promoted by variable sediment feeds, complex bed sediment transfers, variable lateral sediment exchanges, plural channel systems and incomplete mineral sedimentation of the hydraulic corridors set by tectonics and prior-valley trenching. In some of the world's largest rivers it is accessory and tributary channels, rather than main-river branches, which determine patterns of floodplain morphology. In some big rivers, but certainly not all, ponded lacustrine environments are common, with water bodies that vary from smaller water-filled swales and palaeochannels, to floodbasins and km-scale linear lakes in sediment-dammed tributaries. Organic sedimentation is significant along relatively sediment-poor and laterally-stable large rivers that fail to fill their alluvial corridors. Three case studies are used to illustrate this variability in big river pattern and process: the Ob, Jamuna and Paraná. These rivers are respectively dominated by meandering, braiding and mixed mainstream and accessory channel morphologies.

Big rivers have some processes and patterns that are different from smaller rivers including: (i) no simple down-valley sequence in control variables and channel pattern, (ii) main channels with high width:depth ratios, (iii) few or no channel-wide unit bars migrating through the main thalwegs, (iv) extensive and low-gradient floodplains that provide space for channel shifting and floodplain sedimentation, (v) long distances between significant tributaries to allow full mixing of water and sediment discharges, (vi) in some places, partially-decoupled channels and floodplains, and (vii) significant floodplain water bodies that readily act as sinks for fine-grained sediment where this is supplied, or organic deposition.

Although understanding of contemporary big river patterns requires attention to a range of timescales, including inheritance from sediments of Quaternary age, big rivers do have a distinctive character. The variety of patterns on big rivers may usefully be viewed in terms of sediment systems operating at both the catchment and reach scales. Intra-river variability and internal complexity show the need to understand contrasted sediment supply, through-put and alluvial exchange as determinants of big river morphology and pattern.

Keywords: Large rivers, channel patterns, alluvial exchange, floodplains

1. Introduction

For an observer in the field, a river might seem best defined as ‘big’ in terms of a channel dimension threshold. Upstream of tidal influence, the undivided Amazon can be over 5 km wide (e.g., at 3° 50'S, 62° 26'W), the Congo 8 km (e.g., at 2° 31'S, 16° 10'E) and the braided Brahmaputra/Jamuna (including exposed bars and temporary islands) even wider at 10-15 km in places (e.g., 24° 36'N, 89° 44'E). Any river over 1 km wide could reasonably be described as big (e.g., Sambrook Smith et al., 2009) but in field situations, reach-scale complexity makes morphological sizing somewhat equivocal.

Large alluvial rivers commonly widen and narrow over comparatively short distances. Abrupt changes in active braidplain width may be caused by flow divergence and convergence through confluence-diffluence units around km-scale bars (e.g., the Paraná at 31° 33'S, 60° 18'W that narrows from 7 km to 0.5 km along a 14 km reach; see Parsons et al., (2007)), or be controlled by bedrock constriction (e.g., the Mekong at 13° 56'N, 105° 14'E; see Gupta (2007)), or as a river pattern forms a network of ‘island and node’ reaches (e.g., Thorne et al., 1993). Big rivers typically have a hierarchy of mid-channel bars and islands (e.g., Bristow, 1987; Kelly, 2006), some of which may be heavily vegetated (e.g. the Congo River at 1° 29'N, 18° 60'E and the Amazon at 2° 59'S, 67° 50'W) and at a height that can only be overtopped in out-of-bank flows (Thorne et al., 1993). Divided flows with main and accessory channels are commonplace. Some big rivers can be well-connected to their floodplains, frequently interchanging sediment and water with adjacent wetlands (e.g. the Paraná at 28° 22'S, 59° 03'W and Fly at 7° 115'S, 141° 11'E), whereas others are essentially disconnected (e.g. Congo River for nearly its entire length of over 2000 km) and function as a single conduit for sediment and water transfer. Major bedforms may also be drowned out at higher flows and exposed at lower ones (e.g. Rio Negro River at 02^{o} 44'S, 60^{o} 42'W), so that observational river stage and 'bank' definition are critical for describing channel morphology and style (Kleinhans and Van den Berg, 2011). Finally, extremes of scour depth, which may have significant importance for engineering structures (Mosselman, 2006) and determine preserved sedimentation thickness (e.g., Gibling, 2006; Fielding, 2007), vary in both space and time at the reach scale (e.g., Best and Ashworth, 1997), reaching maximum combing depths (Paola and Borgman, 1991) of ~100 m in the middle Amazon (Sioli, 1984). It is therefore perhaps unsurprising that although widths and depths for some larger rivers appear in hydraulic geometry data sets (e.g., Van den Berg, 1995; Xu, 2004; Latrubesse, 2008), channel dimensions are not what have been used to produce a ranked list of the world's largest rivers. With the changeability and complexities of large river channel geometries, it is far from easy to specify a measure of river morphology on an acceptable comparative basis.

In practice, 'big' rivers are identified not by size of channel but in terms of determining factors for which global data are available: catchment area, length, discharge or sediment yield (e.g., Holeman, 1968; Potter, 1978; Milliman and Meade, 1983; Schumm and Winkley, 1994; Hovius, 1998; Gupta, 2007). Different data collations show reasonable agreement on lengths and areas, but representative discharge and sediment loads are more difficult because of gauging limitations and data availability (especially for sediment loadings) and the transforming effects of human activity and river regulation (Meade and Parker, 1984; Syvitski et al., 2005; Walling, 2006; Syvitski and Kettner 2011). Water discharge or sediment data from the centuries of 'genetically-modified' fluvial regimes may not represent well the conditions for sedimentation or landform generation that have operated over a longer term

(Gupta, 2007; Wilkinson and McElroy, 2007; Wasson, 2012). For example, Syvitski and Kettner (2011) calculate that the twentieth century global sediment load delivered to the coastal zone has reduced by 15%, although sediment loads vary widely reflecting different stages of industrial development and land-use change in individual river basins. Likewise, Wang et al. (2011) calculate that there has been a 70% reduction in sediment flux to the ocean since 1000 yr BP from major rivers in East and Southeast Asia (including the Yangtze and Mekong), with an accelerating decrease since the 1950s.

Unfortunately, global data on sediment loads are usually for suspended sediment only, sometimes with a notional allowance for bedload, whereas channel patterning necessarily involves bed material transfer (Kleinhans, 2010). In reality, bedload yield is notoriously difficult to measure (Kuhnle, 2007) and in practice sediment load partitioning can be very varied and strongly dependent on local catchment geology (Turowski et al., 2010). A further challenge is that a mean annual discharge (the usual measure adopted) may be less significant for channel patterning than other measures such as formative (channel-full or bar-top level) discharge, flood magnitude and frequency, or flow duration and annual variability. Despite this, Latrubesse (2008) suggests that 'large' rivers are ones with a mean annual discharge of greater than 1000 $m^3 s^{-1}$, and 'mega' rivers are greater than ~17000 $m^3 s^{-1}$.

Data sets for catchment size, discharge and suspended sediment yield give different river orderings, and there are no simple relationships between catchment size and discharges of water and sediment (Figs 1A-B). Leaving aside the Amazon, both annual runoff and mean sediment yield of some of the world's largest rivers range over two orders of magnitude (Fig. 1A). Latrubesse's (2008) division of 'large' and 'mega' rivers (equivalent to 32 and 536 X 10^9 $m^3 yr^{-1}$, or $km^3 yr^{-1}$, respectively) does not produce a clear separation (Fig.

1A) and those classified as ‘mega’ rivers in Fig. 1A are not all grouped together by catchment area (Fig. 1B). It has been shown that small mountain catchments provide a large proportion of continental sediment yields (Milliman and Syvitski, 1992), and large catchments demonstrate markedly heterogenic behaviour. In some circumstance it may be piedmont Quaternary materials (Church et al., 1989) or lowland agricultural lands (Wilkinson and McElroy, 2007) that dominate sediment supply. On a continental scale, the sourcing, routing and loss of surface-water (from precipitation, evapo-transpiration, groundwater recharge and river flow) is spatially and temporally variable and the supply and throughput of sediment (from erosion, transport, alluvial sequestration and as downstream output) is distinctly non-linear (Jerolmack and Paola, 2010; Van de Wiel and Coulthard, 2010). Furthermore, there are regional differences in climate, lithology and hydrology that may influence the relationship between drainage area and water discharge (cf. Davidson and North, 2009). So it is unsurprising that there is no simple relationship between river size, sediment yield and drainage area (Figs 1A-B). Ranked lists of the world’s largest rivers based on these attributes should therefore be viewed with caution,

Earlier research on channel pattern discrimination for smaller rivers has generally been attempted using measures of discharge, gradient, stream power and bed sediment size (e.g., Leopold and Wolman, 1957; Ferguson, 1987; Van den Berg, 1995; Lewin and Brewer, 2001). These controlling factors are more pertinent to bed material transfers rather than the sub-capacity suspended sediment and sand loads typical of the world’s largest rivers. It has been argued that this whole approach of channel pattern discrimination based on stream power is not fully satisfactory, especially for large anabranching systems that typically have low gradients, fine bed sediment and excess sediment transport capacity (Sarker and

Thorne, 2006; Latrubesse, 2008). Indeed, Kleinhans and Van den Berg (2011) conclude that large anabranching rivers are not clearly empirically or theoretically related to stream power unlike their smaller counterparts. For the world's largest rivers it is contrasts in sediment feed-rates and transfer styles that appear crucial in determining more generally big river channel pattern variety (cf. Smith and Smith, 1984; Church, 2006).

Clearly, there is a need to re-assess the intra and inter-variability in big river channel pattern. With the availability of free, downloadable satellite imagery (most courtesy of the United States Geological Survey; http://glovis.usgs.gov/) it is now possible to access remote parts of the globe where many large river basins dominate, and to document the intricate detail of big river channel pattern as well as quantify big river planform development over decadal time-scales. This paper uses examples from the world's largest rivers to: (i) identify the controls on the style of big river channel patterns at a trans-continental scale; (ii) present a new framework for contemporary channel styles of big rivers and set inter- and intra- large river morphological contrasts within a sediment transport schema; (iii) describe pattern evolutions involving channelised flows, bedforms and floodplains over a range of time scales, and (iv) question whether the processes and patterns of large rivers are explicably different, not only from each other, but also from smaller rivers.

2. Big rivers at a trans-continental scale

The world's largest rivers are bigger than individual sedimentary basins. Big rivers may extend into sedimentary basins, but they also cross them (e.g. Danube, Yangtze), and have longitudinally-extensive depositional zones (e.g. Congo, Ob). Whilst big rivers play an important role in sorting and sequestering coarse sediment in their proximal reaches, sometimes represented by a single or series of mega-fans (e.g. Paraguay River, cf. Assine and Silva (2009)), most of the world's largest rivers go beyond so-called 'distributive fluvial systems' or DFS (Hartley et al., 2010; Weissmann et al., 2010; 2011). As Sambrook Smith et al. (2010) and Fielding et al. (in press) note, the rivers and sedimentary basins used to support the concept of DFS (Weissmann et al., 2010; their Fig. 1, p. 39) exclude over 75% of the Earth's largest rivers (see Fielding et al., in press, their Figure 7). Unlike DFS, big rivers can also include significant reaches dominated by laterally migrating channels, contain channels and floodplains with substantial organic-rich sedimentation and have partially-decoupled channels and floodplains (Lewin and Ashworth, in press). Put simply, the world's largest rivers are bigger than sedimentary basins alone – they transcend geological terrains and individual depositional basins, and have both sediment-rich and sediment-poor tributaries.

At the largest scale, trans-continent sized rivers do not possess unified valley systems created by fluvial erosion but instead involve a series of chains of interlinked domains with contrasting fluvial functions:

(i) dominant headwater orogenic-belt sources for sediment and runoff (Milliman and Syvitski, 1992);
(ii) intramontane and foreland depositional basins and ramps that accumulate large proportions of upstream eroded materials (Miall, 1996; Fielding et al., in press);
(iii) low sediment-yield cratons that may or may not be highly runoff-generating (Latrubesse et al., 2005);
(iv) tectonic troughs that funnel and focus runoff and deposition;

(v) transverse orogens and depositional basins in downstream reaches;

(vi) peri-marine environments that have also been greatly affected by fluctuations in the average level of the sea surface relative to the continents.

Large rivers are composites, many only linked-up together in the recent geological past (Goudie, 2005; see Williams, 2012; his Table 2, p. 2113-2115). From a channel pattern perspective, large rivers are not ‘monotonic’ like most smaller ones, and they do not have a simple down-channel trend in control variable (e.g. discharge, slope, grain size) and geographical progression through zones of sediment-source, transport and deposition (source-to-sink) as in the small-stream model that has dominated fluvial geomorphology (Schumm, 1977). For larger systems, the extent and down-valley sequencing of functioning domain-chains varies between river systems and their tributaries, and one or more may be missing. Thus, the biggest African rivers are largely cratonic, the Yangtze (Changjiang) and the Danube have depositional basins and gorge sections through mountain zones set transversely across their lower courses, whilst the Ganga basin drainage has right-bank cratonic tributaries and left-bank orogenic ones, but no cratonic middle section. The morphology of trunk valley floors and their feeders are subordinate to these large-scale domains. Sediments and water from major rivers are carried both across their boundaries, and wholly or only partially fill the structural troughs that are available as they pass through. Structural steering is also significant at the local scale, so that the middle course of the Amazon is constrained by fault and fracture patterns (Mertes and Dunne, 2007) as is the alignment of many cratonic river courses (Twidale, 2004). Whilst this variety has been widely appreciated (Potter, 1978; Miall, 1996; 2006; Schumm and Winkley 1994; Gupta, 2007;

Meade, 2007), it seems that some expectable consequences for large-river channel patterning have not been acknowledged.

Figure 2 shows in simplified form the possible combinations of functioning domains. This schema broadly follows the typology of Potter (1978) and subsequent variants that have focussed on basin fills (e.g., Miall, 1996; his fig. 11.77). However, the schema in Fig. 2 intentionally emphasises the role of tributaries, whether sediment-rich or sediment-poor, and of the dispersal and sediment storage along big river systems that may or may not terminate in well-defined depositional basins. Some large rivers (e.g., south-east Asia where the gorges of the Yangtze, Mekong, Salween and Irrawaddy run side-by-side in fold mountains) have mountain courses for a considerable proportion of their catchments (Fig. 2A). Elsewhere, supply sources may be lateral from a succession of tributaries (Fig. 2B) that allow repeated sediment replenishment (as along the Ganga basin) or at the head of a trunk river (Figs 2C and 2D) but with extensive sediment exchange along an alluvial corridor (e.g., the Amazon). Even within small catchments, tributaries may of course differ in terms of gradient, discharge and sediment character from their trunk streams, but in large basins there may be far greater contrasts between mainstream and tributary sediment and discharge contributions. This can work either way. The Mato Grosso tributaries of the Amazon are sediment-poor and have failed to fill valley trenches related to lower sea levels (Archer, 2005). The Andes-fed Amazon has alluviated its valley across their mouths resulting in ponded, lacustrine tributaries (Rio Tapajós, Rio Xingu) joining the main river. Some lowland Amazonian rainforest rivers (Purus, Juruá) may have higher yields that they extract from Tertiary basin fills (Latrubesse et al., 2005). On the other hand, the meandering Yamuna-Ganges trough is relatively sediment-poor until fed successively by its braided Himalayan tributaries. It is also possible for large rivers like the Danube to have an alternation between depositional basins and transverse uplands along their courses (Fig. 2E), or even rivers that have few mountainous sediment sources at all (Fig. 2F). Large African rivers can almost reverse the small-river model: upstream plains, with steeper bedrock-controlled and confined courses downstream crossing rifted continental margins (Goudie, 2005).

Equally important is the intra-catchment accommodation space available for deposition, ranging from very little (as in gorge sections through transverse mountains), to intermittently flood-inundated transport corridors of considerable length (including cratonic graben structures), and finally to wide lacustrine and other depositional environments in subsiding depositional basins (for continental basin distribution, see Weissmann et al. 2010, their fig. 1, p. 39). Coarser sediments in particular may be removed in proximal aggrading fan environments and on foreland surfaces like the llanos plains of the Orinoco headwaters (Meade, 2007). But even for fine sediment, the potential for basin sedimentation can be considerable, as in the Dongting Lake of the middle Yangtze (Chen et al., 2007).

For riparian alluvial corridors, short-term studies of both large (Aalto et al., 2006; Allison et al., 1998; Dunne et al., 1998; Ten Brinke et al*.,* 1998; Goodbred and Kuehl, 1999; Meade et al., 2000; Meade, 2007) and smaller (Lambert and Walling, 1987; Marron, 1992; Walling and Quine, 1993, Gomez et al., 1999) rivers show that within-catchment floodplain deposition is important. Alluvial storage has a buffering effect on sediment flux such that the short-term effects of climatic fluctuations are delayed and evened-out (Métivier and Gaudemer, 1999). Sediment may be remobilized by lateral channel migration, and studies of the Fly and Strickland Rivers in Papua New Guinea have shown that recycling rates as well as supply and sequestration rates account for depositional contrasts between the two rivers (Swanson et al., 2008). For the Amazon, Dunne et al. (1998) suggested that system-wide alluvial exchanges (into and out of alluvial storage) may exceed downstream sediment fluxes by a factor of two or more.

For their size and gross stream powers, big rivers may have *relatively low* sediment loadings. But, for three reasons, they strongly refine the sediment load during its passage downstream:

1. Intra-catchment depobasin distribution allows for much sediment removal. This may be in aggrading intramontane and foreland areas, or in cratonic depressions. This is supplemented by alluvial storage and exchange along extended riparian corridors;
2. Large areas of their catchments may be low sediment yielding, thus reducing the downstream impacts of high-yielding sources;
3. Major rivers have exceptional length for achieving sediment fining by abrasion, sorting and exchange (Allison et al., 1998; Goodbred and Kuehl, 1999; Aalto et al., 2006; Frings, 2008).

High or low loadings depend both on *source availability* (e.g., from orogenic belts, prior Quaternary deposits, or agricultural land), but also on *sink distribution* (e.g., intra-catchment depositional basins, riparian floodplains, or present-day reservoirs) and *availability* (i.e. 'accommodation'), involved in dispersal loss or *sequestration* along the way. Whilst erosion loss from uplifting mountains is high, much of this may be deposited in close proximity – although the waters of large rivers drain through and beyond depositional basins. The sediment supply/sink balance leaves the down-valley reaches of some large rivers sediment-rich and others sediment-starved. Furthermore, tropical lowland tributaries that are sediment-poor may nevertheless generate high discharges to produce flooding. Whether or not the fractional catchment input represented by sediment-laden tributaries enters already flooded environments, it can have marked effects on depositional styles. On floodplains, this may involve either widespread sediment advection (e.g., Day et al. 2008) or local bank-side diffusion into wetlands (e.g., Adams et al., 2004; Slingerland and Smith, 2004). Major ephemeral rivers entering drylands may have flood-outs in which both water and sediment are entirely dissipated (Tooth, 1999).

Climatic variety adds an extra dimension in terms of both water discharge and sediment yield. The Ganga River experienced five aggradational periods separated by incisional episodes in the past ~100k years with the timing of incisional periods corresponding broadly with periods of monsoonal intensification (Roy et al., 2012). Other major high-latitude catchments like the Mackenzie have strongly-peaked nival and proglacial runoff regimes and permafrost. Glacigenic sediments are redistributed by rivers that also cross cratonic surfaces stripped of superficial deposits by prior glaciation. For example, Pleistocene ice sheets produced both rearrangement of drainage lines and catastrophic megafloods (Baker, 2007), whilst 90% of the Huanghe's exceptional sediment load is derived from loess terrains (Wohl, 2007). Active hydraulic corridors may be set within suites of Quaternary terraces that may be eroded to provide additional sediment (e.g., Latrubesse and Franzinelli, 2002; Iriondo et al., 2007; Singh, 2007). Alternatively, long reaches of some large rivers may have been in a state of sediment mass-balance equilibrium with general vertical stability of the river and a lack of terraces or a variation in valley-fill depth over the Holocene (e.g. along 1000 km of the Middle Yukon, see Froese et al., 2005). Present-day river systems may not be analogues for ancient fluvial deposits produced in different climate regimes and many river patterns are adjusted to, or in the process of adjusting to, the present interglacial conditions (cf. Valente and Latrubesse, 2012; Wasson et al., 2012). In varied and dynamic Quaternary climatic environments, and for reasons additional to tectonic settings, present-day large-river sediment sources and storages involve a mosaic of domains.

3. Alluvial channel patterns of big rivers

3.1 Channel pattern types

Big rivers show a bewildering range of channel planform – from single to multiple channels, some with bars and islands dominated by lateral accretion and channel migration, yet others with a floodplain that is often dominated by adjacent standing water bodies in a range of size that may be refilled during floods (Fig. 3). Work to distinguish between different alluvial river patterns has been ongoing since the seminal work of Leopold and Wolman (1957) that categorised rivers as braided, meandering or straight. Braided patterns are divided by active bars that are usually ephemeral and submerged at high flow (Ashmore, 1991). Numerous descriptive classification schemes have been proposed since the work of Leopold and Wolman (cf. Eaton et al., 2010) that use a plethora of terms and descriptions (e.g., 16 in Brice (1975) and 14 in Schumm (1981)), which are usually organised according to their dependence on sinuosity, degree of braiding or mode of sediment transport (suspended versus bedload). It is now acknowledged that there are at least two other named channel pattern morphologies besides braided, meandering and straight: (i) wandering rivers that are transitional between meandering and braiding, commonly with islands of greater permanence and large area (Neil, 1973; Carson, 1984; Burge and Lapointe, 2005), and (ii) anastomosing rivers with multiple channels developed in fine-grained sediments, often with lakes and wetlands between levee-flanked channel branches and stable alluvial islands that divide flow up to bankfull (Knighton and Nanson, 1993; Abbado et al., 2005). Anastomosing channels tend to be laterally inactive, although not always the case as described for the Middle Amazon by Rozo et al. (2012). As a separate category of river channel pattern, or more usually at a higher level of classification (Kleinhans and Van den Berg, 2011), is the anabranching river (Rust, 1978; Knighton and Nanson, 1993; Nanson and Knighton, 1996) defined as a system of multiple channels that divide and rejoin. An anabranching river may have individual branches between more permanent islands that have a range of patterns: straight, meandering, braided, wandering or anastomosing (Nanson and Knighton, 1996).

