

1 **How do big rivers come to be different?**

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17 **ABSTRACT**

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

23 At the largest scale, trans-continent sized rivers do not possess unified valley systems  
24 created by fluvial erosion but instead involve chains of interlinked domains with contrasted

25 fluvial functions. Alluvial settings are dependent on mainstream and tributary inputs of water  
26 and sediment, but big river channel pattern variety is determined by contrasts in sediment  
27 feed-rates and differences in the rates and routes of sediment exchange. Four modes of  
28 alluvial exchange are recognised: (i) deposition on the floodplain (e.g., levees, infilled  
29 palaeochannels, floodbasins), (ii) exchanges involving main channels (e.g., bank erosion and  
30 accretion), (iii) deposition within main channels (e.g. bedforms from metres to 10s of  
31 kilometres in size), and (iv) material input from tributaries (sediment-rich or sediment-poor).  
32 Different combinations of sedimentation activity lead to floodplain morphologies for big rivers  
33 that can be classified into four types: (i) lacustrine-dominated, (ii) mainstream-dominated, (iii)  
34 tributary or accessory-stream dominated, and (iv) confined or bedrock-dominated.

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

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

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

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

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71     **1. Introduction**

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73         For an observer in the field, a river might seem best defined as ‘big’ in terms of a  
74         channel dimension threshold. Upstream of tidal influence, the undivided Amazon can be over  
75         5 km wide (e.g., at  $3^{\circ} 50'S$ ,  $62^{\circ} 26'W$ ), the Congo 8 km (e.g., at  $2^{\circ} 31'S$ ,  $16^{\circ} 10'E$ ) and the  
76         braided Brahmaputra/Jamuna (including exposed bars and temporary islands) even wider at  
77         10-15 km in places (e.g.,  $24^{\circ} 36'N$ ,  $89^{\circ} 44'E$ ). Any river over 1 km wide could reasonably be  
78         described as big (e.g., Sambrook Smith et al., 2009) but in field situations, reach-scale  
79         complexity makes morphological sizing somewhat equivocal.

80         Large alluvial rivers commonly widen and narrow over comparatively short distances.  
81         Abrupt changes in active braidplain width may be caused by flow divergence and  
82         convergence through confluence-diffluence units around km-scale bars (e.g., the Paraná at  
83          $31^{\circ} 33'S$ ,  $60^{\circ} 18'W$  that narrows from 7 km to 0.5 km along a 14 km reach; see Parsons et al.,  
84         (2007)), or be controlled by bedrock constriction (e.g., the Mekong at  $13^{\circ} 56'N$ ,  $105^{\circ} 14'E$ ; see  
85         Gupta (2007)), or as a river pattern forms a network of ‘island and node’ reaches (e.g.,  
86         Thorne et al., 1993). Big rivers typically have a hierarchy of mid-channel bars and islands  
87         (e.g., Bristow, 1987; Kelly, 2006), some of which may be heavily vegetated (e.g. the Congo  
88         River at  $1^{\circ} 29'N$ ,  $18^{\circ} 60'E$  and the Amazon at  $2^{\circ} 59'S$ ,  $67^{\circ} 50'W$ ) and at a height that can only  
89         be overtopped in out-of-bank flows (Thorne et al., 1993). Divided flows with main and  
90         accessory channels are commonplace. Some big rivers can be well-connected to their  
91         floodplains, frequently interchanging sediment and water with adjacent wetlands (e.g. the  
92         Paraná at  $28^{\circ} 22'S$ ,  $59^{\circ} 03'W$  and Fly at  $7^{\circ} 115'S$ ,  $141^{\circ} 11'E$ ), whereas others are essentially  
93         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  $02^{\circ} 44'S$ ,  $60^{\circ} 42'W$ ), 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 scouring 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; Latrubblesse, 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

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

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

134 Data sets for catchment size, discharge and suspended sediment yield give different  
135 river orderings, and there are no simple relationships between catchment size and  
136 discharges of water and sediment (Figs 1A-B). Leaving aside the Amazon, both annual runoff  
137 and mean sediment yield of some of the world's largest rivers range over two orders of  
138 magnitude (Fig. 1A). Latrubblesse's (2008) division of 'large' and 'mega' rivers (equivalent to  
139 32 and  $536 \times 10^9 \text{ m}^3 \text{ yr}^{-1}$ , or  $\text{km}^3 \text{ yr}^{-1}$ , respectively) does not produce a clear separation (Fig.

140 1A) and those classified as ‘mega’ rivers in Fig. 1A are not all grouped together by catchment  
141 area (Fig. 1B). It has been shown that small mountain catchments provide a large proportion  
142 of continental sediment yields (Milliman and Syvitski, 1992), and large catchments  
143 demonstrate markedly heterogenic behaviour. In some circumstance it may be piedmont  
144 Quaternary materials (Church et al., 1989) or lowland agricultural lands (Wilkinson and  
145 McElroy, 2007) that dominate sediment supply. On a continental scale, the sourcing, routing  
146 and loss of surface-water (from precipitation, evapo-transpiration, groundwater recharge and  
147 river flow) is spatially and temporally variable and the supply and throughput of sediment  
148 (from erosion, transport, alluvial sequestration and as downstream output) is distinctly non-  
149 linear (Jerolmack and Paola, 2010; Van de Wiel and Coulthard, 2010). Furthermore, there  
150 are regional differences in climate, lithology and hydrology that may influence the relationship  
151 between drainage area and water discharge (cf. Davidson and North, 2009). So it is  
152 unsurprising that there is no simple relationship between river size, sediment yield and  
153 drainage area (Figs 1A-B). Ranked lists of the world’s largest rivers based on these attributes  
154 should therefore be viewed with caution,

155         Earlier research on channel pattern discrimination for smaller rivers has generally  
156 been attempted using measures of discharge, gradient, stream power and bed sediment size  
157 (e.g., Leopold and Wolman, 1957; Ferguson, 1987; Van den Berg, 1995; Lewin and Brewer,  
158 2001). These controlling factors are more pertinent to bed material transfers rather than the  
159 sub-capacity suspended sediment and sand loads typical of the world’s largest rivers. It has  
160 been argued that this whole approach of channel pattern discrimination based on stream  
161 power is not fully satisfactory, especially for large anabranching systems that typically have  
162 low gradients, fine bed sediment and excess sediment transport capacity (Sarker and

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

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

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## 181 **2. Big rivers at a trans-continental scale**

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183 The world's largest rivers are bigger than individual sedimentary basins. Big rivers  
184 may extend into sedimentary basins, but they also cross them (e.g. Danube, Yangtze), and  
185 have longitudinally-extensive depositional zones (e.g. Congo, Ob). Whilst big rivers play an  
186 important role in sorting and sequestering coarse sediment in their proximal reaches,

187 sometimes represented by a single or series of mega-fans (e.g. Paraguay River, cf. Assine  
188 and Silva (2009)), most of the world's largest rivers go beyond so-called 'distributive fluvial  
189 systems' or DFS (Hartley et al., 2010; Weissmann et al., 2010; 2011). As Sambrook Smith et  
190 al. (2010) and Fielding et al. (in press) note, the rivers and sedimentary basins used to  
191 support the concept of DFS (Weissmann et al., 2010; their Fig. 1, p. 39) exclude over 75% of  
192 the Earth's largest rivers (see Fielding et al., in press, their Figure 7). Unlike DFS, big rivers  
193 can also include significant reaches dominated by laterally migrating channels, contain  
194 channels and floodplains with substantial organic-rich sedimentation and have partially-  
195 decoupled channels and floodplains (Lewin and Ashworth, in press). Put simply, the world's  
196 largest rivers are bigger than sedimentary basins alone – they transcend geological terrains  
197 and individual depositional basins, and have both sediment-rich and sediment-poor  
198 tributaries.

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

- 202
- 203 (i) dominant headwater orogenic-belt sources for sediment and runoff (Milliman and  
204 Syvitski, 1992);
- 205 (ii) intramontane and foreland depositional basins and ramps that accumulate large  
206 proportions of upstream eroded materials (Miall, 1996; Fielding et al., in press);
- 207 (iii) low sediment-yield cratons that may or may not be highly runoff-generating  
208 (Latrubblesse et al., 2005);
- 209 (iv) tectonic troughs that funnel and focus runoff and deposition;

- 210 (v) transverse orogens and depositional basins in downstream reaches;  
211 (vi) peri-marine environments that have also been greatly affected by fluctuations in the  
212 average level of the sea surface relative to the continents.

213

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

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

235 Figure 2 shows in simplified form the possible combinations of functioning domains. This  
236 schema broadly follows the typology of Potter (1978) and subsequent variants that have  
237 focussed on basin fills (e.g., Miall, 1996; his fig. 11.77). However, the schema in Fig. 2  
238 intentionally emphasises the role of tributaries, whether sediment-rich or sediment-poor, and  
239 of the dispersal and sediment storage along big river systems that may or may not terminate  
240 in well-defined depositional basins. Some large rivers (e.g., south-east Asia where the gorges  
241 of the Yangtze, Mekong, Salween and Irrawaddy run side-by-side in fold mountains) have  
242 mountain courses for a considerable proportion of their catchments (Fig. 2A). Elsewhere,  
243 supply sources may be lateral from a succession of tributaries (Fig. 2B) that allow repeated  
244 sediment replenishment (as along the Ganga basin) or at the head of a trunk river (Figs 2C  
245 and 2D) but with extensive sediment exchange along an alluvial corridor (e.g., the Amazon).  
246 Even within small catchments, tributaries may of course differ in terms of gradient, discharge  
247 and sediment character from their trunk streams, but in large basins there may be far greater  
248 contrasts between mainstream and tributary sediment and discharge contributions. This can  
249 work either way. The Mato Grosso tributaries of the Amazon are sediment-poor and have  
250 failed to fill valley trenches related to lower sea levels (Archer, 2005). The Andes-fed Amazon  
251 has alluviated its valley across their mouths resulting in ponded, lacustrine tributaries (Rio  
252 Tapajós, Rio Xingu) joining the main river. Some lowland Amazonian rainforest rivers (Purus,  
253 Juruá) may have higher yields than they extract from Tertiary basin fills (Latrubesse et al.,  
254 2005). On the other hand, the meandering Yamuna-Ganges trough is relatively sediment-  
255 poor until fed successively by its braided Himalayan tributaries. It is also possible for large

256 rivers like the Danube to have an alternation between depositional basins and transverse  
257 uplands along their courses (Fig. 2E), or even rivers that have few mountainous sediment  
258 sources at all (Fig. 2F). Large African rivers can almost reverse the small-river model:  
259 upstream plains, with steeper bedrock-controlled and confined courses downstream crossing  
260 rifted continental margins (Goudie, 2005).

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

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

279 et al., 2008). For the Amazon, Dunne et al. (1998) suggested that system-wide alluvial  
280 exchanges (into and out of alluvial storage) may exceed downstream sediment fluxes by a  
281 factor of two or more.

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

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

294

295 High or low loadings depend both on *source availability* (e.g., from orogenic belts, prior  
296 Quaternary deposits, or agricultural land), but also on *sink distribution* (e.g., intra-catchment  
297 depositional basins, riparian floodplains, or present-day reservoirs) and *availability* (i.e.  
298 ‘accommodation’), involved in dispersal loss or *sequestration* along the way. Whilst erosion  
299 loss from uplifting mountains is high, much of this may be deposited in close proximity –  
300 although the waters of large rivers drain through and beyond depositional basins. The  
301 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

325 fluvial deposits produced in different climate regimes and many river patterns are adjusted to,  
326 or in the process of adjusting to, the present interglacial conditions (cf. Valente and  
327 Latrubesse, 2012; Wasson et al., 2012). In varied and dynamic Quaternary climatic  
328 environments, and for reasons additional to tectonic settings, present-day large-river  
329 sediment sources and storages involve a mosaic of domains.

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332 **3. Alluvial channel patterns of big rivers**

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334 *3.1 Channel pattern types*

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336 Big rivers show a bewildering range of channel planform – from single to multiple  
337 channels, some with bars and islands dominated by lateral accretion and channel migration,  
338 yet others with a floodplain that is often dominated by adjacent standing water bodies in a  
339 range of size that may be refilled during floods (Fig. 3). Work to distinguish between different  
340 alluvial river patterns has been ongoing since the seminal work of Leopold and Wolman  
341 (1957) that categorised rivers as braided, meandering or straight. Braided patterns are  
342 divided by active bars that are usually ephemeral and submerged at high flow (Ashmore,  
343 1991). Numerous descriptive classification schemes have been proposed since the work of  
344 Leopold and Wolman (cf. Eaton et al., 2010) that use a plethora of terms and descriptions  
345 (e.g., 16 in Brice (1975) and 14 in Schumm (1981)), which are usually organised according to  
346 their dependence on sinuosity, degree of braiding or mode of sediment transport (suspended  
347 versus bedload). It is now acknowledged that there are at least two other named channel

348 pattern morphologies besides braided, meandering and straight: (i) wandering rivers that are  
349 transitional between meandering and braiding, commonly with islands of greater permanence  
350 and large area (Neil, 1973; Carson, 1984; Burge and Lapointe, 2005), and (ii) anastomosing  
351 rivers with multiple channels developed in fine-grained sediments, often with lakes and  
352 wetlands between levee-flanked channel branches and stable alluvial islands that divide flow  
353 up to bankfull (Knighton and Nanson, 1993; Abbado et al., 2005). Anastomosing channels  
354 tend to be laterally inactive, although not always the case as described for the Middle  
355 Amazon by Rozo et al. (2012). As a separate category of river channel pattern, or more  
356 usually at a higher level of classification (Kleinhans and Van den Berg, 2011), is the  
357 anabranching river (Rust, 1978; Knighton and Nanson, 1993; Nanson and Knighton, 1996)  
358 defined as a system of multiple channels that divide and rejoin. An anabranching river may  
359 have individual branches between more permanent islands that have a range of patterns:  
360 straight, meandering, braided, wandering or anastomosing (Nanson and Knighton, 1996).

