Morphodynamic diversity of the world's largest rivers

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ABSTRACT

Large alluvial rivers transport globally significant quantities of water, sediment, and nutrients to the oceans, temporarily storing and cycling this material within the bars, islands, and floodplains that define their morphology. The world's largest rivers display a remarkable variety of morphologies. However, existing theory and numerical modeling fail to explain this diversity, which remains poorly understood. This study applies a new numerical model of water flow and sediment transport to show how the morphology of large sand-bed rivers is influenced by bed sediment mobility, bank erodibility, and rate of floodplain development. Simulations demonstrate that a wide range of river styles, including meandering, anabranching, and braiding, can occur over a relatively narrow range of environmental conditions. Results highlight the suspension of bed material, which limits the gravitational deflection of sediment in the direction of the local bed slope, as a key control on sediment transport direction and hence river morphology. Moreover, high mobility of bed and bank sediments are hypothesized to favor contrasting river styles, although both may be promoted by increasing stream power. These results explain the inability of existing stream power theory to predict the morphology of the world's largest rivers, and highlight the potential for investigating river-floodplain co-evolution using physics-based simulation models.

INTRODUCTION

The world's largest rivers share many common properties (high discharges, low gradients, and sand-sized bed sediment) yet are characterized by diverse morphologies, including braided, meandering, and anabranching channel patterns (see Fig. 1). Many factors that influence this diversity have been identified, including water and sediment supply regimes, river gradient, channel-floodplain coupling, vegetation, tectonics, geology, drainage basin configuration, and Quaternary history (Gupta, 2007; Latrubesse, 2008; Ashworth and Lewin, 2012). However, the relative importance of, and interactions between, these controls remain uncertain, and recent analysis suggests that the morphological diversity of large rivers cannot be explained using existing theory (Latrubesse, 2008).

Incomplete understanding of large rivers stems from a lack of empirical data sets, and from the short time period over which satellite imagery is available for characterization of river evolution. Furthermore, numerical modeling of rivers has, to date, focused on the simulation of either meandering or braided channels using separate modeling approaches (e.g., Duan and Julien, 2005; Jang and Shimizu, 2005). Representation of both braided and meandering river styles using a single physics-based model has been highlighted as a significant challenge (Kleinhans, 2010), and thus a fundamental barrier to the elucidation of controls on morphodynamic diversity.

NUMERICAL MODELING

Simulations of sand-bed river evolution were conducted here using a new numerical model of river morphodynamics, HSTAR (Hydrodynamics and Sediment Transport in Alluvial Rivers). Details on the modeling approach are provided in the GSA Data Repository[1]. In summary, the model solves the depth-averaged shallow-water equations on a grid of cells representing the channel and floodplain surface. Two sediment fractions are represented (silt and sand). The effects of secondary circulation and the gravitational deflection of sediment in the direction of the local bed slope are included in the model. Active channel cells are converted to vegetated floodplain cells when the depth of inundation experienced over a specified time period (T_{veg}) does not exceed a threshold depth (H_{cr}). Bank erosion converts floodplain cells to active channel.

Model simulations (listed in Table DR2 in the Data Repository) examined a range of sand particle diameters (D), river gradients (S), Chezy bed roughnesses (C), bank erodibilities (E), and rates of vegetation establishment (controlled by T_{veg} and H_{cr}). All simulations (45 in total) used the same initial conditions (a straight channel, 2.4 km wide by 50 km long, having a planar bed with small [±0.1 m] white noise elevation perturbations). Inflow conditions consisted of hydrographs with a minimum discharge of 10,000 m^3s^{-1} and peak discharges that varied from ~15,000 m^3s^{-1} to 30,000 m^3s^{-1} between floods. All simulations used the same flood sequence to investigate controls on channel form independently of variations in hydrologic regime.