Jansen and Nanson (2004) stated that more than 90% of the world's five largest rivers anabranch along more than 90% of their total alluvial tracts and Latrubesse (2008) reported that all rivers with mean annual discharges > 17,000 $m^3 s^{-1}$ anabranch.. However, individual branch channel patterns are determined by the degree of lateral shifting, rate of overbank sedimentation, magnitude of sediment transport capacity and bed material/braiding intensity (Fig. 4). Anabranching itself, as usually defined (e.g., Knighton and Nanson, 1993), is not produced by a single set of processes.

Very rarely, where rivers flow into still freshwaters without an appreciable sand load, there are 'archipelagos' of silty levees. These take the form of highly elongate branching ridges paralleling faster-velocity channels within broad water bodies (Figs 5A-B). Such water bodies, with individual branching levees can run for tens of kilometres, and are found in dammed tributary lakes draining to the Amazon (Archer, 2005; his figure 10, p. 28; Latrubesse and Franzinelli, 2005), in rift valleys in central Africa (e.g., along the Albert Nile in Uganda, 3^{o} 32'N, 31^{o} 52'E) and very extensively along the lower Ob in Russia (see Section 4.1).

Latrubesse and Franzinelli (2005), studying the 275 km-long Mariuá archipelago and the Anavilhanas islands on the Rio Negro in Brazil (Figs 5A-B), describe the development of sandy islands capped with muddy sediments, and then muddy levee ‘trees’ extending downstream for considerable distances. These may enclose lakes where channels and levees rejoin. Archer (2005) suggests that humic acids and low pH contribute to flocculation of clays and silts in the Rio Negro, and the same probably applies to some craton drainages elsewhere. This is an eventual means for rivers to prograde and ‘bridge’ water-filled and possibly subsiding basins with levee-lined river passages, with organic materials playing significant depositional roles. However, Latrubesse and Franzinelli (2005) suggest that the Rio Negro features date from former periods of more active sediment input. The upstream Mariuá basin was filled largely with sandy sediments in the Holocene, with the flooded lower Anavilhanas basin (dammed by the Solimões-Amazon) in an arrested state of development and only partially modified with levee-lined channels. Laterally-mobile and low-energy muddy meandering streams have been described elsewhere, involving oblique accretion and post-depositional bank failure (Brooks, 2003), though there is only limited detail available for cohesive muddy-sediment processes in large freshwater rivers (cf. Maroulis and Nanson, 1996; Grabowski et al., 2011).

3.2 Alluvial exchange in big rivers

Whilst meandering/braiding discrimination on small streams can be attempted through bivariate analysis using their wide range (over several orders of magnitude) in specific stream power and sediment size (e.g., Van den Berg, 1995; Ferguson, 1997; Lewin and Brewer, 2001), such a range in controlling variables is less apparent for big rivers (Latrubesse, 2008; Kleinhans and Van den Berg, 2011), and it is thus less easy to account for their different patterns in such terms. In large rivers, some styles are maintained for hundreds of kilometres when developed at low gradients in sand and finer sediment (e.g., Congo River over 1200 km from 0^{o} 45'N, 24^{o} 26'E to 2^{o} 12'S, 16^{o} 15'E). Others have marked pattern changes, variable sediment feed rates from tributaries and different forms of alluvial exchange with floodplain-stored sediment. Minor gradient changes, often through local plate flexuring and faulting, can have large effects on sedimentation at low slopes (Mertes and Dunne, 2007; Frings, 2008), for example with silty levees prograding across ponded flows rather than sandy lateral accretion at river banks.

Alluvial settings are dependent on mainstream and tributary inputs of water and sediment as discussed in Section 2 (Figs 1A-B), but alluvial morphologies are essentially determined at the reach scale. Sediments are not only transported through reaches (as suspended sediment or as migrating bedforms), but are also subjected to transfer processes into and out of alluvial storage. Figure 6 summarises the various forms of exchange that may take place. These include deposition on the floodplain (a-e), exchanges involving main channels (f-i) and deposition within them (h), or material input from tributaries (j). Whilst the size of channels reflects formative water discharges, it is these sediment exchanges that generate outline channel morphology – whether by bedform development into islands; by loss of load through bed aggradation or slackwater and levee deposition; through recycling by bank erosion and active lateral accretion, or redirection by avulsion. If there is minimal exchange, even large rivers may remain straight (e.g. The Niger for 25 km at 6^{o} 27'N, 6^{o} 40'E, or the Yenisei for 200 km from 63^{o} 43'N, 87^{o} 19'E to 65^{o} 37'N, 88^{o} 03'E) though with the bed diversified by migrating bedforms that are exposed at low flows. Table 1 presents summary characteristics for selected individual reaches on the 20 largest rivers ranked by mean annual runoff. For some, lateral exchange by bank erosion and accretion (f and g in Fig. 6) dominates; others have seemingly non-migrating channels with levees and floodbasins (a, b, and e in Fig. 6); yet others have floodplains blanketed with overbank sediments and infilled palaeochannels (c in Fig. 6). To complicate matters further, within hydraulic floodplains (the area inundated in major floods), large rivers can have genetically-decoupled sediment systems, with the largest channel acting as a dominant or lesser participant for both water and sediment transfer or deposition (e.g., the Amur at 49^{o} 36'N, 136^{o} 32'E). If they are present, smaller but sediment-rich tributaries (j) may dominate alluvial sedimentation. For example, the sediment-rich Madeira provides half the sediment load of the main Amazon channel, and its larger and coarser sediment load is associated with an increase in the number of islands and bank erosion rates downstream of the junction (Mertes et al., 1996). In their absence, a major but relatively sediment-poor river may only alluviate a narrow channel corridor, passing between floodbasins where lakes are impounded (e.g., the Magdalena at 08^{o} 49'N, 74^{o} 22'W, see Fig. 3B). The majority of big rivers have adjacent standing water bodies in a range of sizes and which may be refilled during floods (Table 1, Figs 7A-B). None of the characteristics described above are unique or exclusive to big rivers. The sediment exchanges illustrated in Fig. 6 are common to all floodplain rivers – large and small. But big rivers are characterised more generally by a stronger decoupling from non-alluvial sediment input (i.e. more remote from adjacent valley slopes and flowing over low-gradient surfaces) and a greater role played by channelised flows in tributary or accessory channels for routing flow and sediment.

Given the range of sediment loadings available to trunk and tributary combinations, including bed- and suspension- load, the variety both between but also within large-river floodplains is considerable, even where there is a common valley-floor gradient and flood level set by the major river. The sediment actually available for major rivers to use in alluviating floodplains is as variable as the accommodation space provided, but can be high where regular monsoon-flooding facilitates long periods of overbank flow. For example, Allison et al. (1998) suggest between 31 and 71% of the total alluvial sediment budget may be trapped landward of the Ganges-Brahmaputra mouth whilst Islam et al. (1999) estimate 49% of the total load is deposited before the coastal region with 28% deposited on the floodplain and 21% within the active channels. The proportion of sediment trapped within large river catchments is not necessarily different to small rivers but the absolute volume of sequestration is orders of magnitude greater (Fielding et al., in press). The volume ‘extracted’ by overbank sedimentation can decrease significantly the downstream fining rate of large sand-bed rivers (Frings, 2008) and during high-magnitude floods the volume of overbank sedimentation can be of the same order as the sand input from upstream as observed by Ten Brinke et al. (1998) for the lower River Rhine.

The different combinations of sedimentation type lead to floodplain morphologies for big rivers that can be classified into four main types (Fig. 8, Table 1). The hydraulic and sedimentation systems on big rivers can range from lacustrine-dominated (Type 1) through mainstream-dominated (Type 2), to tributary or accessory stream dominated (Types 3(a)-

(3b)), and finally to confined or bedrock-dominated (Type 4). As noted in Section 3.1, most big river channel patterns are anabranching (Latrubesse, 2008) and individual branches can have different functions and status. Where the channel divides, it is possible for inundated floodplains to have functionally-separate *accessory sedimentation systems* operating within them even without tributary participation (Fig. 8, Type 3(b)(i)). These accessory channels are often characterised by relatively small-scale, laterally accreting point bars with levees. For example, the Amur at 48^{o} 44'N, 135^{o} 16'E has an anabranching mainstream channel that accommodates most flow and sediment transport, but also a system of smaller meandering accessory channels that branch off into the floodplain siphoning off flood sediment and discharge (Fig. 9). In large rivers, and unlike smaller rivers it can be this accessory system, rather than the relatively straight bedload-transporting main channel, which dominates the near-surface sedimentation and the morphology of the floodplain itself. Other examples of accessory channels are along extended lengths on the Solimões-Amazon (e.g., 02^{o} 43'S, 64^{o} 55'W), the upper and middle Paraná (e.g., 27^{o} 14'S, 58^{o} 23'W, see Fig. 8) and over 150 km along the Upper Ob (e.g., 55^{o} 53'N, 83^{o} 45'E) where reaches have relatively straight courses with major migrating bedforms, but also a system of much smaller meandering accessory channels on the floodplain (Latrubesse and Franzinelli, 2002; Iriondo et al., 2007; Rozo et al., 2012). Comparable features also occur on the Amazon (Mertes and Dunne, 2007), and have been observed on the Lena in a permafrost environment (Costard and Gautier, 2007). Accessory streams that branch off from the main channel can form large internal deltas if they enter adjacent flood basins (Latrubesse et al., 2010). On a smaller scale, Rowland et al. (2005), Day et al. (2008) and Constantine et al. (2010) have drawn attention to tie channels, bi-directional channels connecting the main river to lakes and oxbows. On the Fly River in

Papua New Guinea these play a major role in transferring fine sediment from channel to floodbasins with about 40% of the total river sediment load being deposited overbank up to 10 km away from the floodplain channel (Day et al., 2008). On large rivers, the ability differentially to distribute discharges and sediment loadings between two or more channel systems, coupled with tributary diversity, gives their floodplain processes a functional and intrinsic *pluralism* (Type 3, Fig. 8). This is not as common in smaller rivers (though see the example of Magela Creek described by Jansen and Nanson, 2004).

Reach-scale research in recent years has shown that within-channel sediment transfer processes in large rivers are more complicated than outline channel pattern might suggest (Kocurek et al., 2010). For example, migrating bedforms that account for a major proportion of bed sediment transfer in large rivers with predominantly sandy beds (Frings, 2008) pass through channels causing local macro-turbulence such as fluid upwellings (Best, 2005; Shugar et al., 2010) and possibly a disturbance and breakdown of channel-wide secondary circulation (McLelland et al., 1999; Parsons et al., 2007). In large rivers, bedforms such as dunes may respond very differently to an increase in stage so that the relationship between dune height and flow depth may have considerable scatter (e.g. Julien and Klaassen, 1995; Best et al., 2007), be very weak or non-existent (Leclair, 2011) or actually have an inverse relation such that dunes decrease in height with greater flow depths (Amsler and Garcia, 1997). Relict dune topography from high flow stages may still have an influence on the location and size of bedforms that occur at low stages as shown for the Mississippi by Nittrouer et al. (2008), yet the interactions between bedforms themselves can give rise to a self-organised pattern (Kocurek et al., 2010).

Dune bedforms may be passive or active contributors to braid-bar initiation and growth (Ashworth et al., 2000; Sambrook Smith et al. 2009) depending on the local flow and sediment supply conditions and those inherited from immediately upstream. Large rivers typically have channels with width-depth ratios in excess of 100 (Thorne et al., 1993; Xu, 2004; Latrubesse, 2008) that may result in a simple flow convergence and divergence around and over bartops (Richardson and Thorne, 1998; McLelland et al., 1999), but paradoxically, with few channel-wide unit bars migrating through the main thalwegs (Best et al., 2007; Sandbach et al., 2010). Some large rivers bifurcate and remain divided for 100 km and more, and some stay within a wide braidplain but experience extraordinarily high local rates of bank erosion (up to 1 km yr^{-1}, cf. Best et al., 2007). The timescales over which large rivers migrate and evolve vary considerably even for rivers with similar mean annual discharge and slope.

4. Examples of contrasting large river channel pattern

In order to appreciate the variability in big river channel pattern and processes, three examples will now be considered covering a spectrum of channel styles.

4.1 The River Ob

The River Ob has a catchment area ~2.77×10^6 km^2, a mean annual discharge ~400 X 10^9 m^3 with ice-bound winters for reaches north of Barnaul (53^o 21'N, 83^o 48'E), and is characterised by a relatively low suspended sediment yield that *decreases* significantly downstream as discharge increases (Bobrovitskaya et al., 1996; Meade et al., 2000). Upstream of the Irtysh junction at Khanty-Mansiysk (Fig. 10A) sediment yields over several decades have been less than 20 x 10^6 tonnes yr^{-1}. Since 1957, flow has been partially regulated by the Novosibirsk Reservoir (Fig. 10A). In recent decades, and in different parts of the system, there has been a decrease in summer flows because of irrigation, and greater winter flows released during power generation, but there have also been precipitation changes (Yang et al., 2004). From a geomorphological point of view the flow regime remains dominated by high-magnitude annual snowmelt floods that peak in May and June.

Below Krivosheino (Fig. 10A; elevation ~82 m) and as far as Belogor'ye (Fig. 10A; elevation ~24 m), the river flows for some 1000 km within a broad floodplain some 8-25 km wide. Valley gradients are low, generally below 0.1 m km^{-1} and almost imperceptible for long distances. Nevertheless the valley floor itself is characterised throughout by remarkable meandering channel-trace patterns with sinuous sets of scrolls and palaeochannels (Fig. 10B). These meanders have long attracted scientific attention, some reported in English language publications (e.g., Kondrat'yev and Popov, 1967; Kondrat'yev, 1968; Kulemina, 1973; Alabyan and Chalov, 1998). Meandering style involves simple loops with circular arcs and moderate sinuosity without developing low-radius bends or omega shapes. Compound loops are virtually absent, probably due in part to early-stage cutoffs and in part to a relative lack of point bar forcing/pushing (Parker et al., 2011; see further discussion later). Floodplain ridge and swale patterns suggest that radial expansion of loops has dominated.

Emergent mid-channel bars are located sporadically and rarely in the main channels, and, by comparison with channel width (c. 0.5-1.0 km) and meander arc length, many are *relatively* small in size (e.g., 2 by 0.6 km). Satellite imagery covering the period September

1989 to October 2010 near Krivosheino (Fig. 10B) shows mid-channel bars to be mostly transverse-symmetrical forms that wrap around vegetated islands, and deposit at channel junctions. Mean migration rate of the mid-channel bars at Krivosheino is 30 m yr^{-1}.

Emergent bars can have a corrugated appearance or barbed planform as a result of dune stacking (Bridge, 1993; 2003). Following bar stabilisation and growth, islands may be trimmed by bounding channels into hydrodynamic shapes, with pointed ends and elongate curving outlines (e.g., 61^{o} 04'N, 75^{o} 28'E). By contrast, in bank-attached locations, sedimentation may be in the form of narrow but much extended linear or lunate scrolls relating to loop expansion (e.g., 59^{o} 24'N, 80^{o} 02'E). These may assimilate sets of dunes and have shorter and wider stalled bars attached to them (Fig. 10B). Vegetation changes show a degree of mid-channel bar stabilisation, but much more dominant on the floodplain surface are the sets of ridges and swales marking point bar growth (Figs 10B and C).

Secondary channels are prominent across the valley floor. On main channels, there are cutoff chutes producing what Kulemina (1973) called ‘incomplete meandering’ (e.g., 61^{o} 03'N, 75^{o} 48'E) such that loop development becomes divided before the highest sinuosities are reached (cf. Mertes et al., 1996). Large point bar complexes may be bisected in this way to produce islands of asymmetric planform with a concave (inner) and a convex (outer) bank (e.g., 58^{o} 24'N, 82^{o} 27'E). Chute channels may be actively modified into shorter-wavelength meanders. There is also larger-scale anabranching in which separate meandering courses can run for many kilometres, for as much as 400 km at and below Surgut (Fig. 10A, see image in Fig. 10D). The long islands created by these chute channels may be lozenge-shaped or ‘beaded’ in appearance, widening or narrowing in relation to the independent and actively meandering bounding channels (Fig. 10D, also see the Amur at 52^{o} 00'N, 140^{o} 15'E).

This form of anabranching is different from that often associated with successful avulsion from an aggrading channel or narrow channel belt into a lower elevation floodplain or floodbasin (Makaske, 2001; Jerolmack and Mohrig, 2007; Makaske et al., 2009). On the Ob, laterally-mobile rivers occupy the whole valley floor, there are no striking channel-to-floodplain elevation differences arising through aggradation, and division is triggered during the meandering process. Avulsion is facilitated not so much by *raising* the channel or channel belt, but more likely by flood spillage via local bank *lowering* along the line of palaeochannels and swales (cf. Fig. 10D). In responding to topographic control, the meandering Ob follows one of the several avulsion mechanisms described for braided streams in which switching is guided by relict floodplain relief (Leddy et al., 1993; Warburton et al., 1993).

In addition to main channel branches, there are numerous smaller, meandering tributary and accessory channels with shorter meander wavelengths and associated scroll patterns (Figs 10C and D). Tributaries may have high sinuosities, with their own numerous cutoffs and bend dimensions scaling with channel size, but in the main valley some are guided along larger palaeochannel arcs derived from the main river or its branches. All of these channels are picked out by standing water in point bar swales (labelled 1 in Fig. 10C), in arcuate dead channel loops (labelled 2 in Fig. 10C), and in occasional broader unsedimented water bodies (labelled 3 in Fig. 10C). Older parts of the floodplain, and areas beyond the shallow valley floor, have circular thaw ponds and thermokarst features (labelled 4 in Fig. 10C).

Repeat imagery suggests moderate rates of morphological change. Fig. 10C shows scrolls on a developing loop near Ust'-Tym (location in Fig. 10A). Comparison of imagery between October 1972 and September 2010 shows a maximum of 450 m of scroll bar advance over the 38 year period (12 m yr^{-1}). This compares to rates of bank erosion on the

Ob (measured off maps from 1897-1958) of 0-15 m yr^{-1} although displacements of a kilometre or more have been measured for certain sites (Kulemina, 1973).

Even at this maximum rate, the point bar complex at Ust'-Tym would have taken three to four centuries to develop, and perhaps rather longer. In this situation, individual scrolls develop in a spit-like manner as bars accrete following bank erosion on the opposite side of the channel. Growth of detached ridges is terminated repeatedly as a new growth point develops upstream, and a large digitate area of slackwater has formed and remained unsedimented in the counterpoint zone at the downstream end of the point bar complex. The meander evolution is dominated by local bank-to-bar sediment exchange of matching volume (Neill, 1987). The low suspended-sediment supply that characterises the present-day Ob leaves abandoned channel voids as open water variously connected or detached from mainstream low-water channels.

There has been long-running interest in the seemingly paradoxical significance either of eroding bends or of depositing bars in ‘forcing’ channel change, particularly involving bar-bend theory (e.g., Blondeaux and Seminara, 1985; Ikeda and Parker, 1989). It is the dynamic flow fields that interact with particle entrainment or deposition to produce feed-back morphological effects, and both types of forcing may happen. Bars may be regarded as ‘free’ where they migrate quasi-independently, or ‘forced’ if they follow changing bend topography as growing point bars. In much the same way, Lucci et al. (2010) contrast island formation by ‘width forcing’ and ‘curvature forcing’, whilst Parker et al. (2011) describe ‘bank pull’ and ‘bar push’ processes in meanders. On the Ob, it appears that floodplain-dominating elongate point bar scrolls follow bank-arc recession and in gross terms are width-forced. Other bars are more likely related to sediment stalling in width-permitting reaches (both at divergence points and in straighter but relatively wide channels). These only rarely appear to force bank changes to produce small-scale bank ‘bites’ related to mobile/stalled bar dimensions rather than longer meander-scale arcs (cf. Lewin, 1976).

Below the junction of the Ob with the Irtysh at Khanty-Mansiysk (location in Fig. 10A), at an of elevation 80 m, the river runs for a further 650 km in a broad trough (15-50 km wide) with numerous levee-lined channels running between often-flooded wetlands. Some channels are meandering and show some evidence of past lateral migration, but the main channel can be near-straight and lined by straighter levees and scrolls showing small-scale alignment oscillations. In places (e.g., 63^{o} 41'N, 65^{o} 32'E) the main channel divides into four or five meandering ones. Open water occupies the lower ends of tributaries to this partially infilled ria. Upstream of Khanty-Mansiysk, both the Ob and the Irtysh have floodplains dominated by laterally migrating channels, and their junction marks a change to levee and backswamp-dominated sedimentation developed in the finer sediments available here. The river junction appears to coincide with a transition from sand to silt/clay dominance (cf. Latrubesse and Franzinelli, 2005).

In summary, mobile barforms and islands diversify meander morphology along the middle Ob, but it appears that elongate meander scrolls have much greater long-term preservation potential in association with planform evolution. Scrolls are temporally and spatially lagged outcomes relating to bank erosion. Scrolls temporally follow channel widening in association with erosion on the opposite bank, and spatially respond as material is received from upstream bank recession. These scrolls are especially visible and prominent, compared to some examples on smaller rivers (e.g. Nanson, 1980), because they are relatively unmasked by overbank fine sediment deposition, have little mature vegetation, and unfilled curving palaeochannels and elongate and digitate depressions between scrolls dominate.

Four types of anabranching occur on the Ob: (i) small islands generated from stabilised bars in-channel; (ii) islands with asymmetrical convex-concave outlines within larger meander bends resulting from cutoff activity; (iii) longer beaded and lozenge forms that have independently-generated multi-bend meandering outlines, and which may extend for tens to hundreds of kilometres; and (iv) small and often tortuous floodplain drainages often connecting larger palaeoforms to main channels.