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

368 Very rarely, where rivers flow into still freshwaters without an appreciable sand load, there  
369 are 'archipelagos' of silty levees. These take the form of highly elongate branching ridges  
370 paralleling faster-velocity channels within broad water bodies (Figs 5A-B). Such water bodies,

371 with individual branching levees can run for tens of kilometres, and are found in dammed  
372 tributary lakes draining to the Amazon (Archer, 2005; his figure 10, p. 28; Latrubesse and  
373 Franzinelli, 2005), in rift valleys in central Africa (e.g., along the Albert Nile in Uganda, 3°  
374 32'N, 31° 52'E) and very extensively along the lower Ob in Russia (see Section 4.1).

375 Latrubesse and Franzinelli (2005), studying the 275 km-long Mariuá archipelago and the  
376 Anavilhanas islands on the Rio Negro in Brazil (Figs 5A-B), describe the development of  
377 sandy islands capped with muddy sediments, and then muddy levee ‘trees’ extending  
378 downstream for considerable distances. These may enclose lakes where channels and  
379 levees rejoin. Archer (2005) suggests that humic acids and low pH contribute to flocculation  
380 of clays and silts in the Rio Negro, and the same probably applies to some craton drainages  
381 elsewhere. This is an eventual means for rivers to prograde and ‘bridge’ water-filled and  
382 possibly subsiding basins with levee-lined river passages, with organic materials playing  
383 significant depositional roles. However, Latrubesse and Franzinelli (2005) suggest that the  
384 Rio Negro features date from former periods of more active sediment input. The upstream  
385 Mariuá basin was filled largely with sandy sediments in the Holocene, with the flooded lower  
386 Anavilhanas basin (dammed by the Solimões-Amazon) in an arrested state of development  
387 and only partially modified with levee-lined channels. Laterally-mobile and low-energy muddy  
388 meandering streams have been described elsewhere, involving oblique accretion and post-  
389 depositional bank failure (Brooks, 2003), though there is only limited detail available for  
390 cohesive muddy-sediment processes in large freshwater rivers (cf. Maroulis and Nanson,  
391 1996; Grabowski et al., 2011).

392

393 *3.2 Alluvial exchange in big rivers*

394

395 Whilst meandering/braiding discrimination on small streams can be attempted through  
396 bivariate analysis using their wide range (over several orders of magnitude) in specific stream  
397 power and sediment size (e.g., Van den Berg, 1995; Ferguson, 1997; Lewin and Brewer,  
398 2001), such a range in controlling variables is less apparent for big rivers (Latrubesse, 2008;  
399 Kleinhans and Van den Berg, 2011), and it is thus less easy to account for their different  
400 patterns in such terms. In large rivers, some styles are maintained for hundreds of kilometres  
401 when developed at low gradients in sand and finer sediment (e.g., Congo River over 1200 km  
402 from  $0^{\circ} 45'N$ ,  $24^{\circ} 26'E$  to  $2^{\circ} 12'S$ ,  $16^{\circ} 15'E$ ). Others have marked pattern changes, variable  
403 sediment feed rates from tributaries and different forms of alluvial exchange with floodplain-  
404 stored sediment. Minor gradient changes, often through local plate flexuring and faulting, can  
405 have large effects on sedimentation at low slopes (Mertes and Dunne, 2007; Frings, 2008),  
406 for example with silty levees prograding across ponded flows rather than sandy lateral  
407 accretion at river banks.

408 Alluvial settings are dependent on mainstream and tributary inputs of water and sediment  
409 as discussed in Section 2 (Figs 1A-B), but alluvial morphologies are essentially determined at  
410 the reach scale. Sediments are not only transported through reaches (as suspended  
411 sediment or as migrating bedforms), but are also subjected to transfer processes into and out  
412 of alluvial storage. Figure 6 summarises the various forms of exchange that may take place.  
413 These include deposition on the floodplain (a-e), exchanges involving main channels (f-i) and  
414 deposition within them (h), or material input from tributaries (j). Whilst the size of channels  
415 reflects formative water discharges, it is these sediment exchanges that generate outline  
416 channel morphology – whether by bedform development into islands; by loss of load through

417 bed aggradation or slackwater and levee deposition; through recycling by bank erosion and  
418 active lateral accretion, or redirection by avulsion. If there is minimal exchange, even large  
419 rivers may remain straight (e.g. The Niger for 25 km at  $6^{\circ} 27'N$ ,  $6^{\circ} 40'E$ , or the Yenisei for 200  
420 km from  $63^{\circ} 43'N$ ,  $87^{\circ} 19'E$  to  $65^{\circ} 37'N$ ,  $88^{\circ} 03'E$ ) though with the bed diversified by migrating  
421 bedforms that are exposed at low flows. Table 1 presents summary characteristics for  
422 selected individual reaches on the 20 largest rivers ranked by mean annual runoff. For some,  
423 lateral exchange by bank erosion and accretion (f and g in Fig. 6) dominates; others have  
424 seemingly non-migrating channels with levees and floodbasins (a, b, and e in Fig. 6); yet  
425 others have floodplains blanketed with overbank sediments and infilled palaeochannels (c in  
426 Fig. 6). To complicate matters further, within hydraulic floodplains (the area inundated in  
427 major floods), large rivers can have genetically-decoupled sediment systems, with the largest  
428 channel acting as a dominant or lesser participant for both water and sediment transfer or  
429 deposition (e.g., the Amur at  $49^{\circ} 36'N$ ,  $136^{\circ} 32'E$ ). If they are present, smaller but sediment-  
430 rich tributaries (j) may dominate alluvial sedimentation. For example, the sediment-rich  
431 Madeira provides half the sediment load of the main Amazon channel, and its larger and  
432 coarser sediment load is associated with an increase in the number of islands and bank  
433 erosion rates downstream of the junction (Mertes et al., 1996). In their absence, a major but  
434 relatively sediment-poor river may only alluviate a narrow channel corridor, passing between  
435 floodbasins where lakes are impounded (e.g., the Magdalena at  $08^{\circ} 49'N$ ,  $74^{\circ} 22'W$ , see Fig.  
436 3B). The majority of big rivers have adjacent standing water bodies in a range of sizes and  
437 which may be refilled during floods (Table 1, Figs 7A-B). None of the characteristics  
438 described above are unique or exclusive to big rivers. The sediment exchanges illustrated in  
439 Fig. 6 are common to all floodplain rivers – large and small. But big rivers are characterised

440 more generally by a stronger decoupling from non-alluvial sediment input (i.e. more remote  
441 from adjacent valley slopes and flowing over low-gradient surfaces) and a greater role played  
442 by channelised flows in tributary or accessory channels for routing flow and sediment.

443 Given the range of sediment loadings available to trunk and tributary combinations,  
444 including bed- and suspension- load, the variety both between but also within large-river  
445 floodplains is considerable, even where there is a common valley-floor gradient and flood  
446 level set by the major river. The sediment actually available for major rivers to use in  
447 alluviating floodplains is as variable as the accommodation space provided, but can be high  
448 where regular monsoon-flooding facilitates long periods of overbank flow. For example,  
449 Allison et al. (1998) suggest between 31 and 71% of the total alluvial sediment budget may  
450 be trapped landward of the Ganges-Brahmaputra mouth whilst Islam et al. (1999) estimate  
451 49% of the total load is deposited before the coastal region with 28% deposited on the  
452 floodplain and 21% within the active channels. The proportion of sediment trapped within  
453 large river catchments is not necessarily different to small rivers but the absolute volume of  
454 sequestration is orders of magnitude greater (Fielding et al., in press). The volume ‘extracted’  
455 by overbank sedimentation can decrease significantly the downstream fining rate of large  
456 sand-bed rivers (Frings, 2008) and during high-magnitude floods the volume of overbank  
457 sedimentation can be of the same order as the sand input from upstream as observed by Ten  
458 Brinke et al. (1998) for the lower River Rhine.

459 The different combinations of sedimentation type lead to floodplain morphologies for big  
460 rivers that can be classified into four main types (Fig. 8, Table 1). The hydraulic and  
461 sedimentation systems on big rivers can range from lacustrine-dominated (Type 1) through  
462 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  $48^{\circ} 44'N$ ,  $135^{\circ} 16'E$  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.,  $02^{\circ} 43'S$ ,  $64^{\circ} 55'W$ ), the upper and middle Paraná (e.g.,  $27^{\circ} 14'S$ ,  $58^{\circ} 23'W$ , see Fig. 8) and over 150 km along the Upper Ob (e.g.,  $55^{\circ} 53'N$ ,  $83^{\circ} 45'E$ ) 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

486 Papua New Guinea these play a major role in transferring fine sediment from channel to  
487 floodbasins with about 40% of the total river sediment load being deposited overbank up to  
488 10 km away from the floodplain channel (Day et al., 2008). On large rivers, the ability  
489 differentially to distribute discharges and sediment loadings between two or more channel  
490 systems, coupled with tributary diversity, gives their floodplain processes a functional and  
491 intrinsic *pluralism* (Type 3, Fig. 8). This is not as common in smaller rivers (though see the  
492 example of Magela Creek described by Jansen and Nanson, 2004).

493 Reach-scale research in recent years has shown that within-channel sediment transfer  
494 processes in large rivers are more complicated than outline channel pattern might suggest  
495 (Kocurek et al., 2010). For example, migrating bedforms that account for a major proportion  
496 of bed sediment transfer in large rivers with predominantly sandy beds (Frings, 2008) pass  
497 through channels causing local macro-turbulence such as fluid upwellings (Best, 2005;  
498 Shugar et al., 2010) and possibly a disturbance and breakdown of channel-wide secondary  
499 circulation (McLlland et al., 1999; Parsons et al., 2007). In large rivers, bedforms such as  
500 dunes may respond very differently to an increase in stage so that the relationship between  
501 dune height and flow depth may have considerable scatter (e.g. Julien and Klaassen, 1995;  
502 Best et al., 2007), be very weak or non-existent (Leclair, 2011) or actually have an inverse  
503 relation such that dunes decrease in height with greater flow depths (Amsler and Garcia,  
504 1997). Relict dune topography from high flow stages may still have an influence on the  
505 location and size of bedforms that occur at low stages as shown for the Mississippi by  
506 Nittrouer et al. (2008), yet the interactions between bedforms themselves can give rise to a  
507 self-organised pattern (Kocurek et al., 2010).

508 Dune bedforms may be passive or active contributors to braid-bar initiation and growth  
509 (Ashworth et al., 2000; Sambrook Smith et al. 2009) depending on the local flow and  
510 sediment supply conditions and those inherited from immediately upstream. Large rivers  
511 typically have channels with width-depth ratios in excess of 100 (Thorne et al., 1993; Xu,  
512 2004; Latrubesse, 2008) that may result in a simple flow convergence and divergence around  
513 and over bartops (Richardson and Thorne, 1998; McLelland et al., 1999), but paradoxically,  
514 with few channel-wide unit bars migrating through the main thalwegs (Best et al., 2007;  
515 Sandbach et al., 2010). Some large rivers bifurcate and remain divided for 100 km and more,  
516 and some stay within a wide braidplain but experience extraordinarily high local rates of bank  
517 erosion (up to  $1 \text{ km yr}^{-1}$ , cf. Best et al., 2007). The timescales over which large rivers migrate  
518 and evolve vary considerably even for rivers with similar mean annual discharge and slope.

519

520

521 **4. Examples of contrasting large river channel pattern**

522

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

525

526 *4.1 The River Ob*

527

528 The River Ob has a catchment area  $\sim 2.77 \times 10^6 \text{ km}^2$ , a mean annual discharge  $\sim 400 \times$   
529  $10^9 \text{ m}^3$  with ice-bound winters for reaches north of Barnaul ( $53^\circ 21' \text{N}$ ,  $83^\circ 48' \text{E}$ ), and is  
530 characterised by a relatively low suspended sediment yield that *decreases significantly*

531 downstream as discharge increases (Bobrovitskaya et al., 1996; Meade et al., 2000).  
532 Upstream of the Irtysh junction at Khanty-Mansiysk (Fig. 10A) sediment yields over several  
533 decades have been less than  $20 \times 10^6$  tonnes yr<sup>-1</sup>. Since 1957, flow has been partially  
534 regulated by the Novosibirsk Reservoir (Fig. 10A). In recent decades, and in different parts of  
535 the system, there has been a decrease in summer flows because of irrigation, and greater  
536 winter flows released during power generation, but there have also been precipitation  
537 changes (Yang et al., 2004). From a geomorphological point of view the flow regime remains  
538 dominated by high-magnitude annual snowmelt floods that peak in May and June.

539 Below Krivosheino (Fig. 10A; elevation ~82 m) and as far as Belgor'ye (Fig. 10A;  
540 elevation ~24 m), the river flows for some 1000 km within a broad floodplain some 8-25 km  
541 wide. Valley gradients are low, generally below 0.1 m km<sup>-1</sup> and almost imperceptible for long  
542 distances. Nevertheless the valley floor itself is characterised throughout by remarkable  
543 meandering channel-trace patterns with sinuous sets of scrolls and palaeochannels (Fig.  
544 10B). These meanders have long attracted scientific attention, some reported in English  
545 language publications (e.g., Kondrat'yev and Popov, 1967; Kondrat'yev, 1968; Kulemina,  
546 1973; Alabyan and Chalov, 1998). Meandering style involves simple loops with circular arcs  
547 and moderate sinuosity without developing low-radius bends or omega shapes. Compound  
548 loops are virtually absent, probably due in part to early-stage cutoffs and in part to a relative  
549 lack of point bar forcing/pushing (Parker et al., 2011; see further discussion later). Floodplain  
550 ridge and swale patterns suggest that radial expansion of loops has dominated.