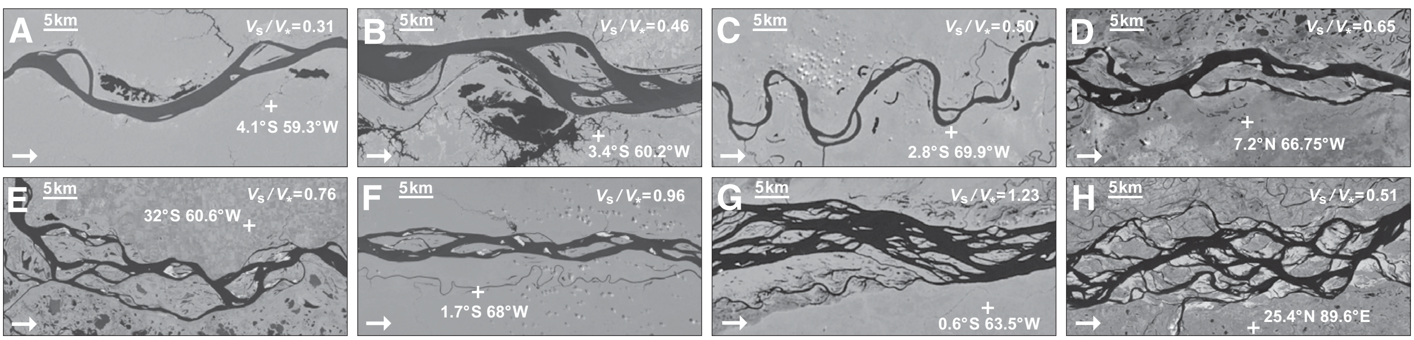

Figure 1. Examples of large river morphology. A: Madeira, Brazil. B: Solimões-Amazon, Brazil. C: Içа, Columbia and Peru. D: Orinoco, Venezuela. E: Middle Paraná, Argentina. F: Japurá, Brazil. G: Negro, Brazil. H: Jamuna, Bangladesh. Flow direction is indicated by arrows. Downstream image extent is 50 km. Average values of the ratio of particle fall velocity to shear velocity (V_S/V_*) for each river are derived using data shown in Table DR1 (see footnote 1). Landsat imagery courtesy of the U.S. Geological Survey.

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[1]GSA Data Repository item 2013122, description of the modeling methodology and datasets, Figure DR1 (flow conditions used in all model simulations), Figure DR2 (relationship between sediment mobility and channel morphology), and Movies DR1 and DR2 (examples of simulated river evolution), is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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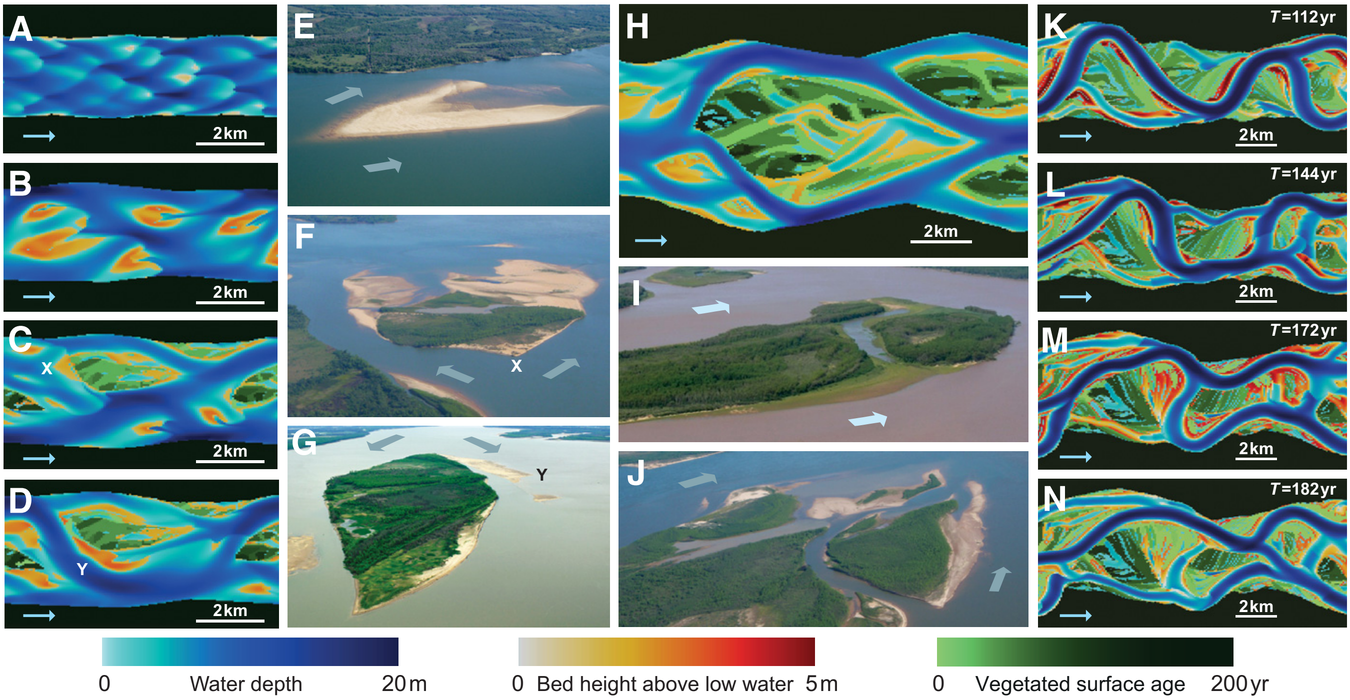