Channel patterns on the Ob may be interpreted as the product of lateral meander mobility and sediment reworking under conditions of low sediment input. Downstream of Khanty-Mansiysk (Fig. 10A) there is a change in style involving levees and floodbasins. The persistence of multiple open channels, only some of which actively transmit sediment, appears to relate to sediment starvation, probably during the Holocene, Floodplain relief is therefore left open for ponding and drainage, and exposed to ongoing avulsion-breaching and reactivation where there is active channel shifting.

4.2 The Jamuna River

The Jamuna is the local name given to the Brahmaputra River for the 240 km reach that flows in Bangladesh from the northern border (25^{o} 48'N, 89^{o} 50'E) down to the junction with the Ganges (23^{o} 48'N, 89^{o} 46'E , see Fig. 11). The Jamuna has one principal tributary, the Teesta River in the north-west (Fig. 11) and two major offtakes on the left bank that are the Old Brahmaputra (abandoned in the mid-19th century, see Bristow, 1999) and the

Dhaleshwari (Fig. 11). The Jamuna is one of the most active braided rivers in the world with a braidplain up to 15 km-wide in flood, scour depths up to 40 m and bank erosion rates on average approximately 50 m yr^{-1}, but up to 1 km yr^{-1} on main channel outer bends (Klaassen and Vermeer, 1988; ISPAN, 1993; Flood Action Plan 24 1996a; Best and Ashworth, 1997; Khan and Islam, 2003; Best et al., 2007). At Bahadurabad (Fig. 11) the mean annual discharge is 20200 m^3 s^{-1}. This varies from a minimum of ~2800 m^3 s^{-1} to a peak of ~100000 m^3 s^{-1} as experienced in both the 1988 and 1998 floods (EGIS, 1997; Chowdhury, 2000). The annual hydrograph has a stage change of ~6 m (Sarker and Thorne, 2006; their figure 2, p. 291) due to monsoonal rainfall with low flow mainly in February/March and peak flows in July/August. Mean water slope is 0.000076 over the first 130 km and 0.000065 further downstream (Flood Action Plan 24, 1996b). The grain size of the Jamuna is mainly fine sand and silt with less than 1% clay (FAP24, 1996b) and an average grain size of 220 µm (Barua, 1994; Sarker and Thorne, 2006). The fine and abundant sediment supply together with high water discharges results in the one of world's highest sediment yields that is estimated at between 590 and 792 Mt yr^{-1} (FAP24, 1996a; Islam et al., 1999) with up to 10% transported as bedload (Klaassen et al., 1988).

The Jamuna is predominantly a braided river characterised by divided flow and strongly stage-dependent bars that are unconsolidated, dynamic, poorly vegetated and overtopped at flows less than bankfull. Some parts of the Jamuna have been described as anastomosing (cf. Bridge, 2003, his fig. 5.5; Sarker and Thorne, 2006, their figure 14) whereby multiple-channels with vegetated islands or stable alluvial islands divide flow up to bankfull and typical width of the channels is much smaller than that of the bars (Nanson and Gibling, 2004). Paradoxically, when slope is plotted against bankfull discharge on the classic channel pattern discrimination diagram of Leopold and Wolman (1957), the Jamuna plots in the meandering field, suggesting the controls on channel planform are more complex than solely slope and discharge (Sarker and Thorne, 2006). The Jamuna is an example of an anabranching river (Nanson and Knighton, 1996) with braided and occasional anastomosing branches that divide around vegetated, stable alluvial islands with heights up to the adjacent floodplain (Best and Ashworth, 2007).

Analysis of historical maps and recent satellite images of the Jamuna show that there has been a progressive widening of the braidbelt by ~50 m yr^{-1} over the period 1834-1992 (Flood Action Plan24, 1996a) although the rate of widening has decreased more recently to ~30 m yr^{-1} between 1992 and 2000 (Sarker and Thorne, 2006). Part of the reason for the increase in braidbelt width is attributed to the westward migration of the main channels due to uplift of the Madhupur Tract Pleistocene sediment (location in Fig. 11) (Coleman, 1969; Thorne et al., 1993; Khan and Islam, 2003), although periods of eastward migration of the braidbelt have also been recorded (EGIS, 1997). Sarker and Thorne (2006) also note that local increases in braidbelt width may be related to the propagation downstream of a sediment pulse generated by the 1950 Richter magnitude 8.6 earthquake in Assam. Localised, high rates of bank erosion are associated with the downstream migration of individual channel bends that abut the weak, non-cohesive floodplain banks that are undercut and experience large-scale slab failure (Thorne et al., 1993; Best et al., their fig. 19.25, p. 423).

Unlike the Ob (Section 4.1) and Paraná (Section 4.3), the floodplain of the Jamuna is decoupled from the main channel for most of the year (cf. Lewin and Ashworth, in press) except during peak monsoonal floods. Extensive wetlands or clusters of water bodies are absent (see Fig. 11). Floodplain relief is relatively modest and associated with (i) abandoned bars, scrolls and dunes (relief up to 2 m), (ii) river levees alongside active main channels (relief up to 3 m), (iii) crevasse splays caused by breaches of natural and human-made levees, and (iv) flood basins or enclosed depressions between the levees of adjacent channels that usually drain on the falling stage, although some permanent water bodies can contain peat accumulations (ISPAN, 1995).

Sediment transport of bed material in the Jamuna is predominantly as sand dunes that migrate at all flow stages in the main channels (Roden, 1998; Best et al., 2007, their fig. 19.7, p. 407). Dune heights range from 0.1 to 6 m (Julien and Klaassen, 1995; Roden, 1998) and with a low leeside angle (generally $< 10^{o}$) suggesting flow separation in the dune leeside is absent or intermittent as has been demonstrated for other large rivers (e.g. Smith and McLean, 1977; Kostaschuk and Villard, 1996; Ten Brinke et al., 1999; Shugar et al., 2010). The majority of flows in the Jamuna generate bedforms within the dune stability field and upper-stage bedforms are rare except in shallow flows on bar-tops (Bristow, 1993; Julien and Klaassen, 1995).

Since dunes are ubiquitous in the Jamuna, they are also responsible for the creation and growth of sand bars from 100s metres to several kilometres in length (Figs 11 and 12). Two scales of bars exist in the Jamuna: (i) ‘compound bars’ (Fig. 12B, labelled 2) that scale with local channel width and mean flow depth, and (ii) ‘vegetated islands’ (Fig. 12B, labelled 3) that are stable, older, bar complexes with heights up to the adjacent floodplain (Thorne et al., 1993; Ashworth et al., 2000). Compound bars in the Jamuna are predominantly composed internally of stacked 2D and 3D dunes although bar-margin slipface accretion is also present at barheads and at obliquely migrating bar edges (Bristow, 1993; Best et al., 2003, their fig. 5, pp. 522-523).

Migrating unit bars that are discrete, solitary barforms with a lobate planform (Bridge, 1993) are rare in the Jamuna (Fig. 12B, labelled 1), which is different from observations in smaller sand-bed rivers (e.g. Smith, 1971; Sambrook Smith et al., 2006). Unit bars are not prevalent as exposed bedforms either at low flow in the main or secondary channels (Figs. 12A-B and D), or in the subsurface (Best et al., 2003). It is unclear why unit bars, that are the fundamental building block in small sand-bed rivers (Sambrook Smith et al. 2006), are not common in large rivers (see the same observation for the Rio Paraná in Section 4.3). One reason may be that the potential for unit bar initiation and channel-wide extension is reduced due to the suppression or absence of significant channel-wide secondary flows as observed in large rivers with high width-depth ratio channels (McLelland et al., 1999; Parsons et al., 2007).

Bar types in the Jamuna are commonly mid-channel, longitudinal forms (Figs 12A-D) with sharp, erosional margins (Fig. 12D) indicative of the high degree of reworking and bar trimming. Mid-channel bars maintain their rhomboidal planform shapes at high flow (Fig. 12C) rather than becoming heavily dissected with cross-channels of different orders. Mid-channel bars enlarge both up-, down- and across-stream by either adding dunes that stall and stack at the bar margins (Best et al., 2003), or through lateral accretion by addition of successive individual scroll bars (Bristow, 1987). Migration rates for small (< 4 km long), unvegetated compound bars are extremely high at up to 3 km yr^{-1}, but larger compound bars (up to 10 km long) move more slowly at up to 1 km yr^{-1} usually through progressive barhead reworking and bartail accretion (cf. Best et al., 2007; their figs 19.26b-h, p. 425). The rapid rates of bar migration, bank erosion and channel change mean that the entire planform of the active parts of the Jamuna braidbelt (usually up to 5 km-wide) is reworked over a decadal time-scale (compare Figs 12A-D) and km-long bars are created, migrate and are then destroyed in under five years (Ashworth et al., 2000; Best et al., 2007). Only the vegetated and higher 'islands' are stable for more than decades often because the main channel has avulsed or migrated over to another part of the braidplain. The Jamuna represents one of the world's most dynamic large rivers with ephemeral bars, a shifting braidbelt and a planform that is continually changing.

4.3 The Rio Paraná

The Río Paraná has a drainage basin of 2.6 x 10^6 km^2 that covers the surface of four countries in South America (Latrubesse et al., 2005; Iriondo, 2007). The 3965 km-long Paraná is divided conventionally into three reaches termed the Upper Reach (source to the junction with the Rio Paraguay near Corrientes), Middle Reach (down to Diamante) and Lower Reach (to the mouth) (locations in Fig. 13A, see Orfeo and Stevaux, 2002; Ramonell et al., 2002; Iriondo, 2007). The discussion herein concentrates on parts of the Upper and Middle reaches from Itati (27^o 16'S, 58^o 14'W) to Santa Fe (31^o 38'S, 60^o 42'W) (Fig. 13A).

Mean annual water discharge of the Paraná at Itati is ~12,000 m^3 s^{-1}, increasing to ~17,000 m^3 s^{-1} at Corrientes, 30 km downstream of the Río Paraguay tributary (Orfeo and Stevaux, 2002). Maximum discharge measured on the Paraná in the last century is associated with an El Niño-driven large flood in 1983 that peaked at 33,740 m^3 s^{-1} in the Upper Reach (Orfeo and Stevaux, 2002) and 55,000 m^3 s^{-1} in the Middle Reach (Amsler and Garcia, 1997). Mean bed slope near Corrientes ranges from 0.000049 (bankfull water surface slope; Latrubesse, 2008) to 0.000085 (channel slope; Orfeo and Stevaux, 2003). Mean annual sediment discharge of the Paraná increases dramatically from ~19 to ~158 x 10^6 t yr^{-1} at the junction with the Río Paraguay, primarily due to the large input of suspended sediment from the Paraguay-Bermejo tributary system (Lane et al., 2008; Amsler and Drago, 2009). Between 80 and 91% of the sediment load in the Middle Reach of the Paraná is silt and clay washload (Amsler et al., 2007; Amsler and Drago, 2009). Bed material of the Upper and Middle Reaches of the Río Paraná is well sorted, predominantly medium-to-fine sand although some fine gravel is present in the channel thalweg (Santos and Stevaux, 2000; Amsler et al., 2007).

Except at the junction with the Rio Paraguay (Fig. 13A), the outline planform of the Upper and Middle Reaches of the Paraná is relatively straight (sinuosity less than 1.3; Amsler et al., 2005), but with downstream alternations between 2-3 km wide 'enlargements' that are characterised by two or more main channels with mean depths of 5-8 m, and 0.6-1.2 km-wide, and well-defined, structurally-controlled constrictions with mean depths of 15-25 m that are generally stable and have not migrated for the last 80 years (Amsler et al., 2005; Iriondo, 2007). The channel planform of the Paraná can be described as anabranching because it contains multiple-channels that contain stable vegetated bars that divide flow up to bankfull (Nanson and Knighton, 1996; Latrubesse, 2008). However, the division of discharge around the km-scale bars is rarely even and usually one anabranch is dominant (Parsons et al., 2007; Szupiany et al., 2009; Sandbach et al., 2010).

The Rio Paraná bed is dominated by dunes at all flow stages (Parsons et al., 2005; Kostaschuk et al., 2009; Shugar et al., 2010). Mean dune height and lengths of 1.5 and 6.4 m respectively have been measured at low flow (~11000 m^3 s^{-1}) near Corrientes with superimposed dune heights and lengths of 0.3 m and 10 m (Parsons et al., 2005; Sambrook

Smith et al., 2009). However, much larger dunes have been observed during floods in the Paraná with heights up to 6.5 m and lengths of 320 m during the historic large flood in 1983 (Amsler and Garcia, 1997). Dunes in the Paraná, and in other large sand-bed rivers such as branches of the Rhine and the Mississippi, may respond differently to rising flow stage compared to smaller rivers (Garcia, 2008). Small dunes grow readily as discharge increases but large dunes have been observed to do the opposite (Amsler and Garcia, 1997; their fig. 9, p. 583). Large dunes (> 1 m in height) may flatten and develop much lower leeside angles during peak discharges possibly in response to an increase in suspended load, although large dunes probably do not reach upper-regime plane bed during major floods (Julien and Klaassen, 1997) Dunes therefore represent significant bed roughness in large rivers and cause disruption to the near-bed flow structure (Parsons et al., 2005; Shugar et al., 2010) that may have a significant effect on flow routing and the development of secondary flow circulation (Parsons et al., 2007; Sandbach et al., in press).

Similar to the Jamuna, sand bar deposits in the Upper and Middle Paraná are dominated by stacked 2D and 3D dunes together with high- and low-angle bar margin accretion surfaces. Also similar to the Jamuna, bathymetric surveys on the Paraná reveal no conclusive evidence for the prevalence or even presence of migrating unit bars through the main channels (e.g., Shugar et al., 2010, their fig. 3, p. 259) even at major channel junctions such as the convergence of the Paraguay and Paraná (Lane et al., 2008; their fig. 2, p. 5).

Four features characterise the Paraná planform morphology. Firstly, within the near-straight channel outline, a dominantly sinuous meandering thalweg, up to 2 km wide and 26 m deep at outer bank scours, with a wavelength of ~12 km (Sandbach et al., 2010, their fig. 1, p. 410). This thalweg can convey up to 70% of the discharge and controls the direction of primary flow in most reaches with only localised curvature-driven secondary flow circulation (Sandbach et al., 2010; Nicholas et al., in press). The dominance of a well-defined sinuous thalweg means the Paraná is essentially a meandering main-stem trapped within an anabranching channel-belt. Enlargement and downstream migration of the sinuous thalweg is responsible for the majority of bankline change with maximum bank retreat rates of 100 m yr^{-1} (Ramonell et al., 2002), but major avulsion over century time-scales is absent.

A second feature is a partially-coupled main and accessory channel system (see Fig. 8C). North of Itati (Fig. 13A), the accessory channels probably owe their origin to former channel belts of a Quaternary alluvial megafan that radiated out from ~200 km upstream of the Paraguay-Paraná junction (Iriondo, 2007; his figure 2.2, p. 35). These accessory channels are highly sinuous and at locations (e.g., at 27^{o} 15'S, 58^{o} 27'W) are close to eroding through the intervening floodplain material and avulsing into the main Paraná channel. Some accessory channels are major offtakes (e.g. the 49 km-long Colastine and the 45 km-long offtake at Puerto Reconquista, locations in Figs 13B-C) and are rivers in their own right, conveying discharges up to 1400 m^3 s^{-1} and experiencing lateral bank erosion of several metres per year (Iriondo, 2007).

A third feature of the Paraná is having few exposed sand bars, particularly in the Middle Reach. Sand bars are typically bank-attached, transverse or medial bars (Santos and Stevaux, 2000) with low-flow, mean geometries of ~0.6 (±0.4) km in length and 0.3 (±0.2) km in width. Drago (2010) measured the prevalence of different sand bar types in a 1087 km reach downstream of the Yacyretá Dam (27^{o} 29'S, 56^{o} 44'W) and noted accumulations of sand onto the barheads of km-scale vegetated bars accounted for up to 77% of all sand bar types. Drago's work showed a strong positive correlation between the number of sandy barheads and distance downstream which he suggested may be attributed to the higher ratio of suspended-to-bedload downstream and therefore access to a source of more sandy material. Isolated, sandy, non-vegetated bars are surprisingly rare in the main channel between Itati and Santa Fe. Figure 14 shows decadal years of channel change and bar development at the downstream end of the Middle Reach of the Paraná. Although a new, 2.5-km long, mid-channel bar developed in the mid-1980s (Figs 14 and 15), probably in response to upstream scour and subsequent bank erosion during the large 1983 flood, the 40–km reach shown in Fig. 14 is characterised by the lack and slowness of channel change. Whilst the internal morphology of the new mid-channel bar is complex and suggests several phases of aggradation and scroll bar addition (Fig. 15), the overall planform is relatively simple and predictable (Fig. 14). Indeed, if the development of the same reach shown in Fig. 14 is extended over longer time-scales using historic bathymetric surveys (Fig. 16), the morphological change is characterised by a slowly migrating, sinuous thalweg that sweeps across the channel-belt rather than rapid rates of bank retreat, bar reworking and local avulsion as seen in the Jamuna (compare to Fig. 12). In the Paraná, heavily vegetated bars, up to 15 km-long, but more typically 5-8 km-long, fix and control the local channel morphology. Sand bars are incidental, ephemeral depositional elements that wrap onto and around these stable islands. The fully vegetated, stable islands are probably 100s to 1000s of years old and are only completely overtopped in low recurrence-interval, major overbank floods (e.g. ~27000 $m^3 s^{-1}$ at Itati in January 2010).

Finally, a fourth feature of the Paraná morphology is the presence of extensive lotic (flowing water) and lentic (still water) ecosystems that are eroded, filled or enlarged in each flood event (Paira and Drago, 2006; 2007). Water bodies are linked ultimately to the short and long-term main river channel dynamics and are associated with (a) secondary channels and ridge and swale topography in or immediately adjacent to the main channels, but also (b) up to 28 km away where the floodplain develops to the margin of the alluvial valley (e.g. Fig. 7A) and water accumulates in depressions associated with older channel scars and zones that are affected by neotectonic uplift and subsidence (Paira and Drago, 2007). Average lake length, width and depth is ~1.1 km, 0.4 km and 1.6 m respectively (1500 lakes measured in the Middle Paraná; Paira and Drago, 2007). Nearly 25% of the Middle Paraná floodplain lakes have 5% of their surfaces covered with free or rooted macrophytes although the coverage of aquatic vegetation ranges from 0 to 100% in lakes with areas less than 2 km^2 (Paira and Drago, 2006). Water bodies are therefore important carbon sinks and large portions of the thick organic matter on their beds can be completely excavated during large floods (Drago et al., 2003).

4.4 Three of the world's largest rivers with three very different styles of channel pattern

The Ob, Jamuna and Paraná are three of the world's greatest rivers whether measured by catchment area, runoff or, in the case of the Jamuna and Paraná, sediment yield (Figs 1A-B, Table 1). Like most big rivers all three rivers are anabranching, not only divided, but also with a plural mixing of styles with accessory and tributary floodplain channels (Figs 8C, and 13B-C). They all have low valley gradients (generally <1 m km^{-1}), main-channel sandy bed sediments, and variable suspended sediment loadings. Latrubesse (2008) suggests that low specific stream powers of <25 W m^{-2} are characteristic of large ('mega') rivers. However, such common properties are associated with different morphologies on the Ob, Jamuna and Paraná and anabranching in each, is in practice, achieved in different ways.

In a spectrum of mainstream channel styles (Table 1, Figs 3 and 8), the Paraná is virtually straight in outline with a sinuous thalweg, the Ob meanders and the Jamuna braids. Sediment transfer styles differ considerably between the three rivers. In terms of the classification introduced in Fig. 6 and Table 1, the Ob is (d,f,g,j)-dominant, the Jamuna (f,g,h,i)-dominant, and the Paraná is a (c,d,e,h) mixture. They are contrasted in terms of bed material in-channel transfers, channel shift rate and lateral floodplain exchange, and the extent to which activity beyond the main channel controls valley floor morphology. Mean rates of bank erosion and bar migration for the three rivers are orders of magnitude apart with the Jamuna reworking its entire active braidplain every 10 years but the Ob and Paraná taking decades-to-centuries to build individual bars. The Jamuna has few permanent floodplain water bodies yet lotic and lentic ecosystems are an integral part of the channel pattern and functioning of the Ob and Paraná. Clearly, some of the inter-river variability in channel pattern is explained by regional and local controls such as climate, neotectonics and regolith/erosion potential, but it is the variable sediment feeds and a range of in-channel and channel-to-floodplain sediment exchanges that give each large river its unique style.

5. Large and small river channel pattern

The world's largest rivers differ from their monotonic smaller counterparts because they have greater complexity introduced by crossing a series of chains of interlinked domains with contrasting fluvial functions (Section 2, see Fig. 2). Large rivers do not have a simple down-valley trend in controlling variables (e.g., discharge, slope, grain size) as experienced in small river catchments, nor do they have the associated downstream progression in channel pattern (Church and Jones, 1982; their fig. 11.8, p. 303). Large rivers are highly-refined sediment transport systems often showing little change in grain size over 100s of kilometres (Amsler et al., 2007; Frings, 2008) in direct contrast to smaller, headwater streams (Ferguson et al., 1996). Big rivers have significant reaches that are dominated by laterally migrating channels because the wide and low-gradient floodplains provide accommodation space for channel shifting that is possible because of available energy. Large rivers usually contain significant (in terms of water and sediment discharge) tributaries, but unlike smaller rivers, big rivers have 100s of kilometres to mix these incoming flows and sediments (Lane at al., 2008) and therefore can absorb any potential perturbation from a new sediment input grain size or volume (cf. Rice, 1998). Big rivers have partially- and temporarily-coupled channels and floodplains (Figs 7A-B; see definitions and discussion in Lewin and Ashworth, in press) where the dispersal and sediment storage overbank and in adjacent water bodies can be a significant process for months of the year (Dunne et al., 1998; Day et al., 2008).