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

554 1989 to October 2010 near Krivosheino (Fig. 10B) shows mid-channel bars to be mostly  
555 transverse-symmetrical forms that wrap around vegetated islands, and deposit at channel  
556 junctions. Mean migration rate of the mid-channel bars at Krivosheino is 30 m yr<sup>-1</sup>.

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

566 Secondary channels are prominent across the valley floor. On main channels, there are  
567 cutoff chutes producing what Kulemina (1973) called ‘incomplete meandering’ (e.g., 61° 03'N,  
568 75° 48'E) such that loop development becomes divided before the highest sinuosities are  
569 reached (cf. Mertes et al., 1996). Large point bar complexes may be bisected in this way to  
570 produce islands of asymmetric planform with a concave (inner) and a convex (outer) bank  
571 (e.g., 58° 24'N, 82° 27'E). Chute channels may be actively modified into shorter-wavelength  
572 meanders. There is also larger-scale anabranching in which separate meandering courses  
573 can run for many kilometres, for as much as 400 km at and below Surgut (Fig. 10A, see  
574 image in Fig. 10D). The long islands created by these chute channels may be lozenge-  
575 shaped or ‘beaded’ in appearance, widening or narrowing in relation to the independent and  
576 actively meandering bounding channels (Fig. 10D, also see the Amur at 52° 00'N, 140° 15'E).

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

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

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

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

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

612 There has been long-running interest in the seemingly paradoxical significance either of  
613 eroding bends or of depositing bars in ‘forcing’ channel change, particularly involving bar-  
614 bend theory (e.g., Blondeaux and Seminara, 1985; Ikeda and Parker, 1989). It is the dynamic  
615 flow fields that interact with particle entrainment or deposition to produce feed-back  
616 morphological effects, and both types of forcing may happen. Bars may be regarded as ‘free’  
617 where they migrate quasi-independently, or ‘forced’ if they follow changing bend topography  
618 as growing point bars. In much the same way, Lucci et al. (2010) contrast island formation by  
619 ‘width forcing’ and ‘curvature forcing’, whilst Parker et al. (2011) describe ‘bank pull’ and ‘bar  
620 push’ processes in meanders. On the Ob, it appears that floodplain-dominating elongate  
621 point bar scrolls follow bank-arc recession and in gross terms are width-forced. Other bars  
622 are more likely related to sediment stalling in width-permitting reaches (both at divergence

623 points and in straighter but relatively wide channels). These only rarely appear to force bank  
624 changes to produce small-scale bank ‘bites’ related to mobile/stalled bar dimensions rather  
625 than longer meander-scale arcs (cf. Lewin, 1976).

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

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

646 and unfilled curving palaeochannels and elongate and digitate depressions between scrolls  
647 dominate.

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

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

661

662 *4.2 The Jamuna River*

663

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

669 Dhaledhwari (Fig. 11). The Jamuna is one of the most active braided rivers in the world with a  
670 braidplain up to 15 km-wide in flood, scour depths up to 40 m and bank erosion rates on  
671 average approximately  $50 \text{ m yr}^{-1}$ , but up to  $1 \text{ km yr}^{-1}$  on main channel outer bends (Klaassen  
672 and Vermeer, 1988; ISPAN, 1993; Flood Action Plan 24 1996a; Best and Ashworth, 1997;  
673 Khan and Islam, 2003; Best et al., 2007). At Bahadurabad (Fig. 11) the mean annual  
674 discharge is  $20200 \text{ m}^3 \text{ s}^{-1}$ . This varies from a minimum of  $\sim 2800 \text{ m}^3 \text{ s}^{-1}$  to a peak of  $\sim 100000$   
675  $\text{m}^3 \text{ s}^{-1}$  as experienced in both the 1988 and 1998 floods (EGIS, 1997; Chowdhury, 2000). The  
676 annual hydrograph has a stage change of  $\sim 6 \text{ m}$  (Sarker and Thorne, 2006; their figure 2, p.  
677 291) due to monsoonal rainfall with low flow mainly in February/March and peak flows in  
678 July/August. Mean water slope is 0.000076 over the first 130 km and 0.000065 further  
679 downstream (Flood Action Plan 24, 1996b). The grain size of the Jamuna is mainly fine sand  
680 and silt with less than 1% clay (FAP24, 1996b) and an average grain size of  $220 \mu\text{m}$  (Barua,  
681 1994; Sarker and Thorne, 2006). The fine and abundant sediment supply together with high  
682 water discharges results in the one of world's highest sediment yields that is estimated at  
683 between 590 and 792 Mt  $\text{yr}^{-1}$  (FAP24, 1996a; Islam et al., 1999) with up to 10% transported  
684 as bedload (Klaassen et al., 1988).

685 The Jamuna is predominantly a braided river characterised by divided flow and strongly  
686 stage-dependent bars that are unconsolidated, dynamic, poorly vegetated and overtapped at  
687 flows less than bankfull. Some parts of the Jamuna have been described as anastomosing  
688 (cf. Bridge, 2003, his fig. 5.5; Sarker and Thorne, 2006, their figure 14) whereby multiple-  
689 channels with vegetated islands or stable alluvial islands divide flow up to bankfull and typical  
690 width of the channels is much smaller than that of the bars (Nanson and Gibling, 2004).  
691 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  $\sim 50 \text{ m yr}^{-1}$  over the period 1834-1992 (Flood Action Plan24, 1996a) although the rate of widening has decreased more recently to  $\sim 30 \text{ m yr}^{-1}$  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

715 bars, scrolls and dunes (relief up to 2 m), (ii) river levees alongside active main channels  
716 (relief up to 3 m), (iii) crevasse splays caused by breaches of natural and human-made  
717 levees, and (iv) flood basins or enclosed depressions between the levees of adjacent  
718 channels that usually drain on the falling stage, although some permanent water bodies can  
719 contain peat accumulations (ISPAN, 1995).

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

729 Since dunes are ubiquitous in the Jamuna, they are also responsible for the creation and  
730 growth of sand bars from 100s metres to several kilometres in length (Figs 11 and 12). Two  
731 scales of bars exist in the Jamuna: (i) 'compound bars' (Fig. 12B, labelled 2) that scale with  
732 local channel width and mean flow depth, and (ii) 'vegetated islands' (Fig. 12B, labelled 3)  
733 that are stable, older, bar complexes with heights up to the adjacent floodplain (Thorne et al.,  
734 1993; Ashworth et al., 2000). Compound bars in the Jamuna are predominantly composed  
735 internally of stacked 2D and 3D dunes although bar-margin slipface accretion is also present  
736 at barheads and at obliquely migrating bar edges (Bristow, 1993; Best et al., 2003, their fig.  
737 5, pp. 522-523).

738 Migrating unit bars that are discrete, solitary barforms with a lobate planform (Bridge,  
739 1993) are rare in the Jamuna (Fig. 12B, labelled 1), which is different from observations in  
740 smaller sand-bed rivers (e.g. Smith, 1971; Sambrook Smith et al., 2006). Unit bars are not  
741 prevalent as exposed bedforms either at low flow in the main or secondary channels (Figs.  
742 12A-B and D), or in the subsurface (Best et al., 2003). It is unclear why unit bars, that are the  
743 fundamental building block in small sand-bed rivers (Sambrook Smith et al. 2006), are not  
744 common in large rivers (see the same observation for the Rio Paraná in Section 4.3). One  
745 reason may be that the potential for unit bar initiation and channel-wide extension is reduced  
746 due to the suppression or absence of significant channel-wide secondary flows as observed  
747 in large rivers with high width-depth ratio channels (McLellan et al., 1999; Parsons et al.,  
748 2007).

749 Bar types in the Jamuna are commonly mid-channel, longitudinal forms (Figs 12A-D) with  
750 sharp, erosional margins (Fig. 12D) indicative of the high degree of reworking and bar  
751 trimming. Mid-channel bars maintain their rhomboidal planform shapes at high flow (Fig. 12C)  
752 rather than becoming heavily dissected with cross-channels of different orders. Mid-channel  
753 bars enlarge both up-, down- and across-stream by either adding dunes that stall and stack  
754 at the bar margins (Best et al., 2003), or through lateral accretion by addition of successive  
755 individual scroll bars (Bristow, 1987). Migration rates for small (< 4 km long), unvegetated  
756 compound bars are extremely high at up to 3 km yr<sup>-1</sup>, but larger compound bars (up to 10 km  
757 long) move more slowly at up to 1 km yr<sup>-1</sup> usually through progressive barhead reworking and  
758 bartail accretion (cf. Best et al., 2007; their figs 19.26b-h, p. 425). The rapid rates of bar  
759 migration, bank erosion and channel change mean that the entire planform of the active parts  
760 of the Jamuna braibelt (usually up to 5 km-wide) is reworked over a decadal time-scale

761 (compare Figs 12A-D) and km-long bars are created, migrate and are then destroyed in  
762 under five years (Ashworth et al., 2000; Best et al., 2007). Only the vegetated and higher  
763 'islands' are stable for more than decades often because the main channel has avulsed or  
764 migrated over to another part of the braidplain. The Jamuna represents one of the world's  
765 most dynamic large rivers with ephemeral bars, a shifting braidbelt and a planform that is  
766 continually changing.

767

768 *4.3 The Río Paraná*

769

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

777 Mean annual water discharge of the Paraná at Itati is  $\sim 12,000 \text{ m}^3 \text{ s}^{-1}$ , increasing to  
778  $\sim 17,000 \text{ m}^3 \text{ s}^{-1}$  at Corrientes, 30 km downstream of the Río Paraguay tributary (Orfeo and  
779 Stevaux, 2002). Maximum discharge measured on the Paraná in the last century is  
780 associated with an El Niño-driven large flood in 1983 that peaked at  $33,740 \text{ m}^3 \text{ s}^{-1}$  in the  
781 Upper Reach (Orfeo and Stevaux, 2002) and  $55,000 \text{ m}^3 \text{ s}^{-1}$  in the Middle Reach (Amsler and  
782 Garcia, 1997). Mean bed slope near Corrientes ranges from 0.000049 (bankfull water surface  
783 slope; Latrubblesse, 2008) to 0.000085 (channel slope; Orfeo and Stevaux, 2003). Mean

784 annual sediment discharge of the Paraná increases dramatically from ~19 to  $\sim 158 \times 10^6$  t yr<sup>-1</sup>  
785 at the junction with the Río Paraguay, primarily due to the large input of suspended sediment  
786 from the Paraguay-Bermejo tributary system (Lane et al., 2008; Amsler and Drago, 2009).  
787 Between 80 and 91% of the sediment load in the Middle Reach of the Paraná is silt and clay  
788 washload (Amsler et al., 2007; Amsler and Drago, 2009). Bed material of the Upper and  
789 Middle Reaches of the Río Paraná is well sorted, predominantly medium-to-fine sand  
790 although some fine gravel is present in the channel thalweg (Santos and Stevaux, 2000;  
791 Amsler et al., 2007).

792 Except at the junction with the Rio Paraguay (Fig. 13A), the outline planform of the Upper  
793 and Middle Reaches of the Paraná is relatively straight (sinuosity less than 1.3; Amsler et al.,  
794 2005), but with downstream alternations between 2-3 km wide ‘enlargements’ that are  
795 characterised by two or more main channels with mean depths of 5-8 m, and 0.6-1.2 km-  
796 wide, and well-defined, structurally-controlled constrictions with mean depths of 15-25 m that  
797 are generally stable and have not migrated for the last 80 years (Amsler et al., 2005; Iriondo,  
798 2007). The channel planform of the Paraná can be described as anabranching because it  
799 contains multiple-channels that contain stable vegetated bars that divide flow up to bankfull  
800 (Nanson and Knighton, 1996; Latrubblesse, 2008). However, the division of discharge around  
801 the km-scale bars is rarely even and usually one anabanch is dominant (Parsons et al.,  
802 2007; Szupiany et al., 2009; Sandbach et al., 2010).

803 The Rio Paraná bed is dominated by dunes at all flow stages (Parsons et al., 2005;  
804 Kostaschuk et al., 2009; Shugar et al., 2010). Mean dune height and lengths of 1.5 and 6.4 m  
805 respectively have been measured at low flow ( $\sim 11000$  m<sup>3</sup> s<sup>-1</sup>) near Corrientes with  
806 superimposed dune heights and lengths of 0.3 m and 10 m (Parsons et al., 2005; Sambrook

807 Smith et al., 2009). However, much larger dunes have been observed during floods in the  
808 Paraná with heights up to 6.5 m and lengths of 320 m during the historic large flood in 1983  
809 (Amsler and Garcia, 1997). Dunes in the Paraná, and in other large sand-bed rivers such as  
810 branches of the Rhine and the Mississippi, may respond differently to rising flow stage  
811 compared to smaller rivers (Garcia, 2008). Small dunes grow readily as discharge increases  
812 but large dunes have been observed to do the opposite (Amsler and Garcia, 1997; their fig.  
813 9, p. 583). Large dunes (> 1 m in height) may flatten and develop much lower leeside angles  
814 during peak discharges possibly in response to an increase in suspended load, although  
815 large dunes probably do not reach upper-regime plane bed during major floods (Julien and  
816 Klaassen, 1997). Dunes therefore represent significant bed roughness in large rivers and  
817 cause disruption to the near-bed flow structure (Parsons et al., 2005; Shugar et al., 2010)  
818 that may have a significant effect on flow routing and the development of secondary flow  
819 circulation (Parsons et al., 2007; Sandbach et al., in press).