Figure 2. Simulated and observed morphodynamics of large sand-bed rivers. Images A–D, H, and K–N show sections of simulated channels. Water depth at low flow (blue), surface elevation of riverbed above low water level (yellow-red), and vegetated surface age (green) are depicted using different color scales. Surface ages are truncated at 200 yr. Photographs (E, F, G, I, and J) show characteristic bars and islands along the Rio Paraná, Argentina. Arrows indicate predominant flow directions. In C and F, "X" indicates an area of bar head accretion. In D and G, "Y" indicates an area of lateral bar accretion. Images K–N represent four time slices over a 70 yr period from a simulation characterized by bend migration and periodic channel abandonment and reactivation.

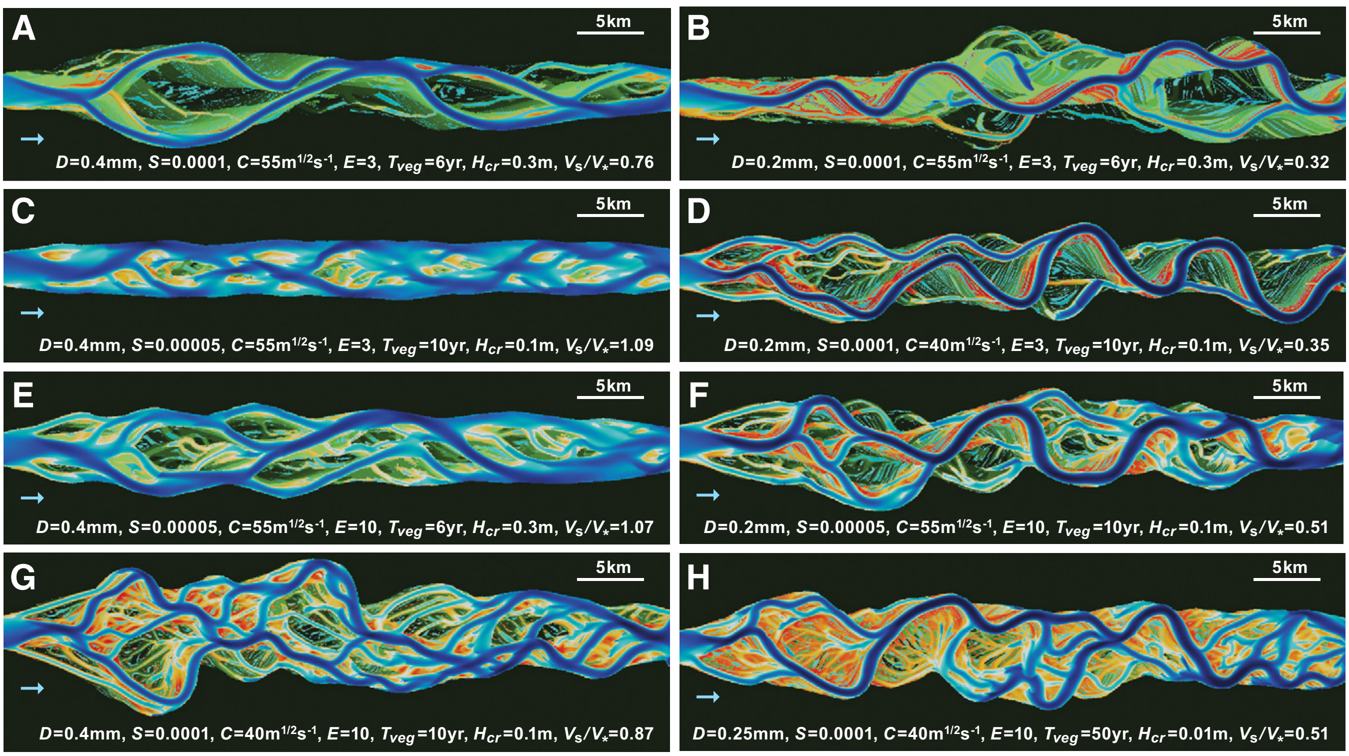

Figure 3. Simulated channel morphology for a sample of model runs with contrasting parameters and boundary conditions. Bed sediment grain diameter (*D*), downstream gradient (*S*), Chezy roughness coefficient (*C*), bank erodibility (*E*), time (T_{veg}) and critical flow depth (H_{cr}) for vegetation establishment, and the ratio of bed sediment fall velocity to mean shear velocity (V_S/V_*) are shown in each case. Flow is left to right. Downstream image extent is 50 km. Color scales are the same as in Figure 2. All images show channel morphology at low flow (~10,000 m^3s^{-1}).

RESULTS

River morphology evolves during simulations by a range of mechanisms that are also observed in natural channels. Morphodynamic behavior can be separated into bar/island- and channel-dominated modes, although most simulations are characterized by elements of both. Initial channel evolution involves unit bar development and downstream migration (Fig. 2A). Flow divergence around unit bar crests promotes initiation of kilometer-scale sandbars with limbs that extend downstream (Figs. 2B and 2E). Bar growth reduces inundation frequency, allowing vegetation establishment (island formation). Islands continue to grow by accretion of unit bars that migrate onto and around bar heads (Figs. 2C and 2F), and by lateral accretion (Figs. 2D and 2G). Large islands form by coalescence of smaller bars and islands, and are characterized by numerous abandoned channels, particularly at island tails (Figs. 2H–2J). Channel-dominated morphodynamic modes involve both single- and multi-thread systems (Figs. 