Some researchers have investigated whether the channel pattern and planform morphology of anabranching rivers is the same for large and small rivers. It has been shown convincingly that braided river network patterns are scale invariant (e.g., Sapozhnikov and Foufoula-Georgiou, 1996; Nykanen et al., 1998; Sapozhnikov et al., 1998; Foufoula-Georgiou and Sapozhnikov, 2001). Likewise, Sambrook Smith et al. (2005) and Kelly (2006) have shown that surface planform (long-to-intermediate axis) of mid-channel bars is scale invariant for a range of anabranching rivers over a four order of magnitude range in size. To some extent this latter result is not surprising given that mid-channel bars will always be streamlined by the flow, but stark variations do exist, seemingly associated only with big rivers. For example, over 1200 km of the Congo (shown in Fig. 3E) and 250 km of the Negro (shown in Figs 5A-B) have mid-channel bars that are especially elongated (mean intermediate-to-long axis of 0.25). It is unclear why these bars should have such different planform morphologies from other large rivers (e.g. the Jamuna, Fig. 12) but it may be related to the local bar-building process that is through inwardly-accreting levees and ridges (Figs 5A-B; Latrubesse and Franzinelli, 2005) and/or the influence of mature vegetation that reduces the potential for avulsion and substantial reworking.

Previous work has shown that the world's largest rivers have main channels with different cross-sectional morphologies than smaller rivers (Xu, 2004; Latrubesse, 2008). For example, Latrubesse (2008) compiled data on the width:depth ratio for 16 large rivers that showed most values were greater than 30, with 5 greater than 100. Two of the world's largest rivers, the Paraná and Jamuna, have channels with width:depth ratios greater than 200 and it has been suggested that such channel geometries may suppress or prevent the development of channel-wide secondary flows that are common in smaller rivers (McLelland et al., 1999; Parsons et al., 2007). Despite widespread agreement that big rivers have different average cross-sectional geometries than smaller rivers, there is a closer correspondence in maximum relative depth of confluence scour for different types and sizes of rivers (Sambrook Smith et al., 2005; their fig. 2, p. 148), therefore suggesting there are some similar underlying processes governing the evolution of both small and large rivers.

6. Conclusions

The world's largest rivers drain about half of the global continental land and are highly-refined sediment transport systems. Most are generally low-gradient and fine-grained yet they are *strongly differentiated* – much more so than most previously-studied smaller rivers. Big rivers have several notable attributes:

1. Trans-continental rivers link up contrasted sets of erosion/sedimentation domains; they are intrinsically more highly differentiated from one another and have greater internally complexity along their courses than smaller monotonic fluvial systems.

2. Despite their high absolute values, sediment loadings in trans-continental rivers may have been considerably reduced by upstream sequestration. Perhaps counter-intuitively, the largest rivers can also be *sediment-poor* for their size because major sub-catchments are low-yielding.

3. Alluvial settings are dependent on mainstream and tributary inputs of water and sediment, but alluvial morphologies are essentially determined at the reach scale by the variable sediment feeds and range of in-channel and channel-to-floodplain sediment exchange styles.

4. Anabranching planform channel patterns dominate, with a system of multiple channels that divide and rejoin. But anabranching is achieved by different processes, as is illustrated by the Ob, Jamuna and Paraná.

5. Big rivers contain a bewildering range of channel planforms – from single to multiple channels, some highly sinuous, with bars dominated by lateral accretion, but others by downstream migration and a floodplain that can be dominated by adjacent standing water bodies in a range of size that may be refilled during floods. Main channels can be straight, meandering, braided, wandering or anastomosing. Individual branch channel patterns are determined by the degree of lateral shifting and avulsion, rate of overbank sedimentation, magnitude of sediment transport capacity and bed material/braiding intensity.

6. Forms of alluvial exchange can be classified as: (i) deposition on the floodplain (e.g., levees, infilled palaeochannel, floodbasins), (ii) exchanges involving main channels (e.g., bank erosion and accretion), (iii) deposition within main channels (e.g. bedforms from metres to 10s of kilometres in size), and (iv) material input from tributaries (sediment-rich or sediment-poor). Whilst the size of channels reflects formative water discharges, it is these variations in sediment exchange that produce the diversity of big river morphologies.

7. Fine out-of-channel sediment deposition may be insufficient to fill hydraulic corridors; ponded lacustrine environments are common. Water bodies vary from smaller water-

filled swales and palaeochannels, to floodbasins between raised alluvial ridges and valley-sides, and to km-scale linear lakes in sediment-dammed tributaries. Organic sedimentation is significant along relatively sediment-poor and laterally-stable major rivers that fail to fill their alluvial corridors.

8. Hydraulic and sedimentation systems may be divided into four types: (i) lacustrine-dominated, (ii) mainstream-dominated, (iii) tributary or accessory-stream dominated, and (iv) confined or bedrock-dominated.

9. Big rivers are commonly *plural systems,* with partial functional decoupling between large rivers and their hydraulic floodplains, and with accessory and tributary channels rather than main-river branches determining patterns of floodplain morphology. Straight, bedform-dominated mainstreams may have accessory channels that actively meander to dominate near-surface floodplain sedimentation.

10. Bed sediment transfers are dominated by migrating sandy bedforms but with a wide range of bar types, shapes and rates of accretion. No style of bar creation or aggradation is unique to big rivers and many barforms are short-lived, ephemeral features that wrap around or onto stable vegetated islands that control the planform morphology. Lobate, unit bars are rare or absent in some of the world's largest sand-bed rivers.

11. Some processes and patterns are different from smaller rivers, including: (i) less straight-forward sequencing of channel pattern downstream, (ii) main channels with high width:depth ratios and possibly limited channel-wide secondary flows, (iii) few or no channel-wide unit bars migrating through the main thalwegs, (iv) extensive and low-gradient floodplains that provide space for channel shifting and floodplain sedimentation, (v) long distances between significant tributaries to allow full mixing of water and sediment discharges, (vi) partial and sometimes temporarily decoupled channels and floodplains, (vii) significant floodplain water bodies that readily act as sinks for fine-grained and organic sediments.

12. There can be an apparent disconnect between observable channel processes and overall patterns of channels and floodplains. In part this arises from different activity timescales, in part from inheritance. The understanding of observed 'contemporary' forms requires attention to: flood-event transfer of sediment, reach-scale incremental reworking of floodplain sediments and bar changes on a timescale of years to centuries, and the inheritance and modification of floodplain forms and sediments that relate to Quaternary change.

Big rivers have a distinctive character and their pattern variety may usefully be viewed in terms of sediment systems operating at *both* the catchment and reach scales. Between-river variability and internal complexity show the need to understand contrasted sediment supply, through-put and local alluvial exchange as determinants of big river morphology and pattern.

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References

Aalto, R.E., Dunne, T., Guyot, J.L., 2006. Geomorphic controls on Andean denudation. Journal of Geology 114, 85-99.

Abbado, D., Slingerland, R., Smith, N.D., 2005. Origin of anastomosis in the upper Columbia River, British Columbia, Canada. In: Blum, M.D., Marriot, S.B., Leclair, S.M. (Eds.), Fluvial Sedimentology VII. Special Publication of the International Association of Sedimentologists, 35, Blackwell, Oxford, UK, 3–15.

Adams, P.N., Slingerland, R.L., Smith, N.D., 2004. Variations in natural levee morphology in anastomosed channel flood plain complexes. Geomorphology 61, 127-142.

Alabyan, A., Chalov, R., 1998. Types of river channel patterns and their natural controls. Earth Surface Processes and Landforms 23, 467-474.

Allison, M.A., Kuehl, S.A., Martin, T.C., Hassan, A., 1998. Importance of flood-plain sedimentation for river sediment budgets and terrigenous input to the oceans: insights from the Brahmaputra-Jamuna River. Geology 26, 175-178.

Amsler, M.L., Drago, E.C., 2009. A review of the suspended sediment budget at the confluence of the Paraná and Paraguay Rivers. Hydrological Processes 23, 3230-3235.

Amsler, M.L., Garcia, M.H., 1997. Sand-dune geometry of large rivers during floods – Discussion. Journal of Hydraulic Engineering 123(6), 582-585.

Amsler, M.L., Drago, E.C., Paira, A.R., 2007. Fluvial sediments: main channel and floodplain interrelationships. In: Iriondo, M.H., Paggi, J.C., Parma, M.J. (Eds.), The Middle Paraná River. Springer-Verlag, Berlin, 123-141.

Amsler, M. L., Ramonell, C. G., Toniolo, H. A., 2005. Morphologic changes in the Paraná River channel (Argentina) in the light of climate variability during the 20th century. Geomorphology 70, 257-278. Doi:10.1016/j.geomorph.2005.02.008.

Archer, A.W., 2005. Review of Amazonian depositional systems. In: Blum, M.D., Marriott, S.B., Leclair, S. (Eds.), Fluvial Sedimentology VII, Special Publication International Association of Sedimentologists 35, 17-39.

Ashmore, P.E., 1991. How do gravel-bed rivers braid? Canadian Journal of Earth Sciences, 28, 326-341.

Ashworth, P.J., Best, J.L., Roden, J.E., Bristow, C.S., Klaassen, G.J., 2000. Morphological evolution and dynamics of a large, sand braid-bar, Jamuna River, Bangladesh. Sedimentology 47, 533-555.

Assine, M.L., Silva, A., 2009 Contrasting fluvial styles of the Paraguay River in the northwestern border of the Pantanal wetland, Brazil. Geomorphology 113, 189-199. DOI: 10.1016/j.geomorph.2009.03.012.

Baker, V.R. 2007. Greatest Floods and Largest Rivers. In: Gupta, A. (Ed.), Large Rivers: Geomorphology and Management, Wiley, Chichester, 65-74.

Barua, D.K., 1994. On the environmental controls of Bangladesh river systems. Asia Pacific Journal on Environment and Development Bangladesh. 1, 81-98.

Best, J.L., 2005. The fluid dynamics of river dunes: A review and some future research directions. Journal of Geophysical Research, 110 (F04S01). Doi:10.1029/2004JF000218.

Best, J.L., Ashworth, P.J., 1997. Scour in large braided rivers and the recognition of sequence stratigraphic boundaries. Nature 387, 275-277.

Best, J.L., Ashworth, P.J., Bristow, C.S., Roden, J.E., 2003. Three-dimensional sedimentary architecture of a large, mid-channel sand braid bar, Jamuna River, Bangladesh. Journal of Sedimentary Research 73, 516-530.

Best, J.L., Ashworth, P.J., Sarker, M.H., Roden, J.E. 2007. The Brahmaputra-Jamuna River, Bangladesh. In: Gupta, A. (Ed.), Large Rivers: Geomorphology and Management. Wiley, Chichester, 395-433.

Blondeaux, P., Seminara, G., 1985. A unified bar-bend theory of river meanders. Journal of Fluid Mechanics 157, 449-470.

Bobrovitskaya, N.N., Zubkova, C., Meade, R.H., 1996. Discharges and yields of suspended sediment in the Ob' and Yenisey Rivers of Siberia. In: Erosion and Sediment Yield: Global and Regional Perspectives, IASH Publication 236, 115-123.

Brice, J.C., 1975. Air photo interpretation of the Form and Behaviour of Alluvial Rivers. Final Report to the US Army Research Office, 13 pp.

Bridge, J.S., 1993. The interaction between channel geometry, water flow, sediment transport and deposition in braided rivers. In: Best, J.L., Bristow, C.S. (Eds.), Braided Rivers, Geological Society of London Special Publication, 75, 13-71.

Bridge, J.S., 2003. Rivers and Floodplains: Forms, Processes and Sedimentary Record. Blackwell, Malden, USA, 491pp.

Bristow, C.S., 1987. Brahmaputra River: Channel migration and deposition. In: Ethridge, F.G., Flores, R.M., Harvey, M.D. (Eds.), Recent Developments in Fluvial Sedimentology, Special Publication Society Economic Palaeontology and Mineralogy 39, 63-74.

Bristow, C.S.. 1993. Sedimentary structures in bar tops in the Brahmaputra River, Bangladesh. In: Best, J.L., Bristow, C.S. (Eds.), Braided Rivers, Special Publication Geological Society, 75, 277-289.

Bristow, C.S., 1999. Avulsion, river metamorphosis and reworking by underfit streams: a modern example from the Brahmaputra River in Bangladesh and a possible ancient example in the Spanish Pyrenees. In: Smith, N.D., Rogers, J. (Eds.), Fluvial Sedimentology VI. International Association of Sedimentologists, Special Publication, 28, 221-230.

Brooks, G.R., 2003. Alluvial deposits of a mud-dominated stream: the Red River, Manitoba, Canada. Sedimentology 50, 441-458.

Burge, L.M., Lapointe, M.F., 2005. Understanding the temporal dynamics of the wandering Renous River, New Brunswick, Canada. Earth Surface Processes and Landforms, 30, 1227-1250. Doi: 10.1002/esp.1196.

Carson M.A., 1984. Observations on the meandering–braided river transition, the Canterbury plains, New Zealand: part two. New Zealand Geographer 40(2), 89–99.

Chen, Z., Xu. K., Watanabe, M. 2007. Dynamic hydrology and geomorphology of the Yangtze River. In: Gupta, A. (Ed.), Large Rivers: Geomorphology and Management. Wiley, Chichester, 457- 469

Chowdhury, M.R., 2000. An assessment of flood forecasting in Bangladesh: the experience of the 1998 flood. Natural Hazards 22, 139-169.

Church, M., 2006. Bed material transport and the morphology of alluvial rivers. Annual Review of Earth and Planetary Sciences 34, 325-354.

Church, M., Jones, D., 1982. Channel bars in gravel-bed rivers. In: Hey, R.D., Bathurst, J.C., Thorne, C.R. (Eds.), Gravel-bed rivers. John Wiley and Sons, Chichester, UK, 291-336.

Church, M., Kellerhals, R., Day, T.J., 1989. Regional clastic sediment yield in British Columbia. Canadian Journal of Earth Sciences 26, 31-45.

Coleman, J.M., 1969. Brahmaputra River: channel processes and sedimentation, Sedimentary Geology 3, 129-239.

Constantine, J.A., Dunne, T., Piégay, H., Kondolf, G.M., 2010. Controls on the alluviation of oxbow lakes by bed-material load along the Sacramento River, California. Sedimentology 57, 389-407. Doi 10.1111/j.1365-3091.2009.01084.x

Costard, F., Gautier, E., 2007. The Lena River: hydromorphodynamic features in a deep permafrost zone. In: Gupta, A. (Ed.), Large Rivers: Geomorphology and Management. Wiley, Chichester, 225-233.

Davidson, S.K., North, C.P., 2009. Geomorphological regional curves for prediction of drainage area and screening modern analogues for rivers in the rock record. Journal of Sedimentary Research 79, 773-792. Doi 10.2110/jsf.2009.080

Day, G., Dietrich, W.E., Rowland, J.C., Marshall, A., 2008. The depositional web on the floodplain of the Fly River, Papua New Guinea. Journal of Geophysical Research 113, F01S02. Doi:10.1029/2006JF000622.

Drago, E.C., 2010. Notes on the upstream growth of sand bars in large rivers. The case of the Paraná River. Instituto Nacional de Limnologia (INALI). Cientificas y Técnicas de Argentina, October 2010, 14 pp.

Drago, E.C., Ezcurra de Drago, I., Oliveros, O., Paira, A., 2003. Aquatic habitats, fish and invertebrate assemblages of the Middle Paraná River, Argentina. Amazoniana 17, 291-341.

Dunne, T., Mertez, L.A.K., Richey, J.E., Forsberg, B.R., 1998. Exchanges of sediment between the floodplain and the channel of the Amazon River in Brazil. Geological Society of America Bulletin 110, 450-467.

Eaton, B., Millar, R., Davidson, S., 2010. Channel patterns: braided, anabranching, and single-threaded. Geomorphology 120, 353-364.

EGIS (Environmental and GIS Support Project for Water Sector Planning), 1997. Morphological dynamics of the Brahmaputra-Jamuna River. Prepared for Water Resources Planning Organization, Dhaka, Bangladesh, 76 pp.Ferguson, R.I., 1987.

Hydraulic and sedimentary controls of channel pattern. In: Richards, K.S. (Ed.). River Channels: Environment and Process, Blackwell, Oxford, 129-158.

Ferguson, R.I., Hoey, T.B., Wathen, S.J., Werritty, A., 1996. Field evidence for downstream fining of river gravels through selective transport. Geology, 24, 179-182.

Fielding, C.R., 2007. Sedimentology and stratigraphy of large river deposits: recognition in the ancient record, and distinction from “incised valley fills”. In: Gupta, A. (Ed.), Large Rivers: Geomorphology and Management, Wiley, Chichester, 97-113.

Fielding, C.R., Ashworth, P.J., Best, J.L., Prokocki, E.W., Sambrook Smith, G.H., in press. Tributary, distributary and other fluvial patterns: what *really* represents the norm in the continental rock record? Sedimentary Geology. DOI: 10.1016/j.sedgeo.2012.03.004.

Flood Action Plan 24; Delft Hydraulics and DHI, 1996a. FAP24 River Survey Project, Final Report, Main Volume (prepared for FPCO), Dhaka, Bangladesh, 280 pp.

Flood Action Plan 24; Delft Hydraulics and DHI, 1996b. FAP24 River Survey Project, Final Report – Annex 3: Hydrology, (prepared for FPCO), Dhaka, Bangladesh.

Foufoula-Georgiou, E., Sapozhnikov, V., 2001. Scale invariances in the morphology and evolution of braided rivers. Mathematical Geology 33, 273–291.

Frings, R.M., 2008. Downstream fining in large sand-bed rivers. Earth-Science Reviews 87, 39-60.

Froese, D.G., Smith, D.G., Clement, D.T., 2005. Characterizing large river history with shallow geophysics: Middle Yukon River, Yukon Territory and Alaska. Geomorphology 67, 391-406. Doi: 10.1016/j.geomorph.2004.11.011.

Garcia, M.H., 2008. Sediment transport and morphodynamics. In: Garcia, M.H. (Ed.), Sedimentation Engineering: Processes, Management, Modeling, and Practice. American Society of Civil Engineers, Virginia, USA, 21-146.

Goudie, A.S., 2005. The drainage of Africa since the Cretaceous. Geomorphology 67, 437-456.

Gibling, M.R., 2006. Width and thickness of fluvial channel bodies and valley fills in the geological record: a literature compilation and classification. Journal of Sedimentary Research 76, 731-770.

Gomez, B., Eden, D.N., Hicks, D.M., Trustrum, N.A., Peacock, D.H., Wilmhurst, J., 1999. Contribution of floodplain sequestration to the sediment budget of the Waipaoa River, New Zealand. In: Marriott, S.B., Alexander, J. (Eds.), Floodplains: Interdisciplinary Approaches, Special Publication Geological Society of London 163, 69-88.

Goodbred, S.L., Kuehl, S.A., 1999. Holocene and modern sediment budgets for the Ganges-Brahmaputra River system: evidence for highstand dispersal to flood-plain, shelf and deep-sea depocentres. Geology 27, 559-562. Doi: 10.1130/0091-7613.

Grabowski, R.C., Droppo, I.G., Wharton, G., 2011. Erodibility of cohesive sediment: The importance of sediment properties. Earth-Science Reviews 105, 101-120. Doi: 10.1016/j.earscirev.2011.01.008.

Gupta, A., (Ed.), 2007. Large Rivers: Geomorphology and Management. Wiley, Chichester, 689pp.

Hartley, A.J., Weissmann, G.S., Nichols, G.J., Warwick, G.L., 2010. Large distributive fluvial systems: Characteristics, distribution, and controls on development. Journal of Sedimentary Research 80, 167–183. Doi:10.2110/jsr.2010.016.

Holeman, J.N., 1968. The sediment yield of major rivers of the world. Water Resources Research 4, 737-747.

Hovius, N., 1998. Controls on sediment supply by large rivers. In: Shanley, K.W., McCabe, P.J. (Eds.), Relative Role of Eustasy, Climate and Tectonics in Continental Rocks, SEPM Special Publication 59, Tulsa Oklahoma, 4-15.

Ikeda, S., Parker, G. (Eds.). 1989. River Meandering. Water Resources Monograph 12, American Geophysical Union, Washington DC. 485pp.

Iriondo, M.H., 2007. Geomorphology. In: Iriondo, M.H., Paggi, J.C., Parma, M.J. (Eds.), The Middle Paraná River. Springer-Verlag, Berlin, 33-52.

Iriondo, M.H., Paggi, J.C., Parma, M.J. (Eds.), 2007. The Middle Paraná River. Springer-Verlag, Berlin, 382pp.

Islam, M.R., Begum, S.F., Yamaguchi, Y., Ogawa, K., 1999. The Ganges and Brahmaputra rivers in Bangladesh: basin denundation and sedimentation. Hydrological Processes 13, 2907-2923.

ISPAN (FAP 16 and FAP 19), 1993. The dynamic physical and human environment of riverine charlands: Jamuna. Dhaka, Bangladesh.

ISPAN (FAP 16 and FAP 19), 1995. A study of sedimentation in the Brahmaputra-Jamuna Floodplain. Dhaka, Bangladesh.

Jerolmack, D.J., Mohrig, D., 2007. Conditions for branching in depositional rivers. Geology 35, 463-466. Doi: 10.1130/G23308A.1.

Jerolmack, D. J., Paola, C., 2010. Shredding of environmental signals by sediment transport. Geophysical Research Letters 37, L19401. Doi:10.1029/2010GL044638.

Julien, P.Y., Klaassen, G.J., 1995. Sand-dune geometry of large rivers during floods. Journal of Hydraulic Engineering 121, 657-663.

Julien, P.Y., Klaassen, G.J. 1997. Closure of Discussion 'Sand-dune geometry of large rivers during floods'. Journal of Hydraulic Engineering 123, 584-585.