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

826 Four features characterise the Paraná planform morphology. Firstly, within the near-  
827 straight channel outline, a dominantly sinuous meandering thalweg, up to 2 km wide and 26  
828 m deep at outer bank scours, with a wavelength of ~12 km (Sandbach et al., 2010, their fig.  
829 1, p. 410). This thalweg can convey up to 70% of the discharge and controls the direction of

830 primary flow in most reaches with only localised curvature-driven secondary flow circulation  
831 (Sandbach et al., 2010; Nicholas et al., in press). The dominance of a well-defined sinuous  
832 thalweg means the Paraná is essentially a meandering main-stem trapped within an  
833 anabranching channel-belt. Enlargement and downstream migration of the sinuous thalweg is  
834 responsible for the majority of bankline change with maximum bank retreat rates of 100 m yr<sup>-1</sup>  
835 (Ramonell et al., 2002), but major avulsion over century time-scales is absent.

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

846 A third feature of the Paraná is having few exposed sand bars, particularly in the Middle  
847 Reach. Sand bars are typically bank-attached, transverse or medial bars (Santos and  
848 Stevaux, 2000) with low-flow, mean geometries of ~0.6 ( $\pm 0.4$ ) km in length and 0.3 ( $\pm 0.2$ ) km  
849 in width. Drago (2010) measured the prevalence of different sand bar types in a 1087 km  
850 reach downstream of the Yacyretá Dam (27° 29'S, 56° 44'W) and noted accumulations of  
851 sand onto the barheads of km-scale vegetated bars accounted for up to 77% of all sand bar  
852 types. Drago's work showed a strong positive correlation between the number of sandy

853 barheads and distance downstream which he suggested may be attributed to the higher ratio  
854 of suspended-to-bedload downstream and therefore access to a source of more sandy  
855 material. Isolated, sandy, non-vegetated bars are surprisingly rare in the main channel  
856 between Itati and Santa Fe. Figure 14 shows decadal years of channel change and bar  
857 development at the downstream end of the Middle Reach of the Paraná. Although a new,  
858 2.5-km long, mid-channel bar developed in the mid-1980s (Figs 14 and 15), probably in  
859 response to upstream scour and subsequent bank erosion during the large 1983 flood, the  
860 40-km reach shown in Fig. 14 is characterised by the lack and slowness of channel change.  
861 Whilst the internal morphology of the new mid-channel bar is complex and suggests several  
862 phases of aggradation and scroll bar addition (Fig. 15), the overall planform is relatively  
863 simple and predictable (Fig. 14). Indeed, if the development of the same reach shown in Fig.  
864 14 is extended over longer time-scales using historic bathymetric surveys (Fig. 16), the  
865 morphological change is characterised by a slowly migrating, sinuous thalweg that sweeps  
866 across the channel-belt rather than rapid rates of bank retreat, bar reworking and local  
867 avulsion as seen in the Jamuna (compare to Fig. 12). In the Paraná, heavily vegetated bars,  
868 up to 15 km-long, but more typically 5-8 km-long, fix and control the local channel  
869 morphology. Sand bars are incidental, ephemeral depositional elements that wrap onto and  
870 around these stable islands. The fully vegetated, stable islands are probably 100s to 1000s of  
871 years old and are only completely overtapped in low recurrence-interval, major overbank  
872 floods (e.g.  $\sim 27000 \text{ m}^3 \text{ s}^{-1}$  at Itati in January 2010).

873 Finally, a fourth feature of the Paraná morphology is the presence of extensive lotic  
874 (flowing water) and lentic (still water) ecosystems that are eroded, filled or enlarged in each  
875 flood event (Paira and Drago, 2006; 2007). Water bodies are linked ultimately to the short

876 and long-term main river channel dynamics and are associated with (a) secondary channels  
877 and ridge and swale topography in or immediately adjacent to the main channels, but also (b)  
878 up to 28 km away where the floodplain develops to the margin of the alluvial valley (e.g. Fig.  
879 7A) and water accumulates in depressions associated with older channel scars and zones  
880 that are affected by neotectonic uplift and subsidence (Paira and Drago, 2007). Average lake  
881 length, width and depth is ~1.1 km, 0.4 km and 1.6 m respectively (1500 lakes measured in  
882 the Middle Paraná; Paira and Drago, 2007). Nearly 25% of the Middle Paraná floodplain  
883 lakes have 5% of their surfaces covered with free or rooted macrophytes although the  
884 coverage of aquatic vegetation ranges from 0 to 100% in lakes with areas less than 2 km<sup>2</sup>  
885 (Paira and Drago, 2006). Water bodies are therefore important carbon sinks and large  
886 portions of the thick organic matter on their beds can be completely excavated during large  
887 floods (Drago et al., 2003).

888

889 *4.4 Three of the world's largest rivers with three very different styles of channel pattern*

890

891 The Ob, Jamuna and Paraná are three of the world's greatest rivers whether measured  
892 by catchment area, runoff or, in the case of the Jamuna and Paraná, sediment yield (Figs 1A-  
893 B, Table 1). Like most big rivers all three rivers are anabranching, not only divided, but also  
894 with a plural mixing of styles with accessory and tributary floodplain channels (Figs 8C, and  
895 13B-C). They all have low valley gradients (generally <1 m km<sup>-1</sup>), main-channel sandy bed  
896 sediments, and variable suspended sediment loadings. Latrubblesse (2008) suggests that low  
897 specific stream powers of <25 W m<sup>-2</sup> are characteristic of large ('mega') rivers. However,

898 such common properties are associated with different morphologies on the Ob, Jamuna and  
899 Paraná and anabranching in each, is in practice, achieved in different ways.

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

915

916

917 **5. Large and small river channel pattern**

918

919 The world's largest rivers differ from their monotonic smaller counterparts because they  
920 have greater complexity introduced by crossing a series of chains of interlinked domains with

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

937 Some researchers have investigated whether the channel pattern and planform  
938 morphology of anabranching rivers is the same for large and small rivers. It has been shown  
939 convincingly that braided river network patterns are scale invariant (e.g., Sapozhnikov and  
940 Foufoula-Georgiou, 1996; Nykanen et al., 1998; Sapozhnikov et al., 1998; Foufoula-Georgiou  
941 and Sapozhnikov, 2001). Likewise, Sambrook Smith et al. (2005) and Kelly (2006) have  
942 shown that surface planform (long-to-intermediate axis) of mid-channel bars is scale invariant  
943 for a range of anabranching rivers over a four order of magnitude range in size. To some

944 extent this latter result is not surprising given that mid-channel bars will always be  
945 streamlined by the flow, but stark variations do exist, seemingly associated only with big  
946 rivers. For example, over 1200 km of the Congo (shown in Fig. 3E) and 250 km of the Negro  
947 (shown in Figs 5A-B) have mid-channel bars that are especially elongated (mean  
948 intermediate-to-long axis of 0.25). It is unclear why these bars should have such different  
949 planform morphologies from other large rivers (e.g. the Jamuna, Fig. 12) but it may be related  
950 to the local bar-building process that is through inwardly-accreting levees and ridges (Figs  
951 5A-B; Latrubblesse and Franzinelli, 2005) and/or the influence of mature vegetation that  
952 reduces the potential for avulsion and substantial reworking.

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

965

966

967 **6. Conclusions**

968

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

973

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

977

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

982

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

987

- 988        4. Anabranching planform channel patterns dominate, with a system of multiple channels  
989              that divide and rejoin. But anabranching is achieved by different processes, as is  
990              illustrated by the Ob, Jamuna and Paraná.
- 991
- 992        5. Big rivers contain a bewildering range of channel planforms – from single to multiple  
993              channels, some highly sinuous, with bars dominated by lateral accretion, but others by  
994              downstream migration and a floodplain that can be dominated by adjacent standing  
995              water bodies in a range of size that may be refilled during floods. Main channels can  
996              be straight, meandering, braided, wandering or anastomosing. Individual branch  
997              channel patterns are determined by the degree of lateral shifting and avulsion, rate of  
998              overbank sedimentation, magnitude of sediment transport capacity and bed  
999              material/braiding intensity.
- 1000
- 1001        6. Forms of alluvial exchange can be classified as: (i) deposition on the floodplain (e.g.,  
1002              levees, infilled palaeochannel, floodbasins), (ii) exchanges involving main channels  
1003              (e.g., bank erosion and accretion), (iii) deposition within main channels (e.g. bedforms  
1004              from metres to 10s of kilometres in size), and (iv) material input from tributaries  
1005              (sediment-rich or sediment-poor). Whilst the size of channels reflects formative water  
1006              discharges, it is these variations in sediment exchange that produce the diversity of  
1007              big river morphologies.
- 1008
- 1009        7. Fine out-of-channel sediment deposition may be insufficient to fill hydraulic corridors;  
1010              ponded lacustrine environments are common. Water bodies vary from smaller water-

1011 filled swales and palaeochannels, to floodbasins between raised alluvial ridges and  
1012 valley-sides, and to km-scale linear lakes in sediment-dammed tributaries. Organic  
1013 sedimentation is significant along relatively sediment-poor and laterally-stable major  
1014 rivers that fail to fill their alluvial corridors.

1015

1016 8. Hydraulic and sedimentation systems may be divided into four types: (i) lacustrine-  
1017 dominated, (ii) mainstream-dominated, (iii) tributary or accessory-stream dominated,  
1018 and (iv) confined or bedrock-dominated.

1019

1020 9. Big rivers are commonly *plural systems*, with partial functional decoupling between  
1021 large rivers and their hydraulic floodplains, and with accessory and tributary channels  
1022 rather than main-river branches determining patterns of floodplain morphology.  
1023 Straight, bedform-dominated mainstreams may have accessory channels that actively  
1024 meander to dominate near-surface floodplain sedimentation.

1025

1026 10. Bed sediment transfers are dominated by migrating sandy bedforms but with a wide  
1027 range of bar types, shapes and rates of accretion. No style of bar creation or  
1028 aggradation is unique to big rivers and many barforms are short-lived, ephemeral  
1029 features that wrap around or onto stable vegetated islands that control the planform  
1030 morphology. Lobate, unit bars are rare or absent in some of the world's largest sand-  
1031 bed rivers.

1032

1033        11. Some processes and patterns are different from smaller rivers, including: (i) less  
1034                  straight-forward sequencing of channel pattern downstream, (ii) main channels with  
1035                  high width:depth ratios and possibly limited channel-wide secondary flows, (iii) few or  
1036                  no channel-wide unit bars migrating through the main thalwegs, (iv) extensive and low-  
1037                  gradient floodplains that provide space for channel shifting and floodplain  
1038                  sedimentation, (v) long distances between significant tributaries to allow full mixing of  
1039                  water and sediment discharges, (vi) partial and sometimes temporarily decoupled  
1040                  channels and floodplains, (vii) significant floodplain water bodies that readily act as  
1041                  sinks for fine-grained and organic sediments.

1042

1043        12. There can be an apparent disconnect between observable channel processes and  
1044                  overall patterns of channels and floodplains. In part this arises from different activity  
1045                  timescales, in part from inheritance. The understanding of observed ‘contemporary’  
1046                  forms requires attention to: flood-event transfer of sediment, reach-scale incremental  
1047                  reworking of floodplain sediments and bar changes on a timescale of years to  
1048                  centuries, and the inheritance and modification of floodplain forms and sediments that  
1049                  relate to Quaternary change.

1050

1051        Big rivers have a distinctive character and their pattern variety may usefully be viewed in  
1052                  terms of sediment systems operating at *both* the catchment and reach scales. Between-river  
1053                  variability and internal complexity show the need to understand contrasted sediment supply,  
1054                  through-put and local alluvial exchange as determinants of big river morphology and pattern.

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1056

1057 **Acknowledgements**

1058

1059 PJA would like to thank the UK Natural Environment Research Council (NERC) for  
1060 support under grant NE/E016022/1 that funded fieldwork on the Rio Paraná, Argentina,  
1061 together with colleagues Mario Amsler, Jim Best, Rich Hardy, Stuart Lane, Andrew Nicholas,  
1062 Oscar Orfeo, Dan Parsons, Arjan Reesink, Greg Sambrook Smith, Steve Sandbach and  
1063 Ricardo Szupiany. Thanks to this team for allowing use of the jointly-collected data shown in  
1064 Fig. 16. Fieldwork on the Jamuna was supported by NERC grant GR9/02034 to PJA and  
1065 colleagues Jim Best, Charlie Bristow and Julie Roden. We are grateful to Chris Simpson of  
1066 Fulcrum Graphic Communications Inc., Vancouver, B.C., for his expertise in sourcing and  
1067 producing all the figures. Referees Gerald Nanson, Chris Fielding and Managing Editor  
1068 Andrew Miall are all thanked for their insightful and supportive comments.

1069

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- 1580

1581 **Figure captions**

1582

1583 1. (A) Sediment yield versus annual runoff, and (B) sediment yield versus catchment  
1584 area for the world's largest rivers with catchment areas greater than 0.5 million km<sup>2</sup>.  
1585 Data are from Milliman and Syvitski (1992) except for runoff for the Ganges and  
1586 Brahmaputra that are from Shiklomanov and Rodda (2003). Runoff is expressed as  
1587 annual gross discharge in km<sup>3</sup> yr<sup>-1</sup> (rather than using unit discharge). This purposely  
1588 discounts the influence of catchment size which does not always control the local  
1589 channel pattern in large river basins. Two rivers (Irrawaddy and Magdalena) are in the  
1590 top ten sediment-yield rivers but have relatively small catchment areas so are not  
1591 plotted here. Note sediment yield values have been adjusted to pre-dam values for the  
1592 Mississippi, Nile, Zambezi, Indus, Columbia and Rio Grande as described in Milliman  
1593 and Syvitski (1992) although some of these data are probably first-order estimates.