2K–2N). Floodplains are characterized by scroll-bar morphology resulting from bend migration and incremental bar growth during individual floods (Figs. 2L and 2M). Meander bends translate, expand, and are cut off. Floodplain and bar chute channels are abandoned and reactivated periodically (Figs. 2K and 2L). Water and sediment partitioning at channel junctions evolve with junction bifurcation angle, and ultimately may promote bifurcate abandonment (Figs. 2M and 2N). Examples of these styles of morphodynamic behavior can be seen in Movies DR1 and DR2 in the Data Repository. Model results are deemed to be realistic based on the consistency between simulated and observed mechanisms of river evolution (described above), and because modeled channel width:depth ratios, degree of branching, bar and island geometries, scour pool depths, and rates of bank erosion and bar migration lie within the range of observations for large sand-bed rivers (see Tables DR1–DR3).

Simulations are characterized by a wide range of river morphologies (see Fig. 3), including meandering (Fig. 3B), braided (Fig. 3C), and anabranching (Fig. 3E) patterns (where braiding and anabranching are distinguished by differences in bar size, vegetation cover, and stability). Model results are analyzed after channels have evolved to statistical equilibrium, indicated by a lack of temporal trend in river width, depth, and number of channel branches. Simulation periods range from 270 to 350 yr. Modeled river morphology is controlled by three interrelated factors: rate of floodplain development, bank erodibility, and the relative mobility of bed sediment. Rapid floodplain development (associated with early vegetation colonization) limits bar migration, enhances vertical accretion of sand and silt, and promotes larger stable islands. Consequently, dynamic braided channels are associated with slow rates of floodplain development (e.g., Figs. 3C, 3G, and 3H). However, rate of floodplain development does not have a statistically significant influence on channel width:depth ratio or degree of branching. In general, lower bank erodibility promotes lower channel width and fewer channel branches (compare Figs. 3A–3D with Figs. 3E–3H, and see Fig. 4B). These differences are statistically significant (see the Data Repository). However, bank erodibility does not have a statistically significant influence on channel width:depth ratio.