Kelly, S., 2006. Scaling and hierarchy in braided rivers and their deposits: examples and implications for reservoir modelling. In: Sambrook Smith, G.H., Best, J.L., Bristow, C.S., Petts, G.E. (Eds.), Braided rivers: process, deposits, ecology and management. Special Publication of the International Association of Sedimentologists, 36, Blackwell, Oxford, 75-106.

Khan, N.I., Islam, A., 2003. Quantification of erosion patterns in the Brahmaputra-Jamuna River using geographical information system and remote sensing techniques. Hydrological Processes 17, 959-966.

Klaassen, G.J., Vermeer, K., 1988. Confluence scour in a large braided river with fine bed material. Proceedings of the International Conference on Fluvial Hydraulics, Budapest, Hungary, 395-408.

Klaassen, G.J., Vermeer, K., Uddin, N., 1988. Sedimentological processes in the Jamuna (Lower Brahmaputra) river, Bangladesh. Proceedings of the International Conference on Fluvial Hydraulics. Budapest, Hungary, 381-394.

Kleinhans, M.G., 2010. Sorting out river channel patterns. Progress in Physical Geography, 34(3), 287-326. Doi: 10.1177/0309133310365300.

Kleinhans, M.G., Van den Berg, J.H., 2011. River channel and bar patterns explained and predicted by an empirical and a physics-based method. Earth Surface Processes and Landforms, 36, 721-735. Doi: 10.1002/esp.2090.

Kocurek, G., Ewing, R.C., Mohrig, D. 2010. How do bedform patterns arise? New views on the role of bedform interactions within a set of boundary conditions. Earth Surface Processes and Landforms 35, 51–63. Doi: 10.1002/esp.1913.

Knighton, D., Nanson, G., 1993. Anastomosis and the continuum of channel pattern. Earth Surface Processes and Landforms, 18, 613–625.

Kondrat'yev, N.Y. 1968. Hydromorphological principles of computation of free meandering. 1.Signs and indexes of free meandering. Soviet Hydrology 4, 309-335.

Kondrat'yev, N.Y., Popov, I.V., 1967. Methodological prerequisits for conducting network observations on the channel process. Soviet Hydrology 3, 273-297.

Kostaschuk, R., Villard, P. 1996. Flow and sediment transport over large subaqueous dunes: Fraser River, Canada. Sedimentology 43, 849-863.

Kostaschuk, R., Shugar, D., Best, J., Parsons, D., Lane, S., Hardy, R. and Orfeo, O., 2009. Suspended sediment transport and deposition over a dune: Rio Paraná, Argentina. Earth Surface Processes and Landforms 34, 1605-1611. DOI: 10.1002/esp.1847.

Kulemina, N.M., 1973. Some characteristics of the process of incomplete meandering of the channel of the upper Ob' River. Soviet Hydrology 6, 518-534.

Kuhlne, R., 2007. Sediment transport measurements. In: Garcia, M.H. (Ed.), Sedimentation Engineering: Processes, Management, Modeling, and Practice. American Society of Civil Engineers, Virginia, USA, 339-346.

Lambert, C.P., Walling, D.E., 1987. Floodplain sedimentation: a preliminary investigation of contemporary deposition within the lower reaches of the River Culme, Devon, UK. Geografiska Annaler 69A, 47-59.

Lane, S.N., Parsons, D.R., Best, J.L., Orfeo, O., Kostaschuk, R., Hardy, R.J., 2008. Causes of rapid mixing at a junction of two large rivers: Río Paraná and Río Paraguay, Argentina. Journal of Geophysical Research, 113, F02019. Doi: 10.1029/2006JF000745.

Latrubesse, E.M. 2008. Patterns of anabranching channels: the ultimate end-member adjustment of mega rivers. Geomorphology 101, 130-145. Doi:10.1016/j.geomorph.2008.05.035.

Latrubesse, E.M., Franzinelli, E., 2002. The Holocene alluvial plain of the middle Amazon River, Brazil. Geomorphology 44, 241-257.

Latrubesse, E.M., Franzinelli, E., 2005. The late Quaternary evolution of the Negro River, Amazon, Brazil: implications for island and floodplain formation in large anabranching tropical systems. Geomorphology 70, 372-397.

Latrubesse, E.M., Cozzuol, M., da Silva-Caminha, S.A.F., Rigsby, C.A., Absy, M.L., Jaramillo, C., 2010. The Late Miocene paleogeography of the Amazon Basin and the evolution of the Amazon River system. Earth-Science Reviews 99, 99-124. DOI: 10.1016/j.earscirev.2010.02.05.Latrubesse, E.M., Stevaux, J.C., Sinha, R., 2005. Tropical rivers. Geomorphology 70, 187-206.

Leddy, J.O., Ashworth, P.J., Best, J.L., 1993. Mechanisms of anabranching avulsion within gravel-bed braided rivers: observations from a scaled physical model. In: Best, J.L., Bristow, C.S. (Eds.), Braided Rivers. Geological Society of London Special Publication 75, 119-127.

Leclair, S.F., 2011. Interpreting fluvial hydromorphology from the rock record: large-river peak flows leave no clear signature. In: Davidson, S.K., Leleu, S., North, C.P. (Eds.), From

River to Rock Record: the Preservation of Fluvial Sediments and their Subsequent Interpretation. SEPM Special Publication, 97, 113-124.

Leopold, L.B., Wolman, M.G., 1957. River channel patterns: braided, meandering and straight. US Geological Survey Professional Paper, 262-B, 50pp.

Lewin, J., 1976. Initiation of bedforms and meanders in coarse-grained sediment. Geological Society of America Bulletin 87, 281-285.

Lewin, J., Ashworth, P.J., in press. Defining large river channel patterns: alluvial exchange and plurality. Geomorphology.

Lewin, J., Brewer, P.A., 2001. Predicting channel patterns. Geomorphology 40, 329-339.

Lucci, R., Zolezzi, G., Tubino M., 2010. Modelling mid-channel bars in meandering channels. Earth Surface Processes and Landforms 35, 902-917.

Makaske, B., 2001. Anastomosing rivers: a review of their classification, origin and sedimentary products. Earth-Science Reviews 53, 149-196.

Makaske, B., Smith, D.G., Berendson, H.J.A., de Boer, A.G., Nielen-Kiezebrink, M.F., Locking, T., 2009. Hydraulic and sedimentary processes causing anastomosing morphology of the upper Columbia River, British Columbia, Canada. Geomorphology 111, 194-205.

Maroulis, J.C., Nanson, G.C., 1996. Bedload transport of aggregated muddy alluvium from Cooper Creek, central Australia; a flume study. Sedimentology 43: 771-790

McLelland, S.J., Ashworth, P.J., Best, J.L., Roden, J.E., Klaassen, G.J., 1999. Flow structure and transport of sand-grade suspended sediment around an evolving braid-bar, Jamuna River, Bangladesh. In: Smith, N.D., Rogers, J. (Eds.), Fluvial Sedimentology VI, Special Publication of the International Association of Sedimentologists 28, 43-57.

Marron, D.C., 1992. Floodplain storage of mine tailings in the Belle Fourche River system: a sediment budget approach. Earth Surface Processes and Landforms 17, 675-685.

Meade, R.H., 2007. Transcontinental moving and storage: The Orinoco and Amazon Rivers transfer the Andes to the Atlantic. In: Gupta, A. (Ed.), Large Rivers: Geomorphology and Management. Wiley, Chichester, 45-63.

Meade, R.H., Bobrovitskaya, N.N., Babkin, V.I., 2000. Suspended-sediment and fresh-water discharges in the Ob and Yenisey rivers, 1960-1988. International Journal of Earth Sciences 89, 461-469.

Meade, R.H., Parker, R.S., 1985. Sediment in rivers of the United States. U.S. Geological Survey Water-Supply Paper 2275, 49-60.

Mertes, L.A.K., Dunne, T., 2007. Effects of tectonism, climatic change, and sea-level change on the form and behaviour of the modern Amazon River and its floodplain. In: Gupta, A. (Ed.), Large Rivers: Geomorphology and Management. Wiley, Chichester, 115-144.

Mertes, L.A.K., Dunne, T., Martinelli, L.A., 1996. Channel-floodplain geomorphology along the Solimões-Amazon River, Brazil. Geological Society of America Bulletin 108, 1089-1107.

Métivier, F., Gaudemer, Y., 1999. Stability of output fluxes of large rivers in South and East Asia during the last 2 million years: implications on floodplain processes. Basin Research 11, 293-303.

Miall, A.D., 1996. The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis and Petroleum Geology. Springer-Verlag, Heidelberg, 582pp.

Miall, A.D., 2006. How do we identify big rivers? And how big is big? Sedimentary Geology 186, 39-50. Doi: 10.1016/j.sedgeo.2005.10.001.

Milliman, J.D., Meade, R.H., 1983. World-wide delivery of river sediment to the ocean. Journal of Geology 91, 1-21.

Milliman, J.D., Syvitski, J.P.M., 1992. Geomorphic/Tectonic Control of sediment discharge to the ocean: the importance of small mountain rivers. Journal of Geology 100, 525-544.

Mosselman, E., 2006. Bank protection and river training along the braided Brahmaputra-Jamuna River, Bangladesh, In: Sambrook Smith, G.H., Best, J.L., Bristow, C.S., Petts, G.E. (Eds.), Braided rivers: process, deposits, ecology and management. Special Publication of the International Association of Sedimentologists, 36, Blackwell, Oxford, 277-289.

Nanson, G.C., 1980. Point bar and floodplain formation of the meandering Beatton River, N.E. British Columbia, Canada. Sedimentology 27, 3-29.

Nanson, G.C., Gibling, M., 2004. Anabranching and anastomosing river, In: Goudie, A.S. (Ed.), Encyclopedia of Geomorphology. Routledge, London, 21-25.

Nanson, G.C., Knighton, A.D., 1996. Anabranching rivers: their cause, character and classification. Earth Surface Processes and Landforms 21, 217-239.

Neill C.R., 1973. Hydraulic and morphologic characteristics of the Athabaska River near Fort Assiniboine. Report REH/73/3, Alberta Research Council, Highway River Engineering Division: Edmonton, 23 pp.

Neill, C.R., 1987. Sediment balance considerations linking long-term transport and channel processes. In: Thorne, C.R., Bathurst, J.C., Hey, R.D. (Eds.), Sediment transport in gravel-bed rivers. John Wiley and Sons, Chichester, 225-240.

Nicholas, A.P., Sandbach, S.D., Ashworth, P.J., Amsler, M.L., Best, J.L., Hardy, R.J., Lane, S.N., Orfeo, O., Parsons, D.R., Reesink, A.J.H., Sambrook Smith, G.H., Szupiany, R.N., in press. Modelling hydrodynamics in the Rio Paraná, Argentina: an evaluation and inter-comparison of reduced-complexity and physics-based models applied to a large sand-bed river. Geomorphology.

Nittrouer, J.A., Allison, M.A., Campanella, R., 2008. Bedform transport rates for the lowermost Mississippi River. Journal of Geophysical Research 113, F03004. Doi:10.1029/2007JF000795.

Nykanen, D.K., Foufoula-Georgiou, E., Sapozhnikov, V.B., 1998. Study of spatial scaling in braided river patterns using synthetic aperture radar imagery. Water Resources Research, 34, 1795–1807.

Orfeo, O., Stevaux, J., 2002. Hydraulic and morphological characteristics of middle and upper reaches of the Paraná River (Argentina and Brazil). Geomorphology 44, 309-322.

Paira, A.R., Drago, E.C., 2006. Genetical, morphological and evolutional relationships of the floodplain lakes in the Middle Paraná River hydrosystem. Zeitschrift für Geomorphologie, 145, 207-228.

Paira A,R,, Drago, E.C., 2007. Origin, evolution, and types of floodplain water bodies. In: Iriondo M.H., Paggi J.C., Parma, M.J. (Eds.), The Middle Paraná River. Springer-Verlag: Berlin; 53-81.

Paola, C., Borgman, L., 1991. Reconstructing random topography from preserved stratification. Sedimentology 38, 553-565.

Parker, G., Shimizu, Y., Wilkerson, G.V., Eke, E.C., Abad, J.D., Lauer, J.D., Paola, C., Dietrich, W.E., Voller, V.R., 2011. A new framework for modeling the migration of meandering rivers. Earth Surface Processes and Landforms 36, 70-86. DOI: 10.1002/esp.2113.

Parsons, D.R., Best, J.L., Orfeo, O., Hardy, R.J., Kostaschuk, R., Lane, S.N., 2005. Morphology and flow fields of three-dimensional dunes, Rio Paraná, Argentina: Results from simultaneous multibeam echo sounding and acoustic Doppler current profiling, Journal of Geophysical Research 110, 1-9. Doi:10.1029/2004JF000231.

Parsons, D.R., Best, J.L., Lane, S.N., Orfeo, O., Hardy, R.J., Kostaschuk, R., 2007. Form roughness and the absence of secondary flow in a large confluence-diffluence, Rio Paraná, Argentina. Earth Surface Processes and Landforms 32, 155-162.

Potter, P.E., 1978. Significance and origin of big rivers. Journal of Geology 86, 13-33.

Ramonell, C.G., Amsler, M.L., Toniolo, H.A., 2002. Shifting modes of the Paraná River thalweg in its middle-lower reaches. Zeitschrift für Geomorphologie Suppl.-Bd. 129**,** 129-142.

Rice, S., 1998. Which tributaries disrupt downstream fining along gravel-bed rivers? Geomorphology 22, 39-56.

Richardson, W.R.R., Thorne, C.R., 1998. Secondary currents around braid bar in Brahmaputra River, Bangladesh. Journal of Hydraulic Engineering 124, 325-328.

Roden, J.E., 1998. Sedimentology and dynamics of mega-sand dunes, Jamuna River, Bangladesh. Unpublished Ph.D. thesis, University of Leeds, UK, 310 pp.

Rowland, J.C., Lepper, K., Dietrich, W.E., Wilson, C.J., Sheldon, R., 2005. Tie channel sedimentation rates, oxbow formation age and channel migration from optically stimulated luminescence (OSL) analysis of floodplain deposits. Earth Surface Processes and Landforms 30, 1161-1179.

Roy, N.G., Sinha, R., Gibling, M.R., 2012. Aggradation, incision and interfluve flooding in the Ganga Valley over the past 100,000 years: Testing the influence of monsoonal precipitation. Palaeogeography, Palaeoclimatology, Palaeoecology. DOI: 10.1016/j.palaeo.2011.08.012.

Rozo, M.G., Nogueira, A.C.R., Truckenbrodt, W. 2012. The anastomosing pattern and the extensively distributed scroll bars in the middle Amazon River. Earth Surface Processes and Landforms. DOI: 10.1002/esp.3249.

Rust, B.R., 1978. A classification of alluvial channel systems. In: Miall, A.D. (Ed.), Fluvial Sedimentology. Canadian Society of Petroleum Geologists, Calgary, 187-198.

Sioli, H., 1984. The Amazon and its main affluents: hydrography, morphology of the river courses, and river types. In: Sioli, H. (Ed.), The Amazon – Limnology and Landscape Ecology of a Mighty Tropical River and its Basin. Monographiae Biologicae 56, Junk, Dordrecht, 127-165.

Sambrook Smith, G.H., Ashworth, P.J., Best, J.L., Lunt, I.A., Orfeo, O., Parsons, D.R., 2009. The sedimentology and alluvial architecture of a large braid bar, Río Paraná, Argentina. Journal of Sedimentary Research 79, 629-642. Doi: 10.2110/jsr.2009.066

Sambrook Smith, G.H., Ashworth, P.J., Best, J.L., Woodward, J., Simpson, C.J., 2005. The morphology and facies of sandy braided rivers: some considerations of scale invariance. In: Blum, M.D., Marriott, S.B., Leclair, S.F. (Eds.), Fluvial Sedimentology VII. International Association of Sedimentologists, Special Publication 35, 145-158, Blackwells.

Sambrook Smith, G.H., Ashworth, P.J., Best, J.L., Woodward, J., Simpson, C.J., 2006. The sedimentology and alluvial architecture of the sandy braided South Saskatchewan River, Canada. Sedimentology 53(2), 413-434.

Sambrook Smith, G.H., Best, J.L., Ashworth, P.J., Fielding, C.R., Goodbred, S.L., Prokocki, E.W., 2010. Fluvial form in modern continental sedimentary basins: Distributive fluvial systems: COMMENT. Geology 2010;38; e230. Doi: 10.1130/G31507C.1.

Sandbach, S.D., Lane, S.N., Hardy, R.J., Amsler, M.L., Ashworth, P.J., Best, J.L., Nicholas, A.P., Orfeo, O., Parsons, D.R., Reesink, A.J.H., Sambrook Smith, G.H., Szupiany, R.N., in press. Application of a roughness-length representation to parameterize energy-loss in 3D numerical simulations of large rivers. Water Resources Research.

Sandbach, S.D., Hardy, R.J., Lane, S.N., Parsons, D.R., Best, J.L., Ashworth, P.J., Reesink, A.J.H., Amsler, M.L., Szupiany, R.N., Nicholas, A.P., Orfeo, O., Sambrook Smith, G.H., 2010. Three-dimensional modelling of a very large river: the Rio Paraná. In: Dittrich, A., Koll, Ka., Aberle, J., Geisenhainer, P. (Eds.), River Flow 2010. Brawnschehhe, Germany, pp. 409-417, Bundesanstalt fuer Wasserbau.

Santos, M. L., Stevaux, J. C., 2000. Facies and architectural analysis of channel sandy macroforms in the upper Paraná River. Quaternary International 72, 87-94.

Sapozhnikov, V.B., Foufoula-Georgiou, E., 1996. Self-affinity in braided rivers. Water Resources Research 33, 1983–1991.

Sapozhnikov, V.B., Murray, A.B., Paola, C., Foufoula-Georgiou, E., 1998. Validation of braided-stream models: spatial state–space plots, self-affine scaling, and island shapes. Water Resources Research 34, 2353–2364.

Sarker, M.H., Thorne, C.R. 2006. Morphological response of the Brahmaputra-Padma-Lower Meghna River system to the Assam earthquake of 1950. In: Sambrook Smith, G.H., Best, J.L., Bristow, C.S., Petts, G. (Eds.), Braided Rivers: process, deposits, ecology and management. Special Publication of the International Association of Sedimentologists, 36, 289-310.

Schumm, S.A., 1977. The Fluvial System. Wiley, New York, 338pp.

Schumm, S.A., 1981. Evolution and response of the fluvial system, sedimentologic implications. In: Ethridge, F.G., Flores R.M. (Eds.). Recent and Ancient Nonmarine Depositional Environments. Special Publication, Society Economic Palaeontology and Mineralogy 31, 19-29.

Schumm, S.A., Winkley, B.R. (Eds.), 1994. The Variability of Large Alluvial Rivers, American Association of Civil Engineers Press, New York. 467pp.

Shugar, D., Koastaschuk, R., Best, J.L., Parsons, D.R., Lane, S.N., Orfeo, O., Hardy, R.J., 2010. On the relationship between flow and suspended sediment transport over a crest of a sand dune, Rio Paraná, Argentina. Sedimentology 57(1), 252-272. Doi: 10.1111/j.1365-3091.2009.01110.x

Shiklomanov I.A., Rodda J.C. (Eds.), 2003. World Water Resources at the Beginning of the Twenty-first Century. Cambridge University Press, Cambridge.

Singh, I.B. 2007. The Ganga River. In: Gupta, A. (Ed.), Large Rivers: Geomorphology and Management. Wiley, Chichester, 347-371.

Slingerland, R., Smith, N.D. 2004. River avulsions and their deposits. Annual Reviews Earth and Planetary Science, 32, 257-285.

Smith, N.D., 1971. Transverse bars and braiding in the Lower Platte River, Nebraska. Geological Society of America Bulletin 82, 3407-3420.

Smith, N.D., Smith, D.G., 1984. William River: an outstanding example of channel widening and braiding caused by bed-load addition. Geology 12, 78-82.

Smith, J.D., McLean, S.R., 1977. Spatially-averaged flow over a wavy surface. Journal of Geophysical Research 82, 1735-1746.

Swanson, K.M., Watson, E., Aalto, R., Lauer, J.W., Bera, M.T., Marshall, A., Taylor, M.P., Apte, S.C., Dietrich, W.E. 2008. Sediment load and floodplain deposition rates: Comparison of the Fly and Strickland Rivers, Papua New Guinea. Journal of Geophysical Research 113, F01S03. Doi:10.1029/2006JF000623.

Syvitski, J.P.M., Kettner, A., 2011. Sediment flux and the Anthropocene. Philosophical Transactions of the Royal Society A, 369: 957-975. Doi.10.1098/rsta.2010.0329.

Syvitski, J.P.M., Vőrősmarty, C.J., Kettner, A.J., Green, P. 2005. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Science 308, 376-380.

Szupiany R.N., Amsler, M.L., Parsons, D.R., Best, J.R., 2009. Morphology, flow structure, and suspended bed sediment transport at two large braid-bar confluences. Water Resources Research 45. doi: W05415. Doi:10.1029/2008WR007428.

Ten Brinke, W.B.M., Schoore, M.M., Sorber, A.M., Berendsen, H.J.A., 1998. Overbank deposits in relation to transport volumes during large-magnitude floods on the Dutch sand-bed Rhine river system. Earth Surface Processes and Landforms 23, 809-824.

Ten Brinke, W.B.M., Wilbers, A.W.E., Wesseling, C., 1999. Dune growth, decay and migration rates during a large-magnitude flood at a sand and mixed sand-gravel bed in the Dutch Rhine river system. In: Smith, N.D., Rogers, J. (Eds.), Fluvial Sedimentology VI. International Association of Sedimentologists, Special Publication, 28, 15-32.

Thorne, C.R., Russell, A.P.G., Alam, M.K. 1993. Planform pattern and channel evolution of the Brahmaputra River, Bangladesh. In: Best. JL. and Bristow, C.S. (Eds.), Braided Rivers, Special Publication of the Geological Society of London, 75, 257-276.