1594 .

1595 2. Schema of domain chains for trans-continental catchments. Types are: A = Mountain-  
1596 dominated (e.g., Amur, Mekong), B = Lateral tributary-dominated (e.g., Ganges,  
1597 Mississippi, Paraná), C = Headwater-dominated with foreland depositional basins  
1598 (e.g., Amazon, Orinoco), D = Headwater-dominated with lowland alluvial corridor (e.g.,  
1599 Ob, Mackenzie), E = Alternation between depositional basins and mountain belts (e.g.,  
1600 Danube, Yangtze), F = Few mountainous sources (e.g., Congo, Rio Xingu). Detailed  
1601 description of the domains is given in the text.

1602

1603 3. Examples of the wide variety of channel pattern in large rivers: (A) Amazon (image  
1604 taken on 24 November 2000), (B) Magdalena (image taken on 12 January 2001), (C)

1605 Ob (image taken on 17 September 2002), (D) Mackenzie (image taken on 7  
1606 September 2002), (E) Congo (image taken on 17 May 2003) and (F) Orinoco (image  
1607 taken on 7 March 2001). All images are plotted at the same scale. Landsat imagery  
1608 courtesy of the U.S. Geological Survey.

1609  
1610 4. Channel patterning in big rivers and examples using reaches from the 20 world's  
1611 largest rivers (defined by mean annual runoff, see Table 1). Most big rivers are  
1612 anabranching with a system of multiple channels that divide and rejoin but individual  
1613 branch channel patterns may be straight, meandering, braided, wandering or  
1614 anastomosing.

1615  
1616 5. (A) Mariuá archipelago, upstream of the Branco tributary (mosaic taken on 5 August  
1617 2002 and 21 September 1999), and (B) the Anavilhanas islands ~50 km upstream of  
1618 Manaus (image taken on 10 July 2001), both on the Rio Negro, Brazil. Images  
1619 correspond to reaches IIIb and V described in Latrubesse and Franzinelli (2005). Note  
1620 in (A) the vegetated islands vary up-to-downstream from sandy, topped with muddy  
1621 sediments to those that are predominantly mud, and in (B) the vegetated islands are  
1622 mostly a homogeneous mix of sand, silt and clay that probably owe their origin to  
1623 former conditions when elongated levees were built in water loaded with suspended  
1624 sediment (interpretation and description from Latrubesse and Franzinelli (2005)).  
1625 Landsat imagery courtesy of the U.S. Geological Survey.

1626

- 1627        6. Alluvial exchanges in large rivers: deposition on the floodplain (a-e), exchanges  
1628                 involving main channels (f-i) and deposition within them (h), or material input from  
1629                 tributaries (j).
- 1630
- 1631        7. (A) Rio Paraná near Esquina (image taken on 2 April 2001), and (B) Amazon near  
1632                 Manacapuru (image taken on 21 January 2003), showing a range of adjacent standing  
1633                 water bodies that may be refilled during floods. Labels are: 1 = swale ponds, 2 = cutoff  
1634                 channels, 3 = floodbasins (ponded between raised alluvial ridges or against valley-  
1635                 sides), 4 = ponded tributary valleys. More details on the origin, evolution and types of  
1636                 floodplain water bodies for the Paraná are in Paire and Drago (2007). See Table 1 for  
1637                 a list of the type of standing water bodies found in the 20 largest rivers in the world.  
1638                 Landsat imagery courtesy of the U.S. Geological Survey.
- 1639
- 1640        8. The four main hydraulic systems, with examples, that characterise large rivers: (A)  
1641                 Type 1: lacustrine-dominated; (B) Type 2: mainstream-dominated; (C) Types 3(a)-(b):  
1642                 equi-style and contra-style (tributary or accessory stream dominated); (D) Type 4:  
1643                 confined or bedrock-dominated. Landsat imagery courtesy of the U.S. Geological  
1644                 Survey and all images are plotted at the same scale.
- 1645
- 1646        9. The Amur at Malyshevo (image taken on 5 September 2002) showing an example of  
1647                 accessory channels that run alongside the main channel that can be of a different  
1648                 channel pattern from the main stem. Landsat imagery courtesy of the U.S. Geological  
1649                 Survey. Darker brown colours in the main and accessory channels represent zones of

1650 lower velocity and sediment load and potential areas for deposition. Label 1 =  
1651 accessory channel.

1652

1653 10. (A) Map showing upper course of the River Ob and locations of points referred to in  
1654 text, (B) River Ob at Krivosheino taken on 7 July 1999, (C) River Ob at Ust'-Tym taken  
1655 on 27 September 2010, (D) River Ob at Alekino taken on 21 May 2003. Landsat  
1656 imagery courtesy of the U.S. Geological Survey. Note (B) shows the multiplicity of  
1657 channels with different radius of curvature associated with several styles of meander  
1658 development. Lateral accretion dominates floodplain construction and avulsion is  
1659 controlled by the strong, local floodplain relief, (C) shows the slow rates of meander  
1660 migration and scroll bar accretion, and (D) shows the complexity of floodplain relief  
1661 that favours meander-bend avulsion. Labels for standing water bodies are 1 = in point  
1662 bar swales, 2 = in arcuate dead channel loops, 3 = as broader unsedimented water  
1663 bodies, 4 = in circular thaw ponds and thermokarst features.

1664

1665 11. Braided river planform of the Jamuna River, Bangladesh and locations referred to in  
1666 the text. Images courtesy of U.S. Geological Survey and mosaic taken at low flow on  
1667 17 February 2002 and 24 February 2002.

1668

1669 12. Channel change on the Jamuna River near Sirajganj. Images taken on (A) 13  
1670 February 1989, (B) 19 February 2000, (C) 4 November 2004, and (D) 21 January  
1671 2010. Note image (C) is taken following the discharge peak that usually occurs in  
1672 August. Labels on (B) are 1 = unit bars, 2 = compound bar, 3 = vegetated islands. The

1673 main channels are generally ‘clean’ and devoid of emergent unit bars. The Jamuna  
1674 reworks most of its active braidbelt in less than 10 years.

1675

1676 13.(A) The anabanching Rio Paraná, Argentina and locations referred to in the text, (B)  
1677 Puerto Reconquista offtake, and (C) Colastine offtake. Images courtesy of U.S.  
1678 Geological Survey and mosaic taken on 26 December 2002, 8 April 2003, 15 April  
1679 2003, 3 May 2003 and 24 May 2003.

1680

1681 14. Channel change on the Rio Paraná between 1972 and 2010 in a reach 25 km south-  
1682 east of Santa Fe (location in Fig. 13A). Images courtesy of U.S. Geological Survey  
1683 and taken on dates shown in Figure. Label 1 on 2 December 1991 image is the new  
1684 mid-channel bar that was probably created in the 1983 flood (see Fig. 16) and is  
1685 pictured fully emergent in Fig. 15.

1686

1687 15. View of 2.5 km-long mid-channel bar near Santa Fe that developed in the mid-1980s  
1688 (bar location labelled in Fig. 14). Note the dune field on the incipient sand bar at the  
1689 main bartail. Photograph taken on 1 October 2010.

1690

1691 16. Channel change in the Rio Paraná from 1905-2010 reproduced from historic and  
1692 recent bathymetric surveys (data courtesy of Prof. M. Amsler, Dr R. Szupiany and  
1693 Dirección Nacional de Vias Navegables). All data are reduced to the same common  
1694 datum. The 18 km-reach is 25 km south-east of Santa Fe and satellite images of

1695 planform change since 1972 are presented in Fig. 14. Label 1 = mid-channel bar  
1696 shown in Figs 14 and 15.