Bed sediment mobility exerts a critical control on channel form, due to its influence on the direction of sediment transport. Sand transport deviates from the mean flow direction due to the effects of secondary circulation (Struiksma et al., 1985). Moreover, sand transported as bedload is deflected by gravity in the direction of the local bed slope, whereas sand suspended above the bed is not (Lesser et al., 2004). The sand fraction transported as bedload is calculated here using established theory (van Rijn, 1984, his equation 45), and depends on the ratio of the particle fall velocity (V_S) to the shear velocity (V_*). For the flow conditions and grain sizes examined here, the ratio V_S/V_* varies between 0.2 and 1.2. This range is typical of large sand-bed rivers with mixed load transport regimes, and causes the sand fraction transported as bedload (and hence influenced by the local bed slope) to vary between <5% and ~60% (see Church, 2006, his figure 3). This order-of-magnitude range drives significant differences

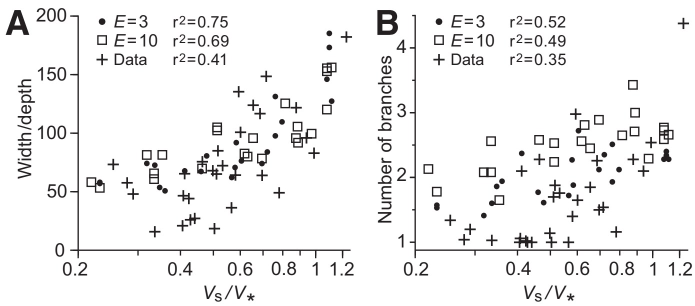

Figure 4. Relationships between bed sediment mobility and channel morphology in natural and simulated rivers. Average width to depth ratio (A) and number of channel branches (B) are plotted against the ratio of sediment fall velocity (V_S) to mean shear velocity (V_*). Model results represent average values over the final 20 yr of each simulation, and are divided into two subsets with strong banks (*E* = 3) and weak banks (*E* = 10). Data for natural rivers (crosses) are presented in Table DR1 (see footnote 1). All correlations are significant at the 99% level or better.

in river morphodynamics between model runs. For example, coarser sand sizes and lower shear velocities (due to lower river gradients) are associated with reduced sediment mobility, and with relative enhancement of sand transport as bedload in the direction of the local bed slope. This promotes sediment transport away from bar tops, reduced vertical bar aggradation, slower conversion of bars to vegetated islands and floodplain, and wider channels. In contrast, a reduction in sand size (e.g., between Figs. 3A and 3B, and between Figs. 3G and 3D) or an increase in channel gradient (e.g., between Figs. 3C and 3A) enhances sand transport in suspension and reduces transport down lateral bar slopes. This promotes vertical bar growth and conversion to floodplain, and thus stronger topographic steering of flow, which in turn drives the formation of narrower, sinuous channels, and larger bifurcation angles, which are inherently less stable. This leads to a reduction in the number of channel branches and/or a transition from braiding or anabranching to meandering.

Model results exhibit statistically significant relationships between V_S/V_*, channel width:depth ratio (Fig. 4A), and number of channel branches (Fig. 4B). Equivalent relationships for natural rivers can be identified using existing data (Latrubesse and Franzinelli, 2005; Latrubesse, 2008), combined with analysis of satellite imagery to determine channel width and branch numbers (see Table DR1). Satellite images shown in Figure 1 for a selection of the world's largest rivers also suggest a relationship between V_S/V_* and channel pattern. Overall, this analysis supports the hypothesis that the fraction of sand transported in suspension is an important control on channel morphology in large sand-bed rivers.