Tooth, S. 1999. Downstream changes in floodplain character on the Northern Plains of arid central Australia. In: Smith, N.D., Rogers, J. (Eds.), Fluvial Sedimentology VI. International Association of Sedimentologists, Special Publication, 28, 93-112.

Turowski, J.M., Rickenmann, D., Dadson S.J. 2010. The partitioning of the total sediment load of a river into suspended and bedload: a review of empirical data. Sedimentology 57, 1126-1146.

Twidale, C.R., 2004. River patterns and their meaning. Earth-Science Reviews 67, 159-218.

Valente, C.R., Latrubesse, E.M. 2012. Fluvial archive of peculiar avulsive fluvial patterns in the largest Quaternary intracratonic basin of tropical South America: The Bananal Basin, Central-Brazil. Palaeogeography, Palaeoclimatology, Palaeoecology. DOI: 10.1016/j.palaeo.2011.10.002.

Van den Berg, J.H., 1995. Prediction of channel patterns of alluvial channel patterns of alluvial rivers. Geomorphology 12, 259-279.

Van de Wiel, M.J., Coulthard, T.J., 2010. Self-organized criticality in river basins: challenging sedimentary records of environmental change. Geology 38, 87–90. Doi: 10.1130/G30490.1

Walling, D.E., 2006. Human impact on land-ocean sediment transfer by the world's rivers. Geomorphology 79, 192-216.

Walling, D.E., Quine, T.A., 1993. Using Chernobyl-derived fallout radionuclides to investigate the role of downstream conveyance losses in the suspended budget of the River Severn, United Kingdom. Physical Geography 14, 239-253.

Wang, H., Saito, Y., Zhang, Y., Naishuang, B., Sun, X., Yang, Z., 2011. Recent changes of sediment flux to the western Pacific Ocean from major rivers in East and Southeast Asia. Earth-Science Reviews. Doi: 10.1016/j.earscirev.2011.06.003.

Warburton, J., Davies, T.R.H., Mandl, M.G. 1993. A meso-scale field investigation of channel change and floodplain characteristics in an upland braided gravel-bed river, New Zealand. In: Best, J.L., Bristow, C.S. (Eds.), Braided Rivers. Geological Society of London Special Publication 75, 241-255.

Wasson, R.J., 2012. Geomorphic histories for river and catchment management. Philosophical Transactions of the Royal Society A 370, 2240-2263. DOI: 10.1098/rsta.2011.0599.

Weissmann, G.S., Hartley, A.J., Nichols, G.J., Scuderi, L.A., Olson, M., Buehler, H., Banteah, R., 2010. Fluvial form in modern continental sedimentary basins: Distributive fluvial systems. Geology, 38, 39-42. doi:10.1130/G30242.1

Weissmann, G.S., Hartley, A.J., Nichols, G.J. Scuderi, L.A., Olson, M.E., Buehler, H.A., Massengill, L.C., 2011. Alluvial facies distributions in continental sedimentary basins – distributive fluvial systems. In: Davidson, S.K., Leleu, S., North, C.P. (Eds.), River to Rock Record: The Preservation of Fluvial Sediments and Their Subsequent Interpretation, SEPM Special Publication, 97, 327-355.

Williams, M., 2012. River sediments. Philosophical Transactions of the Royal Society A 370, 2093-2122, doi 10.1098/rsta.2011.0504.

Wilkinson, B.H., McElroy, B.J., 2007. The impact of humans on continental erosion and sedimentation. Geological Society of America Bulletin 119, 140-156.

Wohl, E.E., 2007. Hydrology and discharge. In: Gupta, A. (Ed.), Large Rivers: Geomorphology and Management. Wiley, Chichester, 29-44.

Xu, J., 2004. Comparison of hydraulic geometry between sand- and gravel-bed rivers in relation to channel pattern discrimination. Earth Surface Processes and Landforms 29, 645-657.

Yang, D., Ye, B., Shiklomanov, A., 2004. Discharge characteristics and changes over the Ob River watershed in Siberia. Journal of Hydrometeorology 5, 595-610.

Zongyuan C., Xu. K., Watanabe, M. 2007. Dynamic hydrology and geomorphology of the Yangtze River. In: Gupta, A. (Ed.), Large Rivers: Geomorphology and Management. Wiley, Chichester, 457- 469

Figure captions

1. (A) Sediment yield versus annual runoff, and (B) sediment yield versus catchment area for the world's largest rivers with catchment areas greater than 0.5 million km^2. Data are from Milliman and Syvitski (1992) except for runoff for the Ganges and Brahmaputra that are from Shiklomanov and Rodda (2003). Runoff is expressed as annual gross discharge in km^3 yr^{-1} (rather than using unit discharge). This purposely discounts the influence of catchment size which does not always control the local channel pattern in large river basins. Two rivers (Irrawaddy and Magdalena) are in the top ten sediment-yield rivers but have relatively small catchment areas so are not plotted here. Note sediment yield values have been adjusted to pre-dam values for the Mississippi, Nile, Zambezi, Indus, Columbia and Rio Grande as described in Milliman and Syvitski (1992) although some of these data are probably first-order estimates.

   .

2. Schema of domain chains for trans-continental catchments. Types are: A = Mountain-dominated (e.g., Amur, Mekong), B = Lateral tributary-dominated (e.g., Ganges, Mississippi, Paraná), C = Headwater-dominated with foreland depositional basins (e.g., Amazon, Orinoco), D = Headwater-dominated with lowland alluvial corridor (e.g., Ob, Mackenzie), E = Alternation between depositional basins and mountain belts (e.g., Danube, Yangtze), F = Few mountainous sources (e.g., Congo, Rio Xingu). Detailed description of the domains is given in the text.

3. Examples of the wide variety of channel pattern in large rivers: (A) Amazon (image taken on 24 November 2000), (B) Magdalena (image taken on 12 January 2001), (C)

Ob (image taken on 17 September 2002), (D) Mackenzie (image taken on 7 September 2002), (E) Congo (image taken on 17 May 2003) and (F) Orinoco (image taken on 7 March 2001). All images are plotted at the same scale. Landsat imagery courtesy of the U.S. Geological Survey.

4. Channel patterning in big rivers and examples using reaches from the 20 world's largest rivers (defined by mean annual runoff, see Table 1). Most big rivers are anabranching with a system of multiple channels that divide and rejoin but individual branch channel patterns may be straight, meandering, braided, wandering or anastomosing.

5. (A) Mariuá archipelago, upstream of the Branco tributary (mosaic taken on 5 August 2002 and 21 September 1999), and (B) the Anavilhanas islands ~50 km upstream of Manaus (image taken on 10 July 2001), both on the Rio Negro, Brazil. Images correspond to reaches IIIb and V described in Latrubesse and Franzinelli (2005). Note in (A) the vegetated islands vary up-to-downstream from sandy, topped with muddy sediments to those that are predominantly mud, and in (B) the vegetated islands are mostly a homogeneous mix of sand, silt and clay that probably owe their origin to former conditions when elongated levees were built in water loaded with suspended sediment (interpretation and description from Latrubesse and Franzinelli (2005)). Landsat imagery courtesy of the U.S. Geological Survey.

6. Alluvial exchanges in large rivers: deposition on the floodplain (a-e), exchanges involving main channels (f-i) and deposition within them (h), or material input from tributaries (j).

7. (A) Rio Paraná near Esquina (image taken on 2 April 2001), and (B) Amazon near Manacapuru (image taken on 21 January 2003), showing a range of adjacent standing water bodies that may be refilled during floods. Labels are: 1 = swale ponds, 2 = cutoff channels, 3 = floodbasins (ponded between raised alluvial ridges or against valley-sides), 4 = ponded tributary valleys. More details on the origin, evolution and types of floodplain water bodies for the Paraná are in Paira and Drago (2007). See Table 1 for a list of the type of standing water bodies found in the 20 largest rivers in the world. Landsat imagery courtesy of the U.S. Geological Survey.

8. The four main hydraulic systems, with examples, that characterise large rivers: (A) Type 1: lacustrine-dominated; (B) Type 2: mainstream-dominated; (C) Types 3(a)-(b): equi-style and contra-style (tributary or accessory stream dominated); (D) Type 4: confined or bedrock-dominated. Landsat imagery courtesy of the U.S. Geological Survey and all images are plotted at the same scale.

9. The Amur at Malyshevo (image taken on 5 September 2002) showing an example of accessory channels that run alongside the main channel that can be of a different channel pattern from the main stem. Landsat imagery courtesy of the U.S. Geological Survey. Darker brown colours in the main and accessory channels represent zones of

lower velocity and sediment load and potential areas for deposition. Label 1 = accessory channel.

10. (A) Map showing upper course of the River Ob and locations of points referred to in text, (B) River Ob at Krivosheino taken on 7 July 1999, (C) River Ob at Ust'-Tym taken on 27 September 2010, (D) River Ob at Alekino taken on 21 May 2003. Landsat imagery courtesy of the U.S. Geological Survey. Note (B) shows the multiplicity of channels with different radius of curvature associated with several styles of meander development. Lateral accretion dominates floodplain construction and avulsion is controlled by the strong, local floodplain relief, (C) shows the slow rates of meander migration and scroll bar accretion, and (D) shows the complexity of floodplain relief that favours meander-bend avulsion. Labels for standing water bodies are 1 = in point bar swales, 2 = in arcuate dead channel loops, 3 = as broader unsedimented water bodies, 4 = in circular thaw ponds and thermokarst features.

11. Braided river planform of the Jamuna River, Bangladesh and locations referred to in the text. Images courtesy of U.S. Geological Survey and mosaic taken at low flow on 17 February 2002 and 24 February 2002.

12. Channel change on the Jamuna River near Sirajganj. Images taken on (A) 13 February 1989, (B) 19 February 2000, (C) 4 November 2004, and (D) 21 January 2010. Note image (C) is taken following the discharge peak that usually occurs in August. Labels on (B) are 1 = unit bars, 2 = compound bar, 3 = vegetated islands. The

main channels are generally 'clean' and devoid of emergent unit bars. The Jamuna reworks most of its active braidbelt in less than 10 years.

13. (A) The anabranching Rio Paraná, Argentina and locations referred to in the text, (B) Puerto Reconquista offtake, and (C) Colastine offtake. Images courtesy of U.S. Geological Survey and mosaic taken on 26 December 2002, 8 April 2003, 15 April 2003, 3 May 2003 and 24 May 2003.

14. Channel change on the Rio Paraná between 1972 and 2010 in a reach 25 km south-east of Santa Fe (location in Fig. 13A). Images courtesy of U.S. Geological Survey and taken on dates shown in Figure. Label 1 on 2 December 1991 image is the new mid-channel bar that was probably created in the 1983 flood (see Fig. 16) and is pictured fully emergent in Fig. 15.

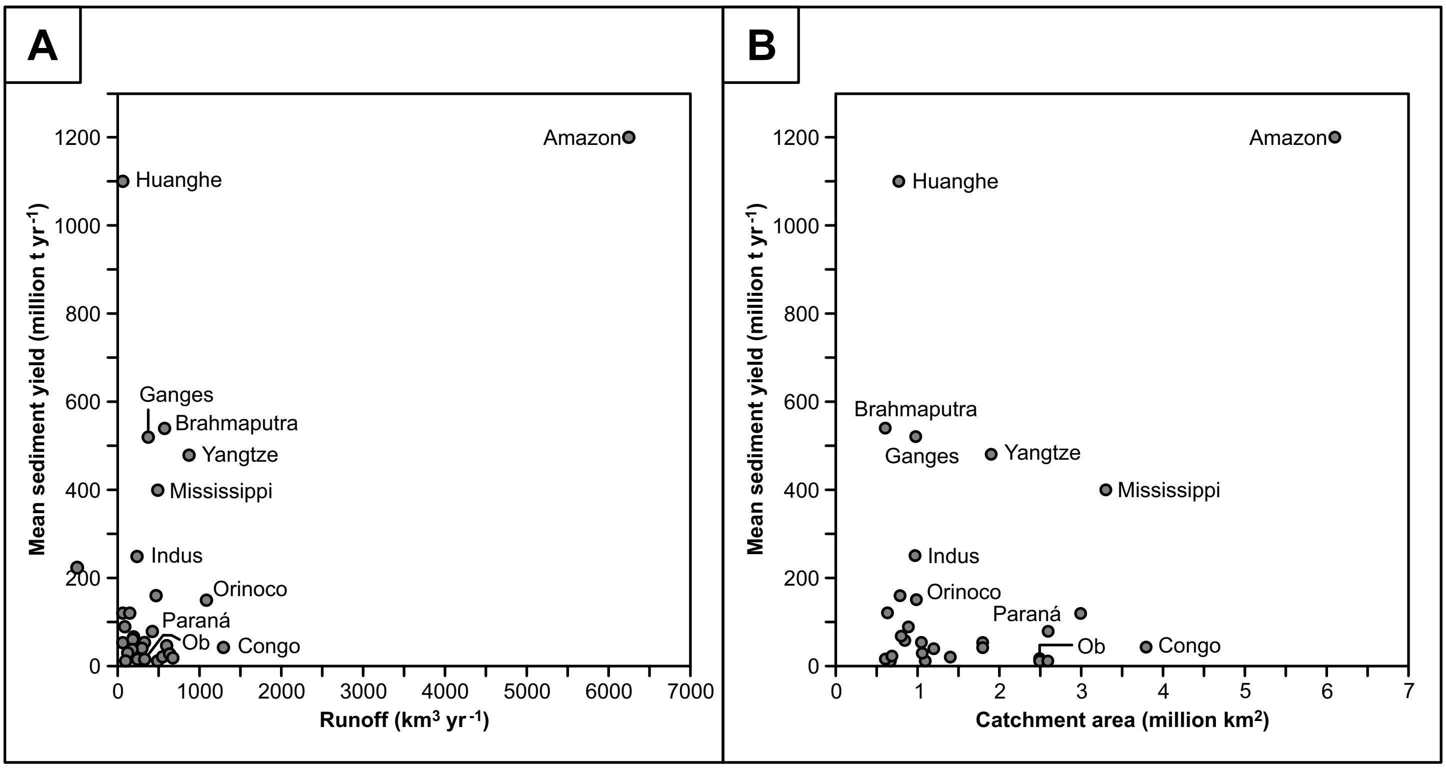
15. View of 2.5 km-long mid-channel bar near Santa Fe that developed in the mid-1980s (bar location labelled in Fig. 14). Note the dune field on the incipient sand bar at the main bartail. Photograph taken on 1 October 2010.

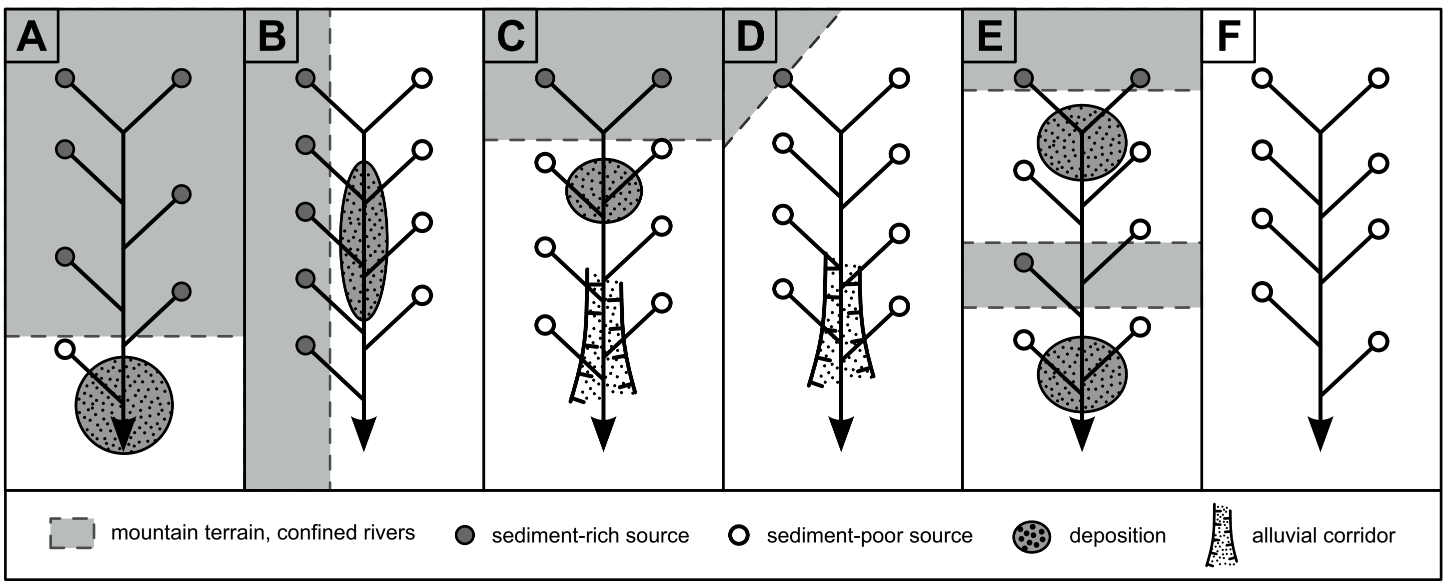
16. Channel change in the Rio Paraná from 1905-2010 reproduced from historic and recent bathymetric surveys (data courtesy of Prof. M. Amsler,Dr R. Szupiany and Dirección Nacional de Vias Navegables). All data are reduced to the same common datum. The 18 km-reach is 25 km south-east of Santa Fe and satellite images of

planform change since 1972 are presented in Fig. 14. Label 1 = mid-channel bar shown in Figs 14 and 15.

Table captions

1. Reach character on the world's 20 largest rivers


A
Mean sediment yield (million t yr-1)
Runoff (km3 yr-1)
Amazon
Huanghe
Ganges
Brahmaputra
Yangtze
Mississippi
Indus
Orinoco
Paraná
Ob
Congo
B
Catchment area (million km2)


A
B
C
D
E
F
mountain terrain, confined rivers
sediment-rich source
sediment-poor source
deposition
alluvial corridor