1697 **Table captions**

1698

1699 1. Reach character on the world's 20 largest rivers

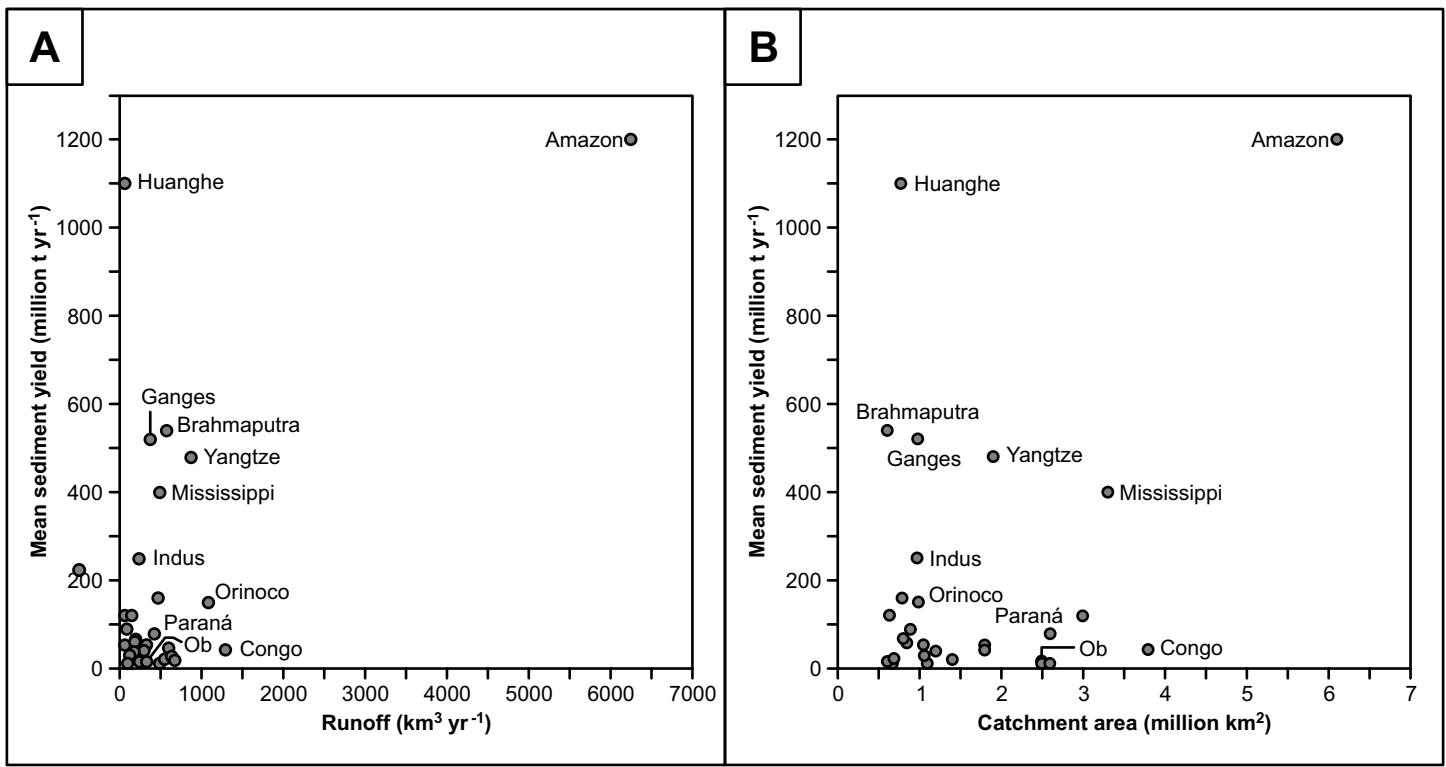


Figure 1

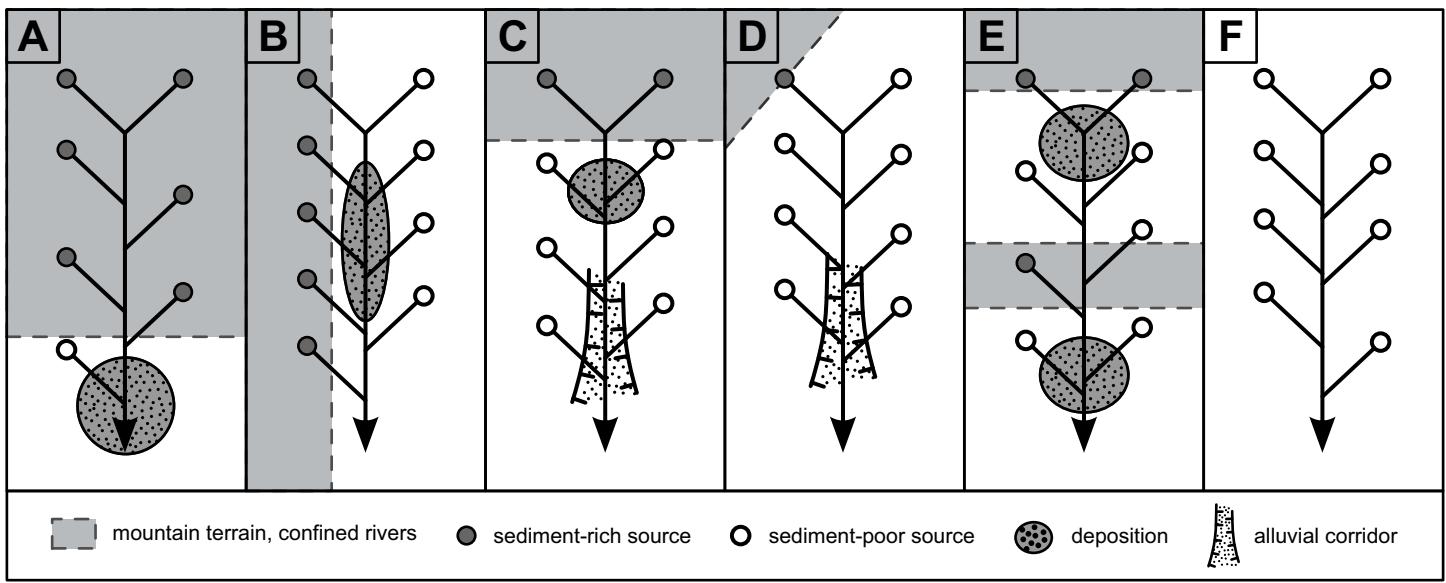


Figure 2

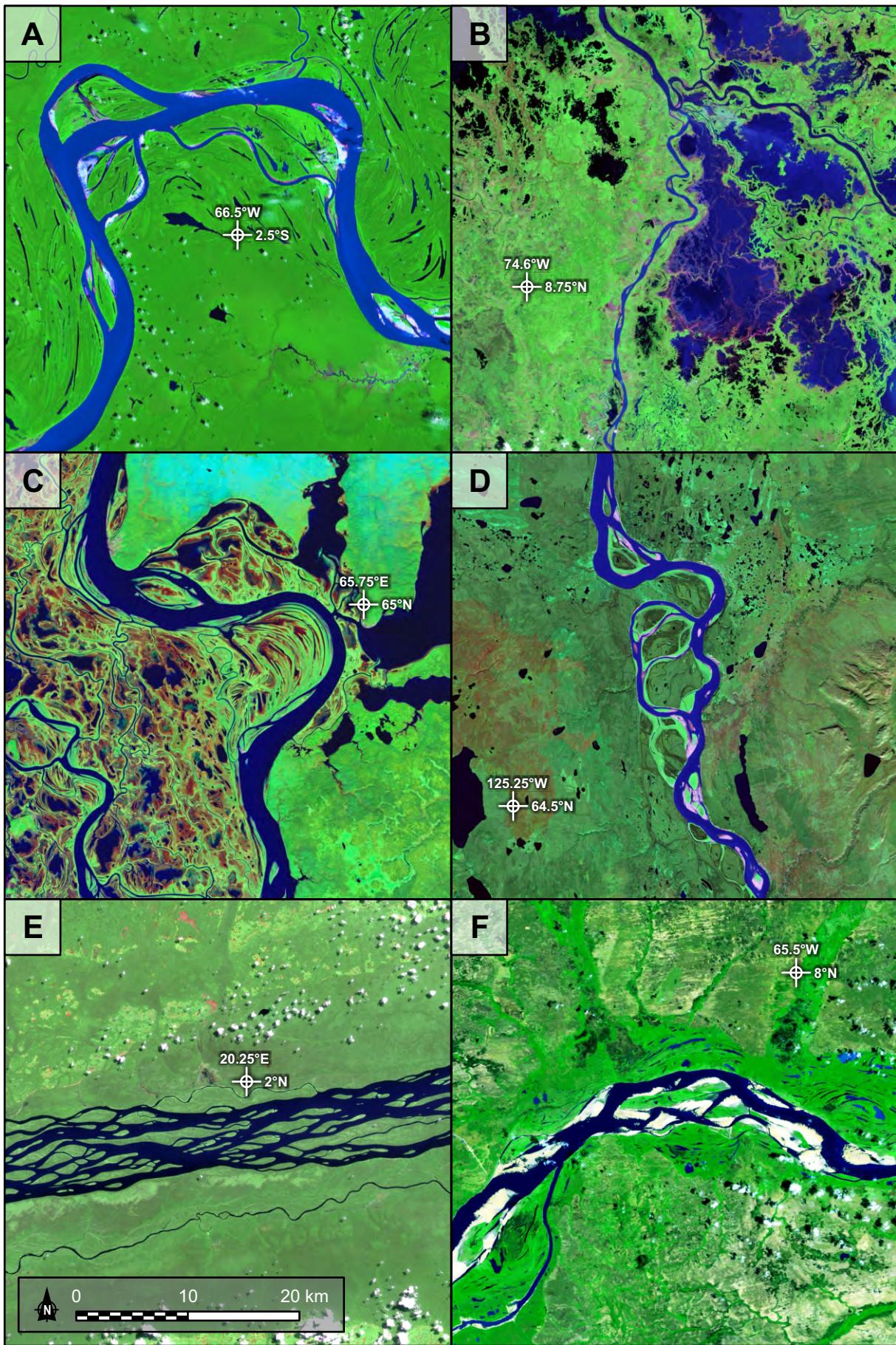
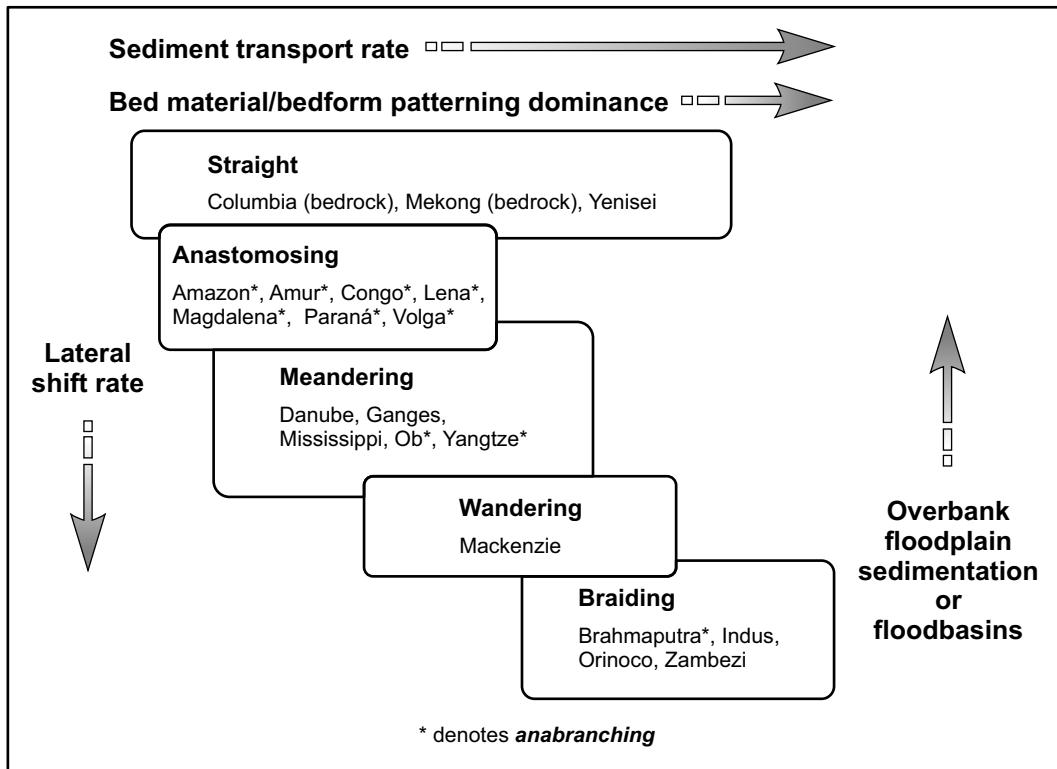


Figure 3



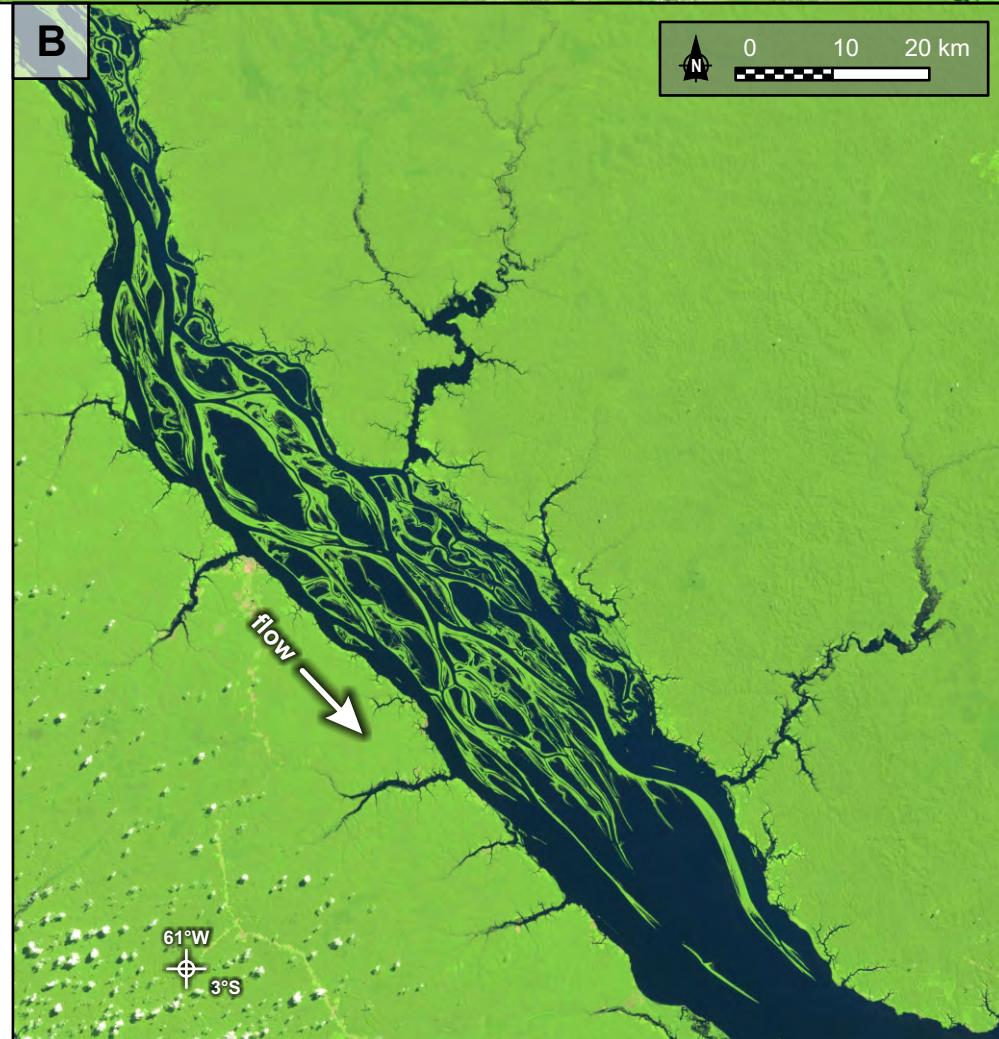
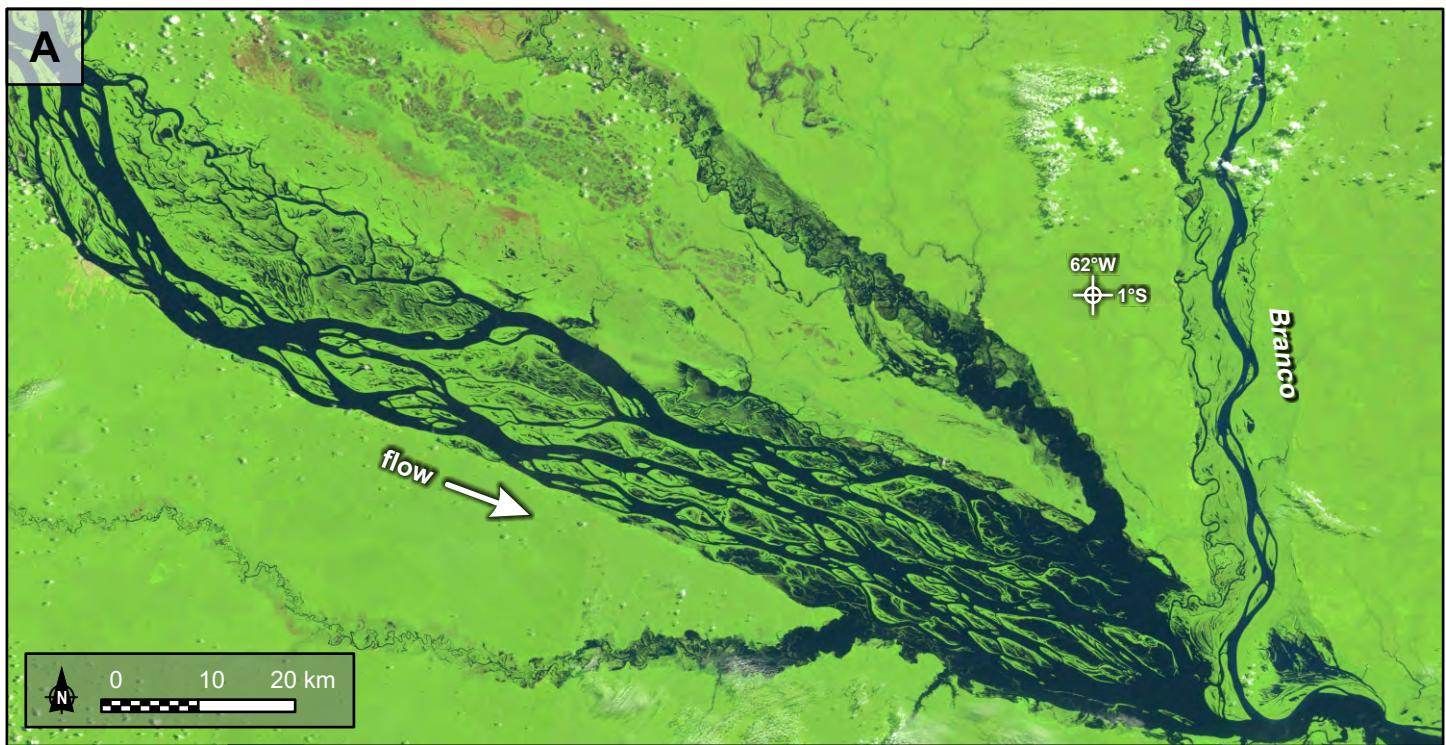
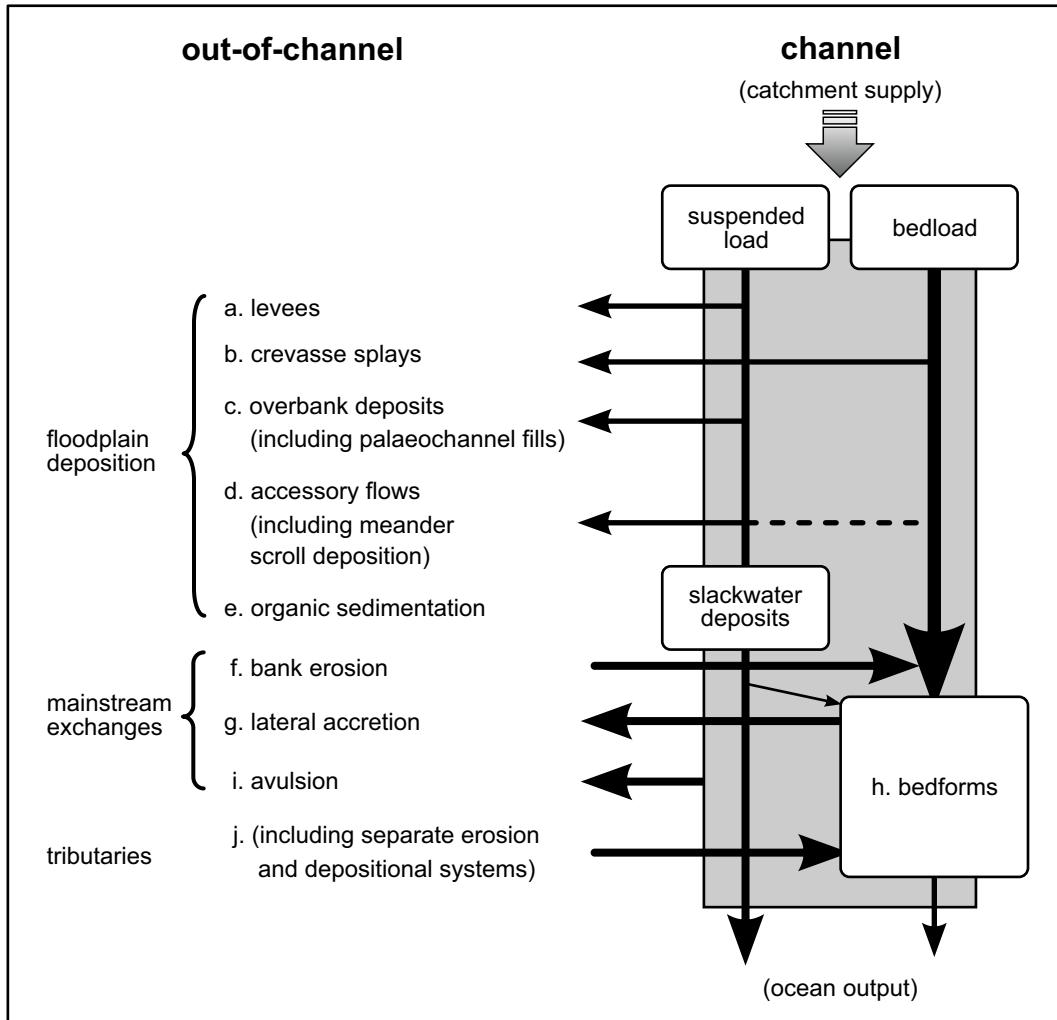


