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How do big rivers come to be different?

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ABSTRACT

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

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

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

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

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

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1. Introduction

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

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

In practice, 'big' rivers are identified not by size of channel but in terms of determining factors for which global data are available: catchment area, length, discharge or sediment yield (e.g., Holeman, 1968; Potter, 1978; Milliman and Meade, 1983; Schumm and Winkley, 1994; Hovius, 1998; Gupta, 2007). Different data collations show reasonable agreement on lengths and areas, but representative discharge and sediment loads are more difficult because of gauging limitations and data availability (especially for sediment loadings) and the transforming effects of human activity and river regulation (Meade and Parker, 1985; Syvitski et al., 2005; Walling, 2006; Syvitski and Kettner, 2011). Water discharge or sediment data from the centuries of 'genetically-modified' fluvial regimes may not represent well the conditions for sedimentation or landform generation that have operated over a longer term (Gupta, 2007; Wilkinson and McElroy, 2007; Wasson, 2012). For example, Syvitski and Kettner (2011) calculate that the twentieth century global sediment load delivered to the coastal zone has reduced by 15%, although sediment loads vary widely reflecting different stages of industrial development and land-use change in individual river basins. Likewise, Wang et al. (2011) calculate that there has been a 70% reduction in sediment flux to the ocean since 1000 yr BP from major rivers in East and Southeast Asia (including the Yangtze and Mekong), with an accelerating decrease since the 1950s.

Unfortunately, global data on sediment loads are usually for suspended sediment only, sometimes with a notional allowance for bedload, whereas channel patterning necessarily involves bed material transfer (Kleinhans, 2010). In reality, bedload yield is notoriously difficult to measure (Kuhlne, 2007) and in practice sediment load partitioning can be very varied and strongly dependent on local catchment geology (Turowski et al., 2010). A further challenge is that a mean annual discharge (the usual measure adopted) may be less significant for channel patterning than other measures such as formative (channel-full or bar-top level) discharge, flood magnitude and frequency, or flow duration and annual variability. Despite this, Latrubesse (2008) suggests that 'large' rivers are ones with a mean annual discharge of greater than 1000 $m^3\ s^{-1}$, and 'mega' rivers are greater than ~17,000 $m^3\ s^{-1}$.

Data sets for catchment size, discharge and suspended sediment yield give different river orderings, and there are no simple relationships between catchment size and discharges of water and sediment (Fig. 1A–B). Leaving aside the Amazon, both annual runoff and mean sediment yield of some of the world's largest rivers range over two orders of magnitude (Fig. 1A). Latrubesse's (2008) division of 'large' and 'mega' rivers (equivalent to 32 and $536 \times 10^9\ m^3\ yr^{-1}$, or $km^3\ yr^{-1}$, respectively) does not produce a clear separation (Fig. 1A) and those classified as 'mega' rivers in Fig. 1A are not all grouped together by catchment area (Fig. 1B). It has been shown that small mountain catchments provide a large proportion of continental sediment yields (Milliman and Syvitski, 1992), and large catchments demonstrate markedly heterogenic behaviour. In some circumstance it may be piedmont Quaternary materials (Church et al., 1989) or lowland agricultural lands (Wilkinson and McElroy, 2007) that dominate sediment supply. On a continental scale, the sourcing, routing and loss

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