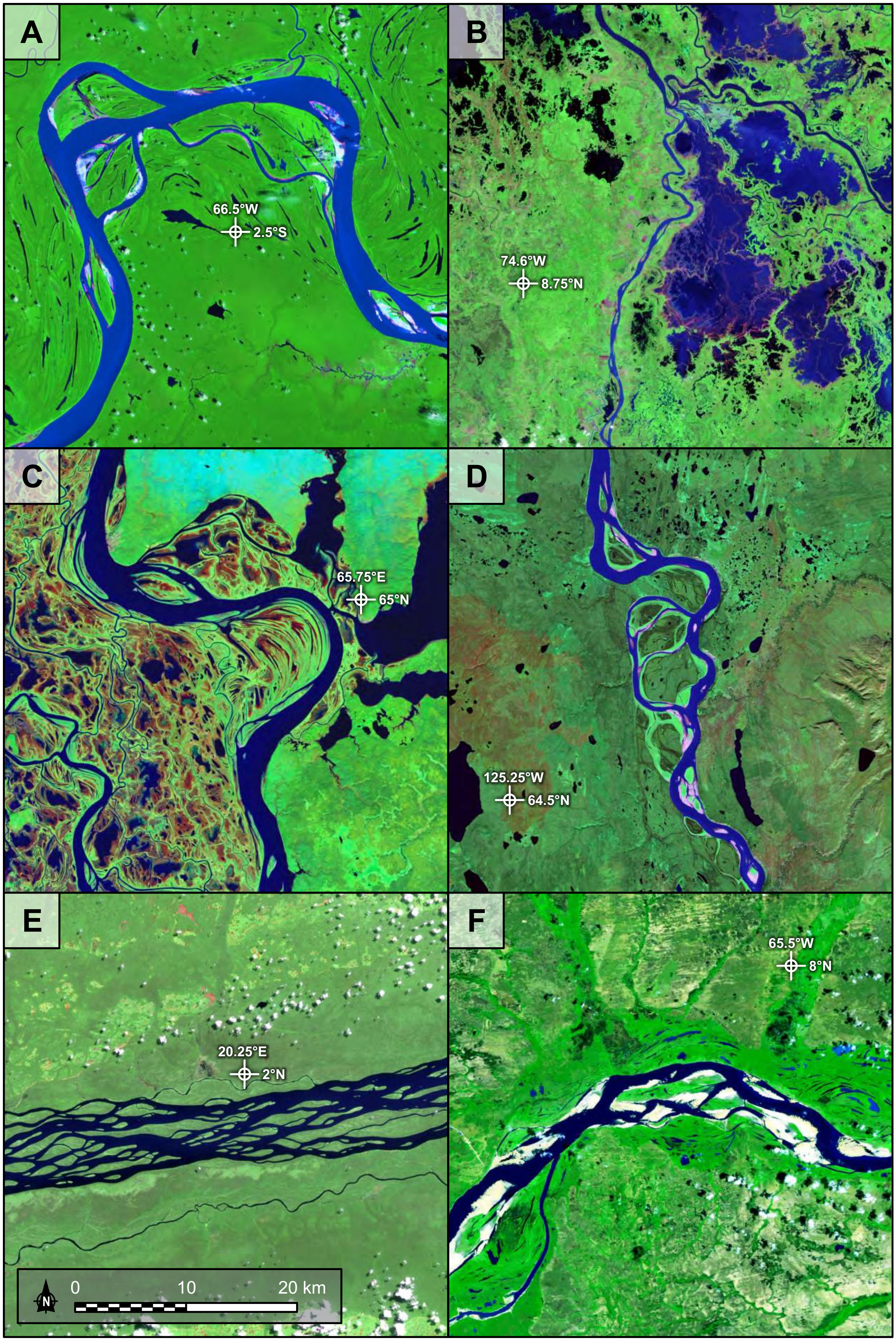
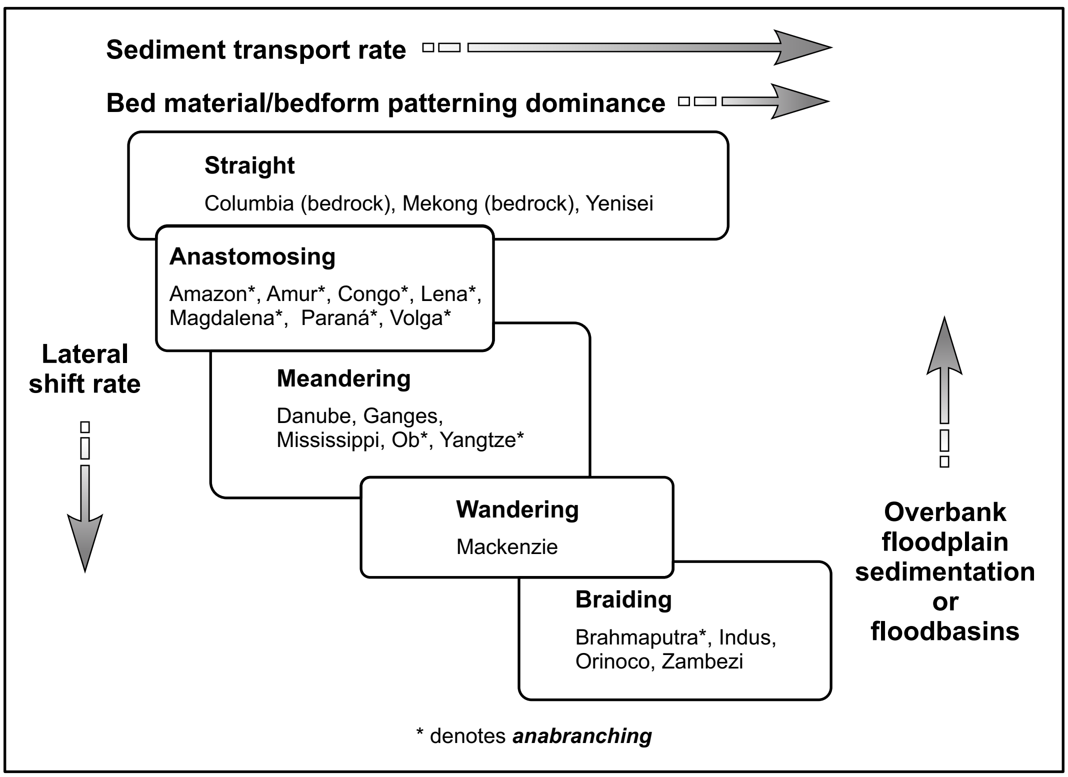
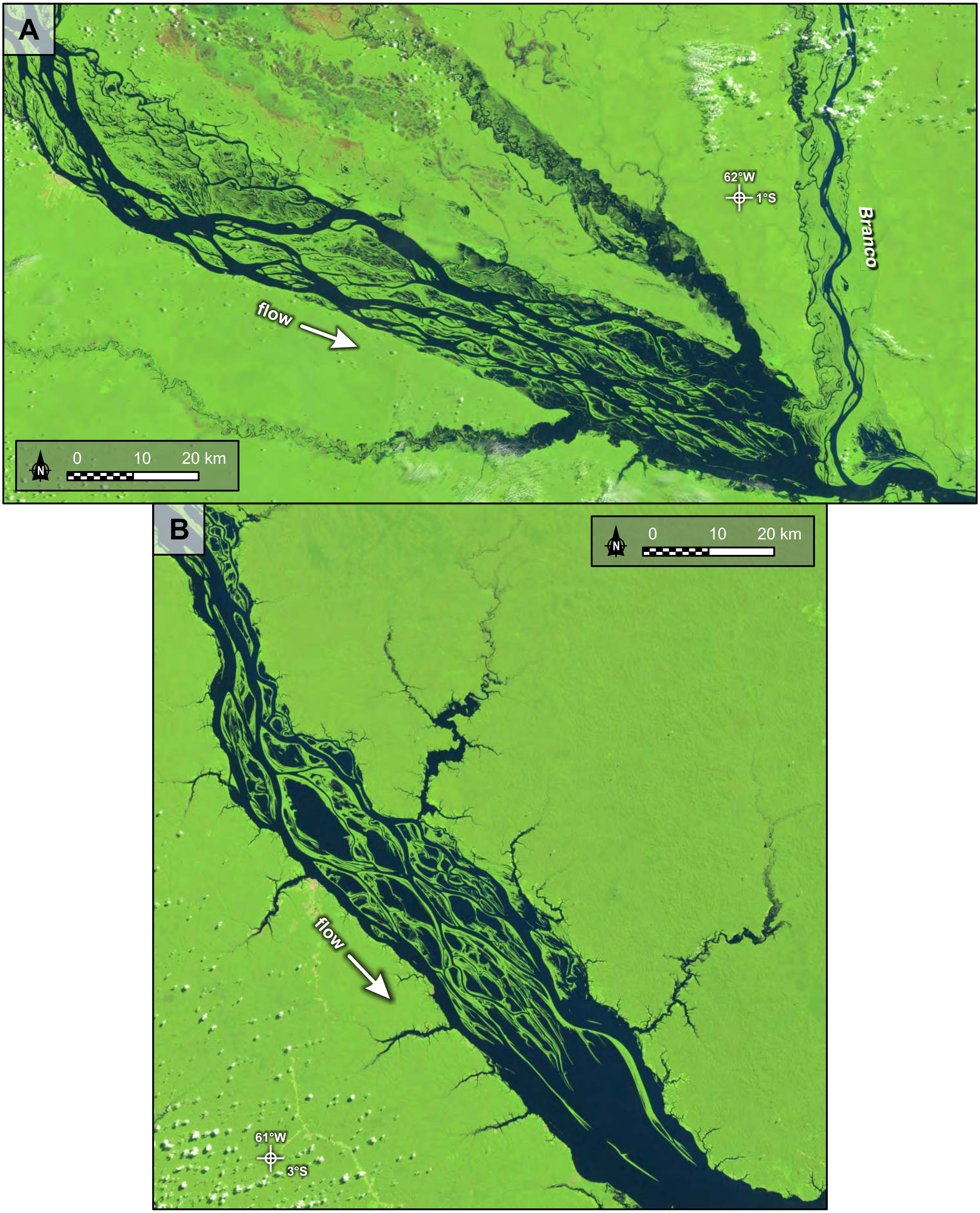
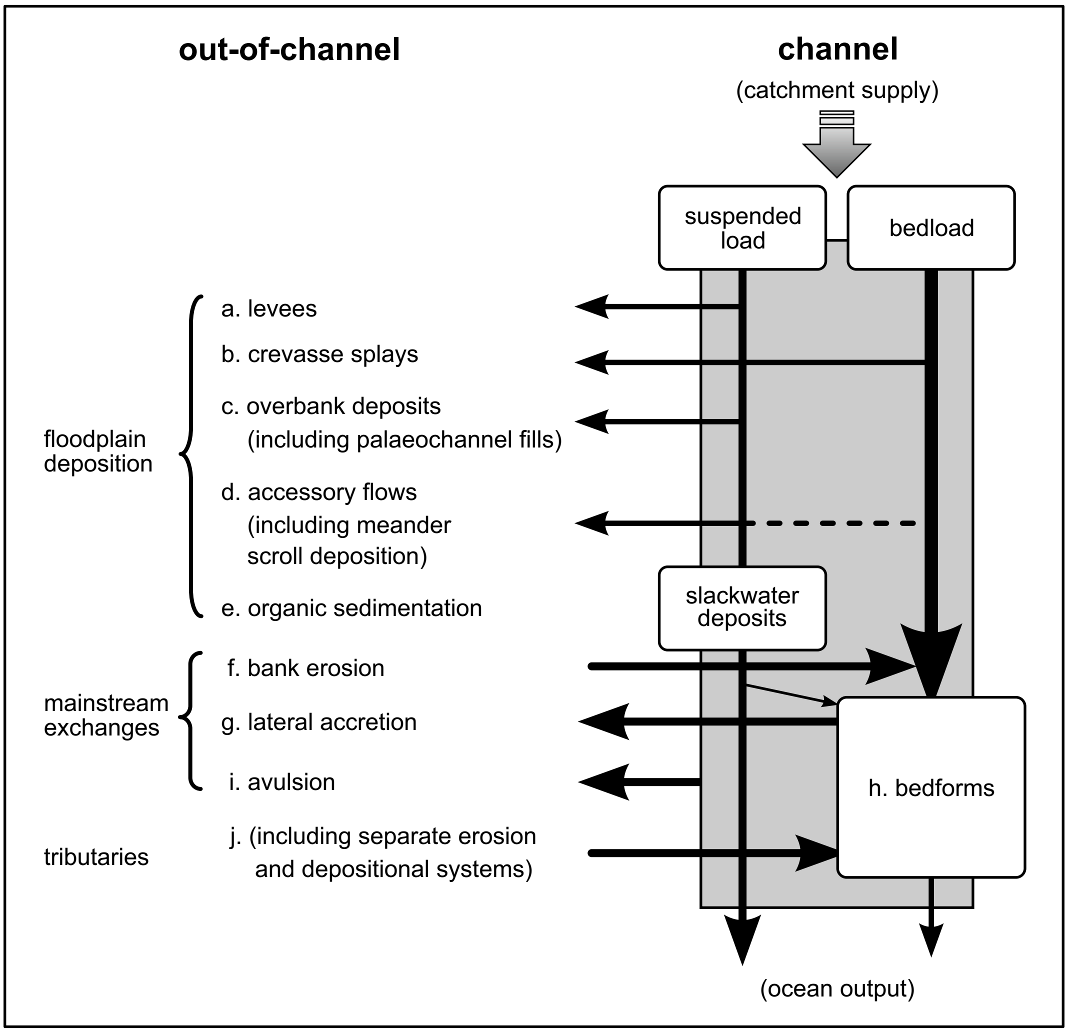

A
66.5°W
2.5°S
B
74.6°W
8.75°N
C
65.75°E
65°N
D
125.25°W
64.5°N
E
20.25°E
2°N
N
0
10
20 km
F
65.5°W
8°N

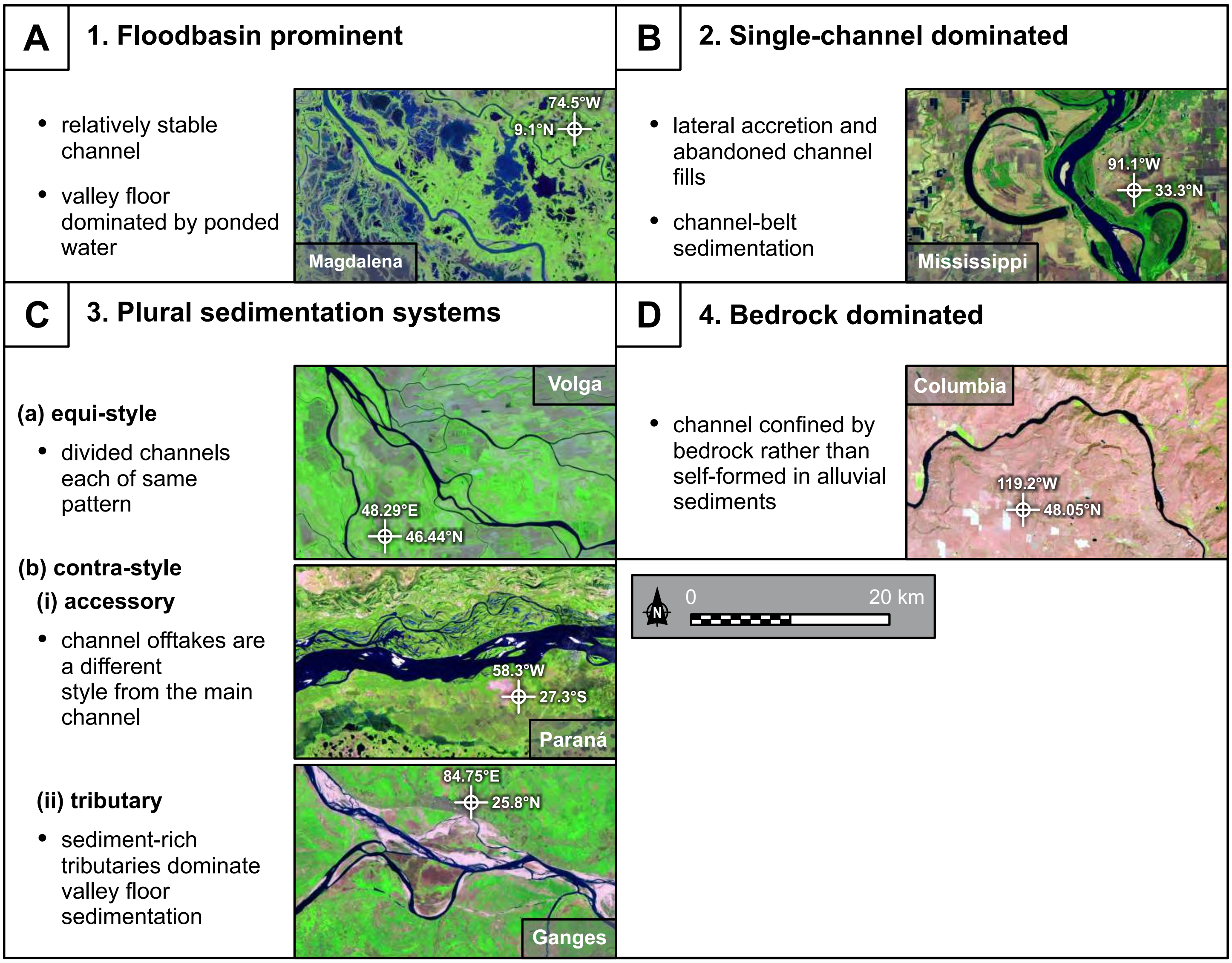
Figure 3


Sediment transport rate
Bed material/bedform patterning dominance
Straight
Columbia (bedrock), Mekong (bedrock), Yenisei
Anastomosing
Amazon*, Amur*, Congo*, Lena*, Magdalena*, Paraná*, Volga*
Lateral shift rate
Meandering
Danube, Ganges, Mississippi, Ob*, Yangtze*
Wandering
Mackenzie
Braiding
Brahmaputra*, Indus, Orinoco, Zambezi
Overbank floodplain sedimentation or floodbasins
* denotes *anabranching*


A
62°W
1°S
Branco
flow
0
10
20 km
N
B
0
10
20 km
N
flow
61°W
3°S


out-of-channel
channel
(catchment supply)
suspended load
bedload
a. levees
b. crevasse splays
c. overbank deposits
(including palaeochannel fills)
floodplain deposition
d. accessory flows
(including meander scroll deposition)
e. organic sedimentation
slackwater deposits
f. bank erosion
mainstream exchanges
g. lateral accretion
i. avulsion
h. bedforms
tributaries
j. (including separate erosion and depositional systems)
(ocean output)

A
59.5°W
29.75°S
2
3
flow
1
0
5
10 km
N
B
flow
1
4
4
60.5°W
3.5°S
4
1
0
10
20 km
N


A
1. Floodbasin prominent
relatively stable channel
valley floor dominated by ponded water
74.5°W
9.1°N
Magdalena
B
2. Single-channel dominated
lateral accretion and abandoned channel fills
channel-belt sedimentation
91.1°W
33.3°N
Mississippi
C
3. Plural sedimentation systems
(a) equi-style
divided channels each of same pattern
Volga
48.29°E
46.44°N
(b) contra-style
(i) accessory
channel offtakes are a different style from the main channel
58.3°W
27.3°S
Paraná
(ii) tributary
sediment-rich tributaries dominate valley floor sedimentation
84.75°E
25.8°N
Ganges
D
4. Bedrock dominated
channel confined by bedrock rather than self-formed in alluvial sediments
Columbia
119.2°W
48.05°N
N
0
20 km