DISCUSSION

A relationship between mode of sediment transport (bedload versus suspended load) and river morphology has been proposed previously (Schumm, 1985; Church, 2006). However, such conceptual channel pattern classification schemes lack mechanistic process-based explanations. Moreover, they have emphasized the role of silt/clay transport in suspension leading to cohesive bar tops and floodplains that promote meandering by reducing bank erosion (Schumm, 1977, 1985). Simulations conducted here imply that the suspension of uncohesive, sand-sized bed material exerts a key control on channel morphology because it reduces the gravitational deflection of sediment in the direction of the local bed slope and promotes vertical bar accretion and subsequent conversion to floodplain. Consequently, this mechanism exerts a significant control on channel form that is distinct from the role of bank strength and the transport of cohesive sediment.

The Brahmaputra-Jamuna River is a notable exception to the trends shown in Figures 1 and 4, having a braided planform, a channel width:depth ratio of ~200, and a large number of branches (approximately four to six on average, and more than ten at some locations) despite being characterized by values of V_S/V_* in the range 0.3–0.51 in different reaches (Latrubesse, 2008; Kleinhans and van den Berg, 2011). The dynamic behavior and intense braiding of the Jamuna have been attributed to the river's mobile bars and highly erodible banks (Ashworth and Lewin, 2012). Simulated rivers with similar V_S/V_* values are dominantly meandering or weakly anabranching (e.g., Figs. 3B, 3D, and 3F). However, these simulations are associated with stable vegetated islands and floodplains. A further simulation conducted for the case of very slow vegetation establishment yielded a more dynamic, braided channel (Fig. 3H) despite a value of V_S/V_* more typical of the Jamuna in the reach shown in Figure 1H ($V_S/V_* = 0.51$). These results are consistent with field and laboratory observations that emphasize the influence of vegetation on channel pattern (Tal and Paola, 2007). Moreover, they illustrate the complex interplay between bank erodibility, vegetation establishment, and bed sediment mobility, which controls channel morphodynamics by mediating the balance between the accretion and erosion of bar and floodplain surfaces (cf. Allmendinger et al., 2005). In doing so, model results show why established channel pattern classifications based on stream power thresholds have not been applied successfully to the world's largest rivers.

Numerous studies have sought to discriminate between single- and multi-thread channels by defining threshold values of slope, stream power, or sediment mobility above which braiding occurs (Leopold and Wolman, 1957; Eaton et al., 2010; Kleinhans and van den Berg, 2011). However, such approaches have been unsuccessful when applied to the world's largest sand-bed rivers (Latrubesse, 2008), leading to the suggestion that large rivers with multiple channels divided by vegetated floodplain islands cannot be related to stream power, either empirically or theoretically (Kleinhans and van den Berg, 2011). Simulation results suggest that this apparent lack of a clear relationship between stream power and channel morphology results from the competing influences of bed and bank sediment mobility. High bank sediment mobility, associated with high stream power and/or erodible bank material, favors channel widening and the development of multi-thread rivers. It is this tendency that forms the basis of much existing analysis. However, such theory neglects the role of floodplain construction as a control on channel width and pattern. Moreover, simulations conducted here show that high bed sediment mobility favors enhanced suspension of sand and reduced gravitational deflection of sediment in the direction of the local bed slope. This restricts channel widening and favors vertical accretion of bars, more rapid floodplain development, and formation of predominantly meandering channel forms. Consequently, high mobility of bed and bank sediment, both of which may be linked to high stream power, favor contrasting channel morphologies, thus explaining the apparent failure of stream power–based classification schemes.

SUMMARY

This study has applied a new numerical simulation model to show how the morphology of large sand-bed rivers is influenced by bed sediment mobility, bank erodibility, and rate of floodplain development. Model simulations highlight the suspension of bed material as a key control on river morphology, which promotes an inverse relationship between bed sediment mobility and the degree of channel branching. This relationship is consistent with analysis of data from natural rivers, and with qualitative channel pattern classifications that emphasize the role of sediment suspension (Schumm, 1985). Moreover, these results help to explain the failure of popular stream power theories to predict the morphology of the world's largest rivers (Latrubesse, 2008). This work illustrates the fundamental link between grain-scale sediment transport mechanics and floodplain-scale river morphology, and provides a first demonstration that a single physically based simulation model can successfully reproduce much of the morphodynamic diversity seen in large sand-bed rivers.

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