Figure 5





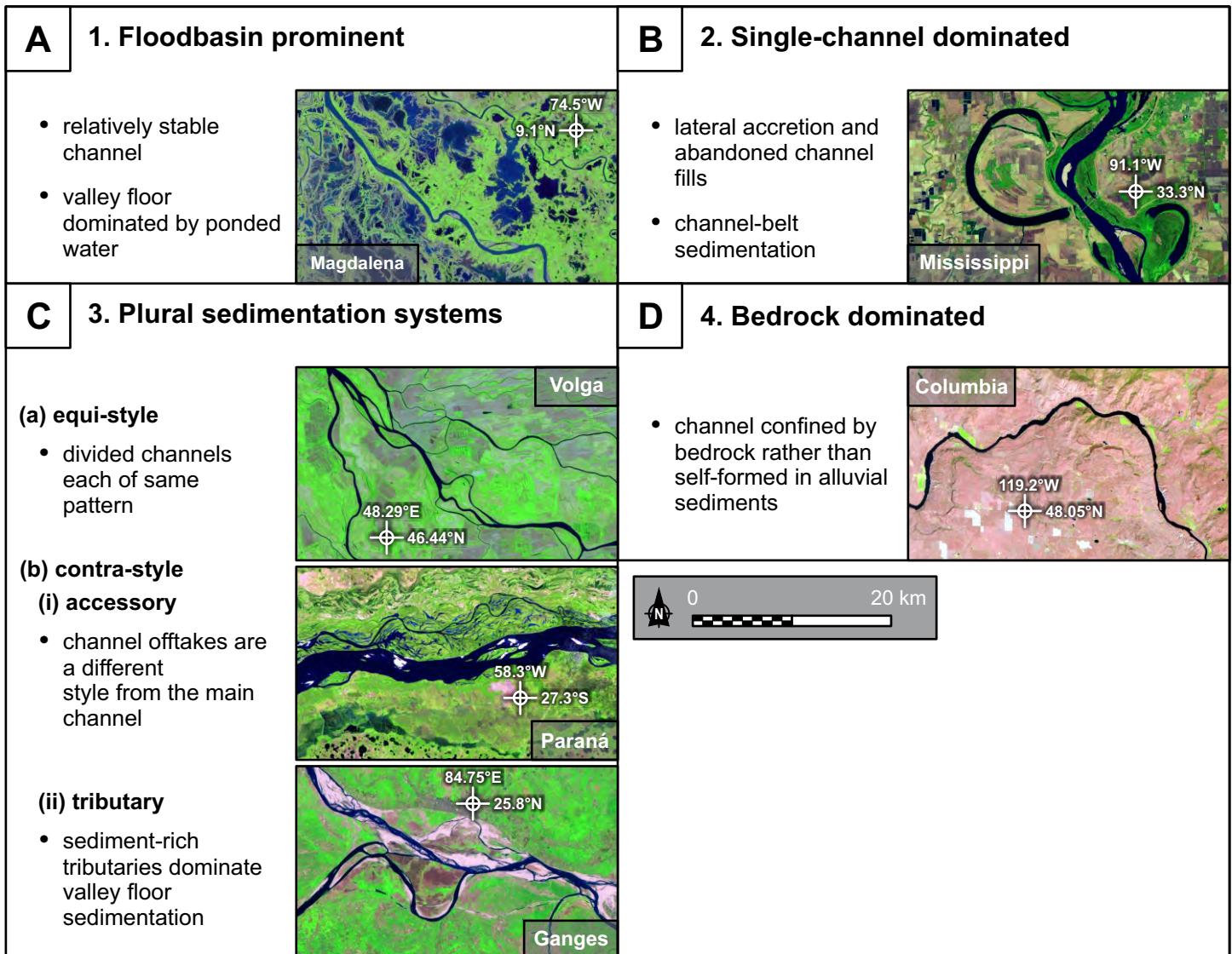




Figure 9

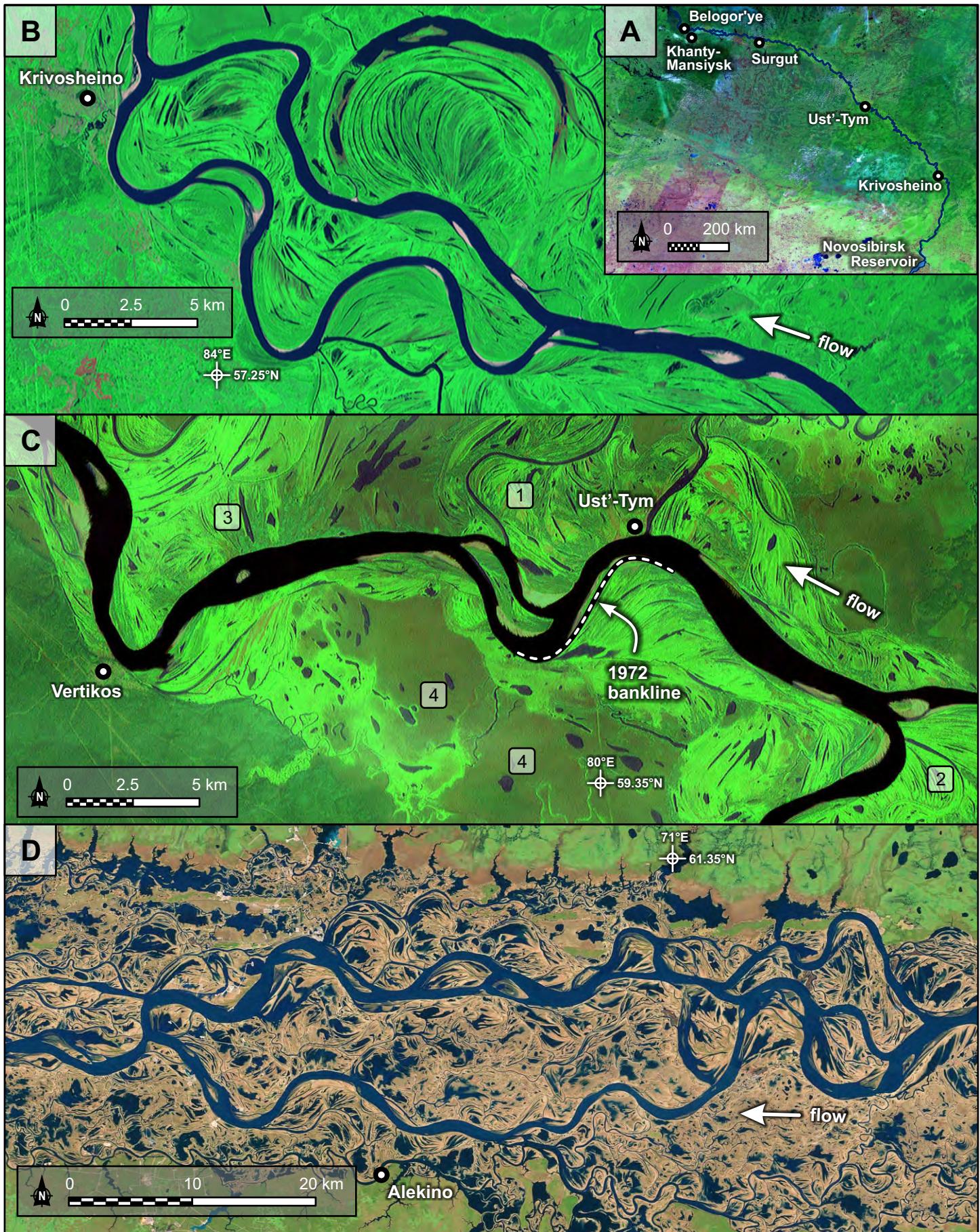


Figure 10



Figure 11

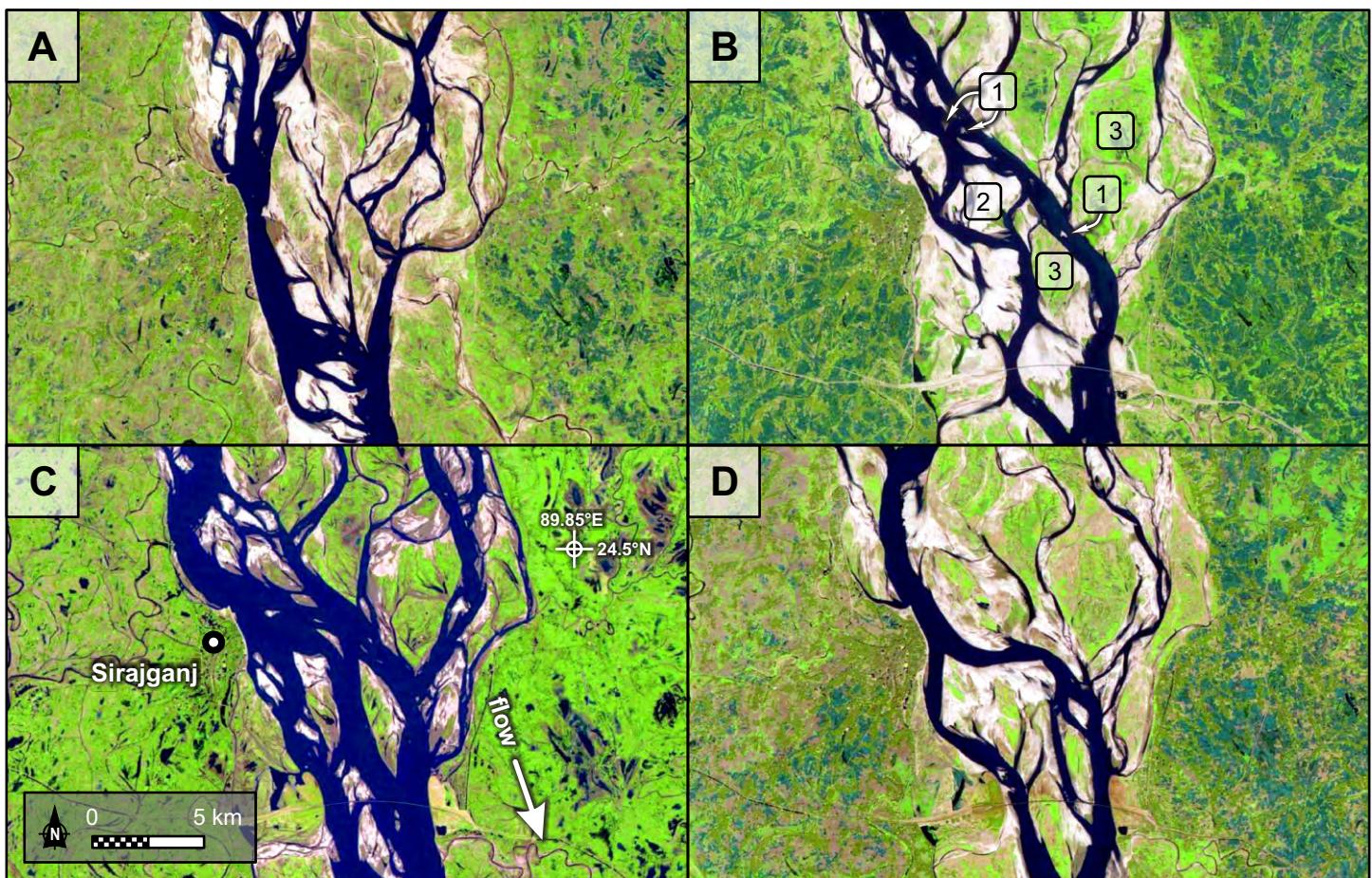


Figure 12

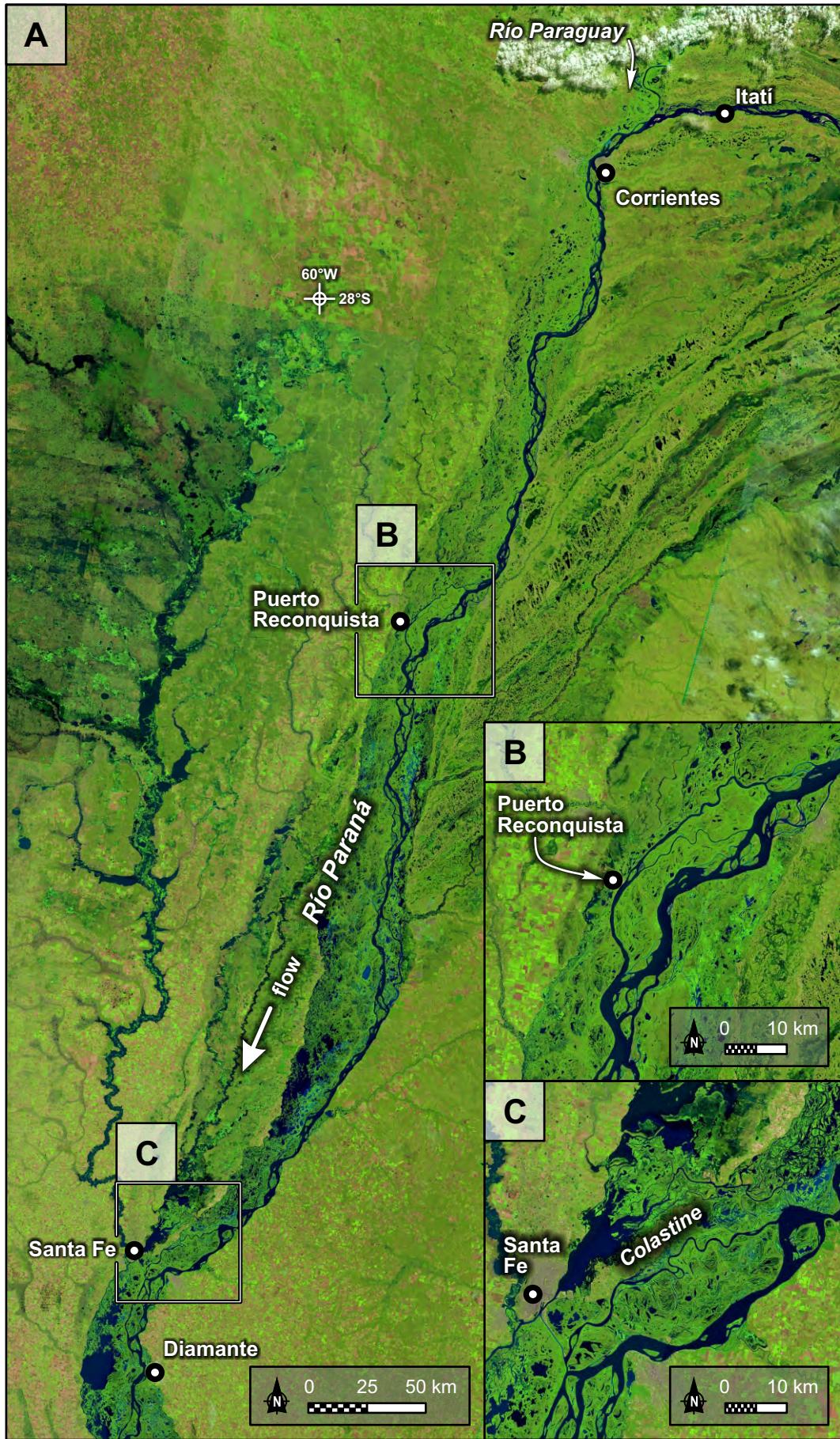


Figure 13

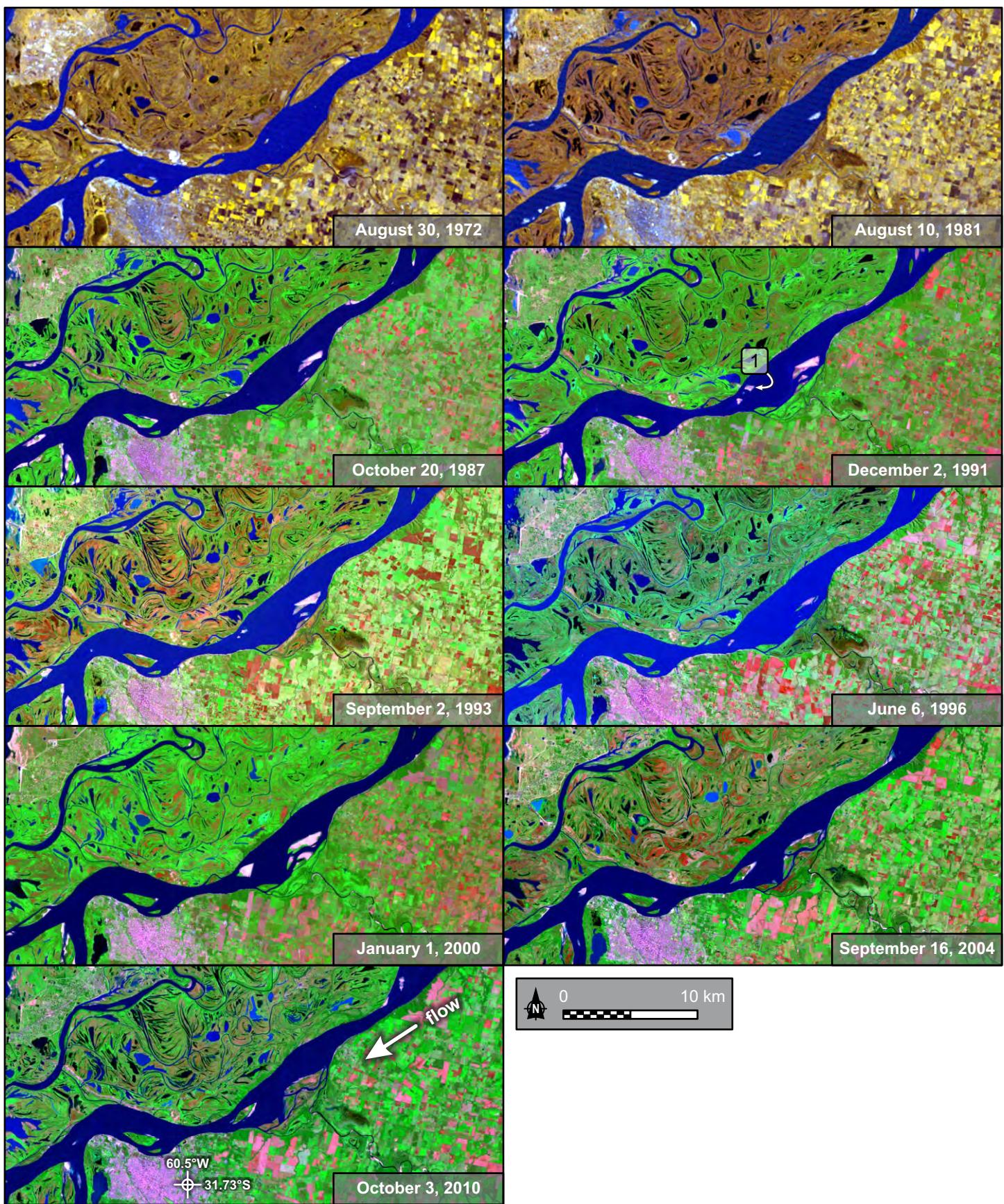


Figure 14



Figure 15

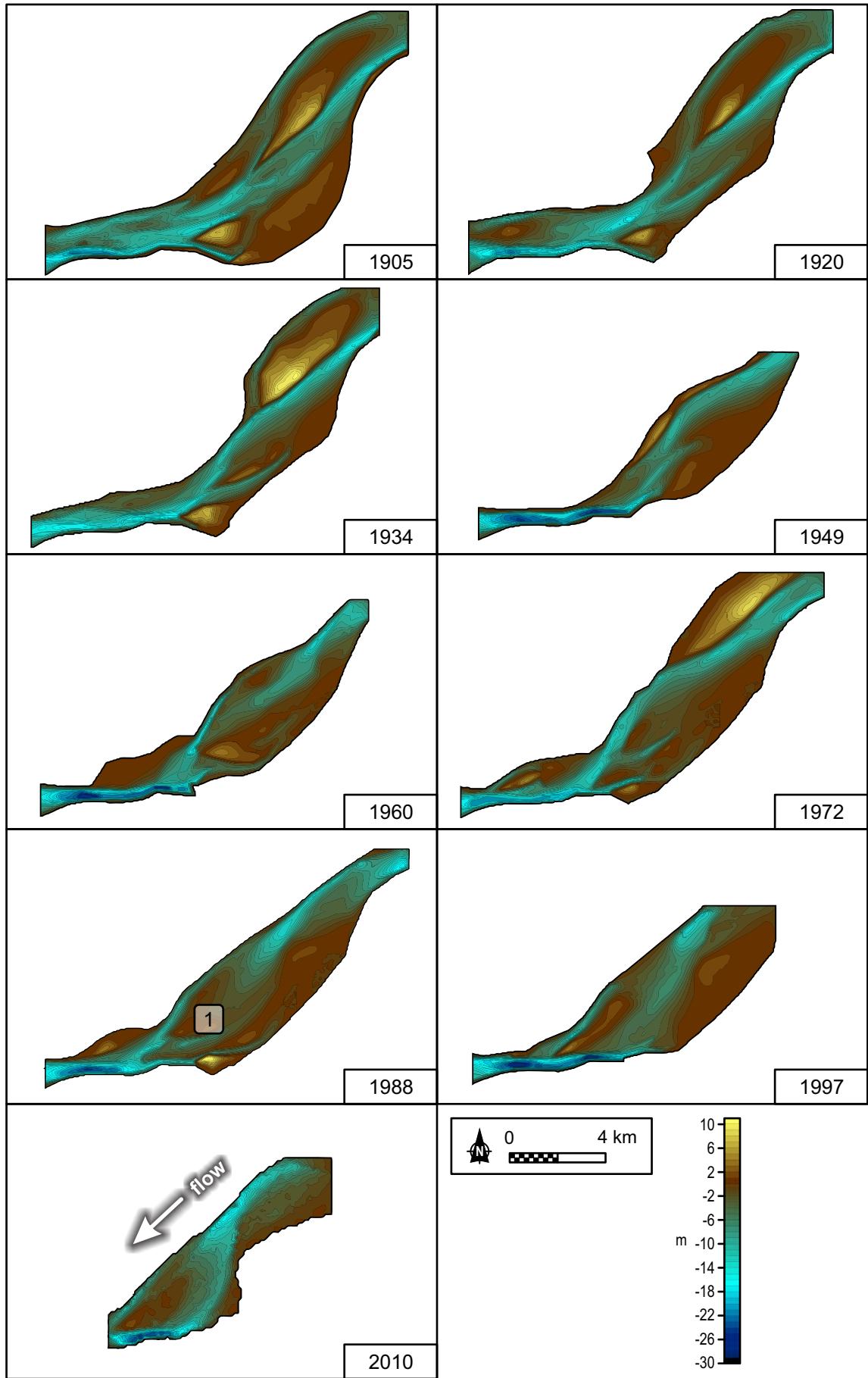


Figure 16

	Mean annual runoff <sup>(1)</sup> (10 <sup>9</sup> m <sup>3</sup> )	Reach location	Gradient (m km <sup>-1</sup> ) <sup>(6)</sup>	Valley floor width (km) <sup>(7)</sup>	Mainstream character <sup>(2)</sup>	Channel width (km)	Sedimentation elements <sup>(3)</sup>										Surface waters <sup>(4)</sup>	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 <sup>(5)</sup>	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 <sup>(5)</sup>	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	

<sup>(1)</sup>From Milliman and Syvitski (1992) with unit adjustment; separate figures for Ganges and Brahmaputra from Shiklomanov and Rodda (2003)

<sup>(2)</sup>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)

<sup>(3)</sup>Sedimentation elements (a-j) are given in Figure 6 (● dominant, ○ present, □ not significant)

<sup>(4)</sup>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

<sup>(5)</sup>Runoff adjusted for regulation as described in Milliman and Syvitski (1992)

<sup>(6)</sup>Gradients measured over 50 km on adjacent flooplain using GoogleEarth (- indicates so flat it is unquantifiable)

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