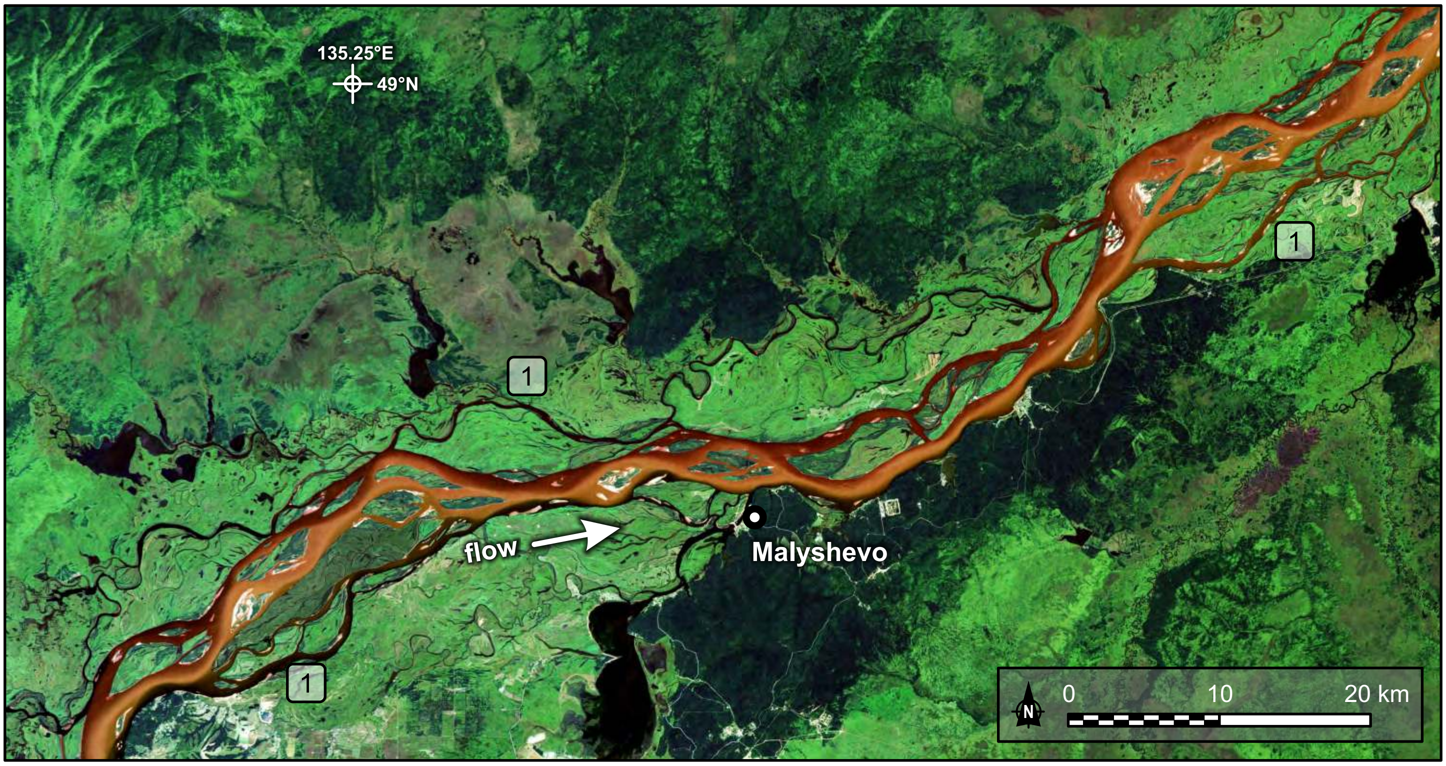
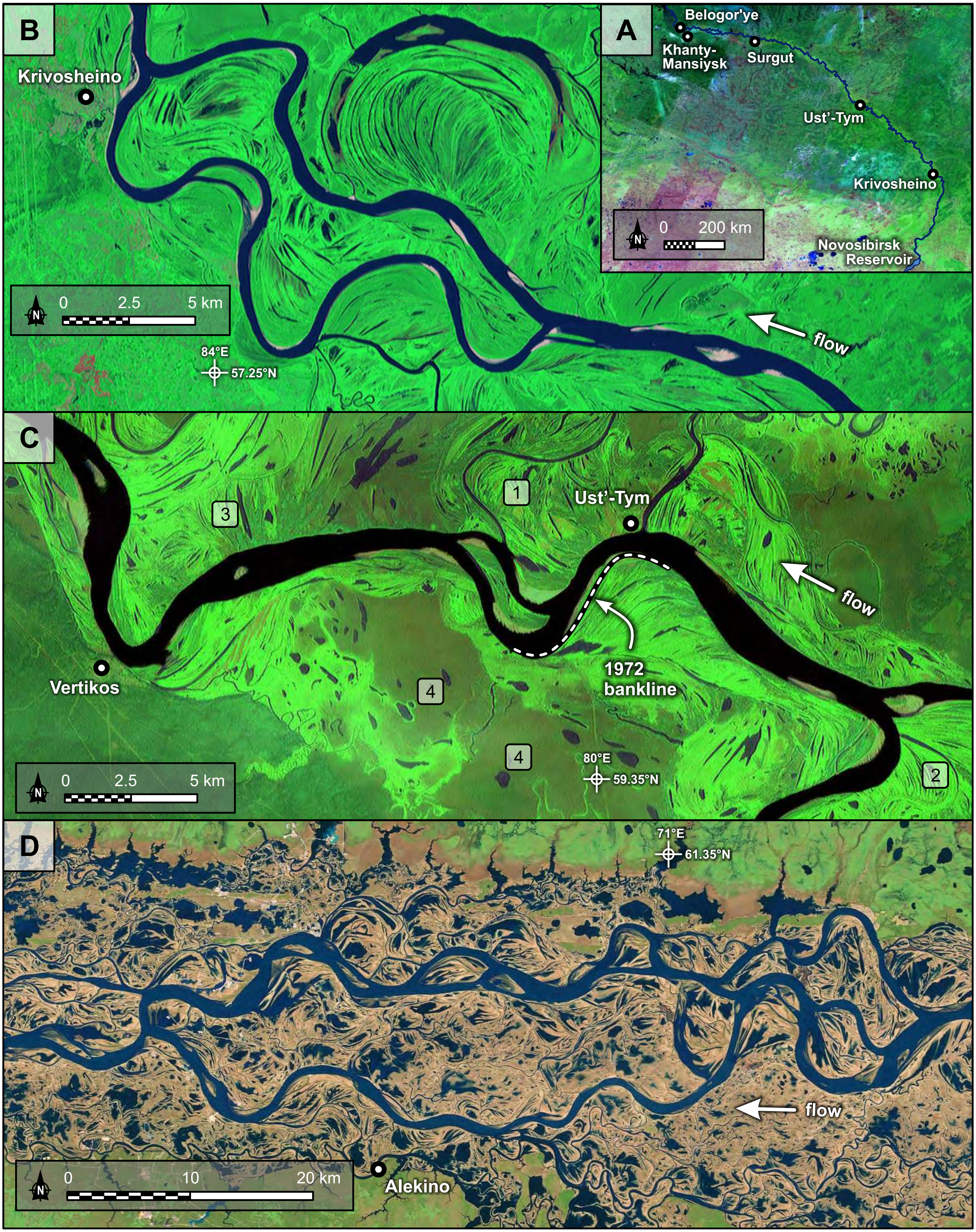
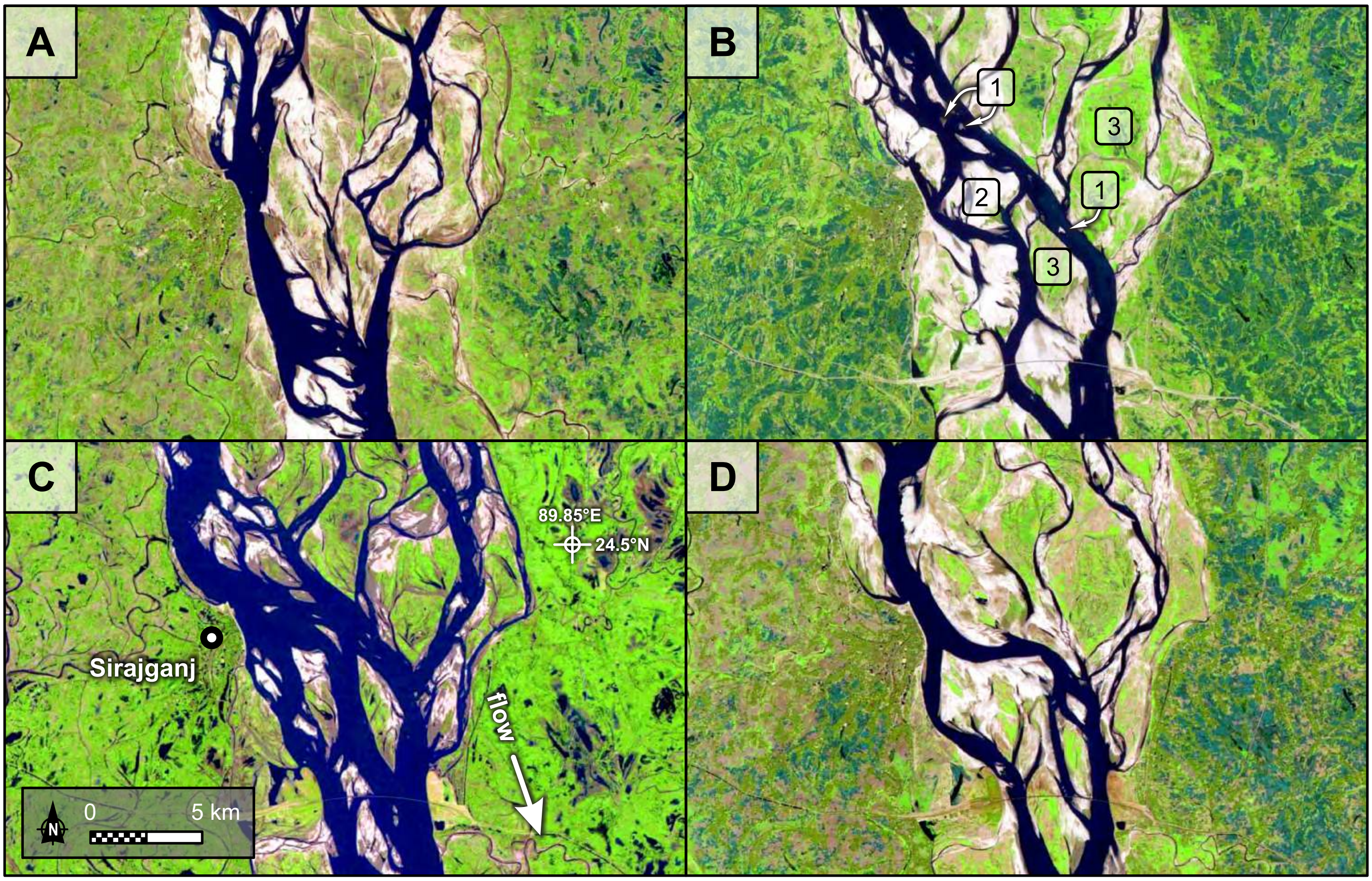
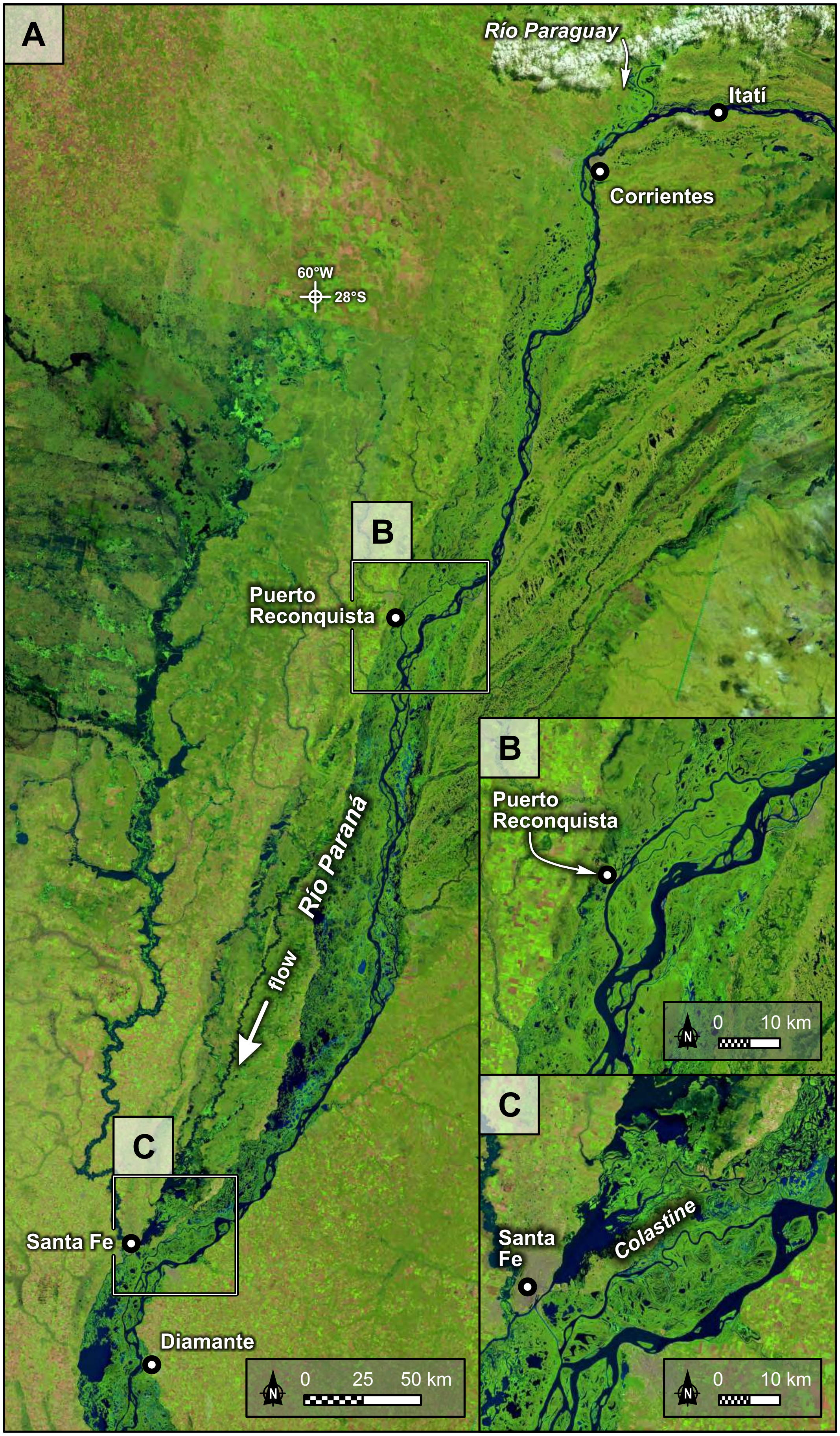


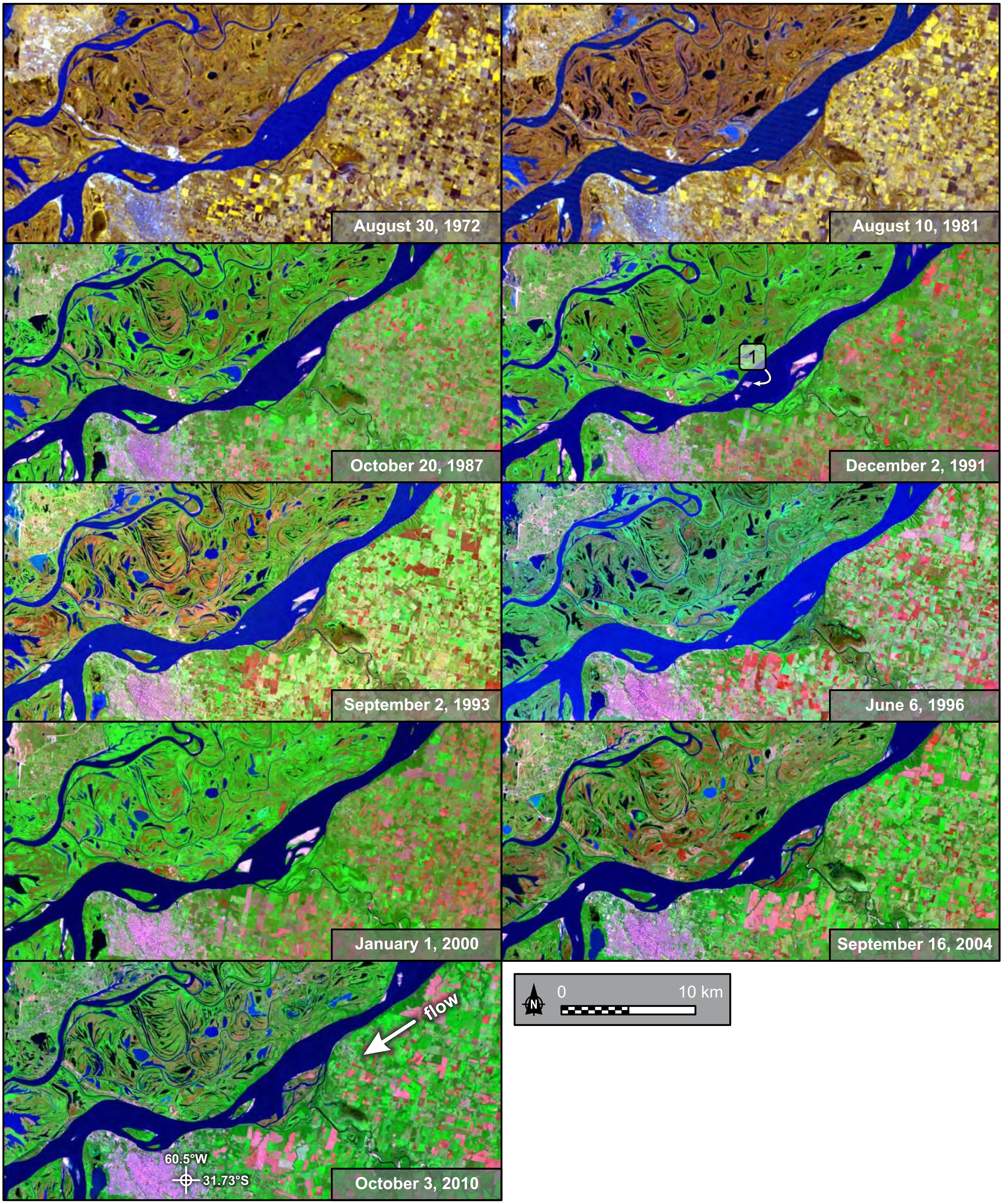
Figure 9


B
Krivosheino
0 2.5 5 km
N
84°E
57.25°N
flow
A
Belogor'ye
Khanty-Mansiysk
Surgut
Ust'-Tym
Krivosheino
0 200 km
Novosibirsk Reservoir
C
1
2
3
4
4
Ust'-Tym
flow
1972 bankline
Vertikos
0 2.5 5 km
80°E
59.35°N
D
71°E
61.35°N
flow
0 10 20 km
Alekino


Teesta R.
INDIA
Jamuna
Bahadurabad
90°E
25°N
Old Brahmaputra R.
flow
BANGLADESH
Sirajganj
Madhupur
Tract
Dhaleshwari R.
Ganges
Dhaka
N
0
25
50 km

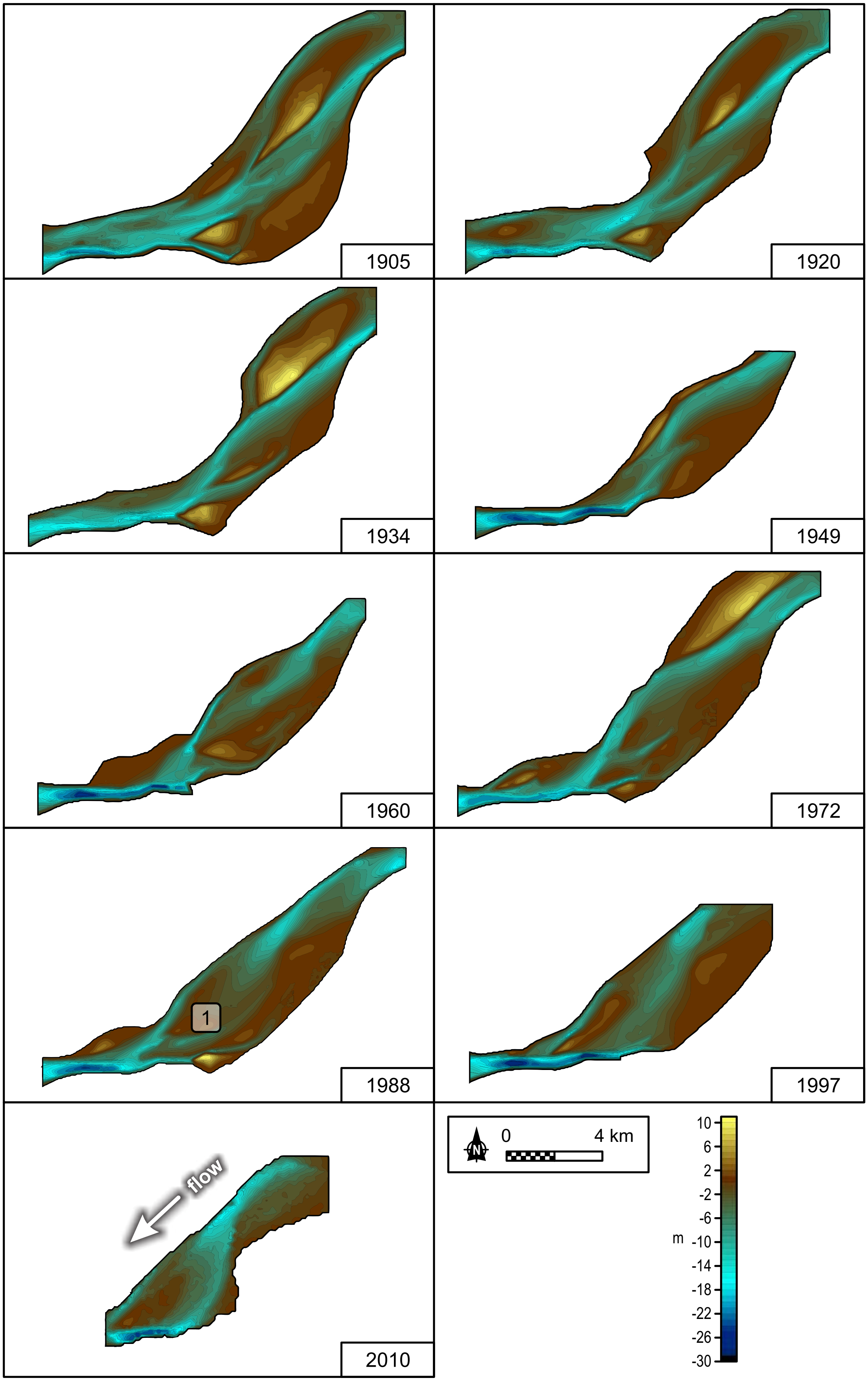

A
B
1
3
2
1
3
C
D
89.85°E
24.5°N
Sirajganj
flow
N
0
5 km


A
Río Paraguay
Itatí
Corrientes
60°W
28°S
B
Puerto Reconquista
Río Paraná
flow
C
Santa Fe
Diamante
0 25 50 km
N
B
Puerto Reconquista
0 10 km
N
C
Santa Fe
Colastine
0 10 km
N



August 30, 1972
August 10, 1981
October 20, 1987
December 2, 1991
1
September 2, 1993
June 6, 1996
January 1, 2000
September 16, 2004
October 3, 2010
flow
60.5°W
31.73°S
N
0
10 km


flow


1905
1920
1934
1949
1960
1972
1988
1
1997
2010
flow
0
4 km
N
10
6
2
-2
-6
m
-10
-14
-18
-22
-26
-30

	Mean annual runoff [1] (10^9 m^3)	Reach location		Gradient (m km^{-1})[6]	Valley floor width (km)[7]	Mainstream character[2]	Channel width (km)	Sedimentation elements[3] Floodplain					Mainstream				Tribs	Surface waters[4]	Hydraulic system (Fig. 8)
								a	b	c	d	e	f	g	h	i	j		
Amazon	6246	2°33'S	66°30'W	0.10	50	*M/A	2.5	○	○	◉	◉	●	●	●	◉	◉	○	1,2,4	1,2,3(b)(i)
Congo	1292	2°09'N	21°36'E	0.14	10-26	*A	4.8+	○	○	○	○	○	○	●	○	○	○	-	2
Orinoco	1089	7°53'S	65°30'W	0.04	8	B	2.6	○	◉	◉	◉	◉	●	●	●	◉	○	1,2	3(a)
Yangtze (Changjiang)	872	30°37'N	117°13'E	-	15	*M/A	2.5	●	○	◉	◉	●	◉	◉	●	○	◉	1,2,3,4	1,2
Brahmaputra	574	25°50'N	89°39'E	0.22	20	*B	12.0+	○	◉	○	◉	○	●	●	●	●	◉	1	3(a)
Yenisei	572	65°16'N	87°56'E	-	9	S	2.4	○	○	○	●	●	◉	◉	●	○	○	1	2
Volga	560	57°07'N	47°18'E	0.08	18	*A	-	◉	○	◉	●	●	◉	◉	◉	◉	◉	1,2	3(a)
Zambezi [5]	546	17°57'S	35°30'E	0.22	9	*B	0.80	○	◉	◉	●	◉	●	●	●	◉	○	1,2	3(a)
Lena	512	62°42'N	129°49'E	0.06	14	*A	2.30	○	◉	○	●	◉	●	●	●	◉	○	1,2	2,3(b)(i)
Mississippi[5]	495	32°43'N	91°09'W	0.06	50+	M	1.50	●	○	●	○	◉	●	●	◉	◉	○	1,2	2
Mekong	466	14°00'N	105°53'E	0.46	10	*	1.80	(mostly bedrock)										-	4
Paraná	429	31°41'S	60°33'W	0.06	28	*A	2.20	◉	○	◉	●	●	◉	◉	●	◉	●	1,2,3,4	1,3(b)(i)(ii)
Ob	400	58°22'N	82°43'E	0.04	21	*M	0.90	○	○	◉	●	◉	●	●	◉	●	◉	1,2	3(a)
Ganges	380	25°24'N	83°10'E	0.08	10	M	1.00	○	○	◉	○	○	●	●	◉	○	○	-	2
Amur	324	48°48'N	135°46'E	0.36	11	*A/B	2.60	○	○	◉	●	◉	●	●	◉	○	◉	1,2,3,4	3(b)(i)(ii)
Mackenzie	306	64°38'N	125°03'W	0.38	6	*W	1.20	○	○	◉	◉	◉	●	●	●	◉	○	-	3(a)
Columbia	251	45°47'N	120°04'W	0.26	2	S	1.80	(mostly bedrock)										-	4
Indus	238	27°20'N	68°15'E	0.14	90+	*B/M	1.10	○	●	●	◉	○	●	●	●	●	◉	2	3(b)(ii)
Magdalena	238	8°55'N	74°29'W	-	25+	*A	0.70	●	◉	◉	●	●	○	○	○	◉	◉	2,3,4	1,3(a)
Danube	203	46°15'N	18°55'E	0.20	15	M	0.60	○	○	◉	○	◉	●	●	◉	○	◉	1,2	2

[1]From Milliman and Syvitski (1992) with unit adjustment; separate figures for Ganges and Brahmaputra from Shiklomanov and Rodda (2003)

[2]Main channels may be anabranching (*), anastomosing (A) or wandering (W). Single channels or sub-branches may be straight (S), actively meandering (M) or braided (B)

[3]Sedimentation elements (a-j) are given in Figure 6 (● dominant, ◉ present, ○ not significant)

[4]Surface waters may be in: 1 scroll ponds, 2 cutoff channels, 3 floodbasins (ponded between raised alluvial ridges or against valley-sides), 4 ponded tributary valleys

[5]Runoff adjusted for regulation as described in Milliman and Syvitski (1992)

[6]Gradients measured over 50 km on adjacent flooplain using GoogleEarth (- indicates so flat it is unquantifiable)

[7]Channel widths (+ including bars/islands) and valley floor widths (that may include low terraces) are locally very variable; figures give an approximate guide