Conditions for branching in depositional rivers

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ABSTRACT

It is often taken for granted that rivers organize transport into a single active channel. In some net-depositional environments, however, flow of water and sediment is distributed in several stable channels. Such branching rivers may be confined in valleys (anabranching or anastomosed) or unconfined on deltas (distributaries), and their existence confronts us with the very basic question of what governs the spatial organization of channel patterns in sedimentary landscapes. Current models for equilibrium channel morphology cannot predict the occurrence of branching rivers because they do not consider dynamical processes such as avulsion, i.e., the rapid abandonment of a channel in favor of a new path at lower elevation. The requisite conditions for avulsion have been the subject of ongoing debate. Here we resolve the conditions leading to channel avulsion, and show that branching rivers occur when avulsion is the dominant mechanism of lateral channel motion. A compilation of field and laboratory data demonstrates that avulsion frequency scales with the time required for sedimentation on channel beds to produce a deposit equal to one channel depth. From the relative rates of bank erosion and channel sedimentation, we derive a dimensionless mobility number that accurately predicts the conditions under which anabranching and distributary channels occur. Results may be directly applied to modeling landscape evolution over human and geologic time scales, and for inverting formative environmental conditions from channel deposits on Earth and other planetary surfaces.

Keywords: morphodynamics, bifurcation, wandering rivers, braided, avulse, fluvial.

INTRODUCTION

Anabranching rivers (or anastomosing) may be defined as a system of multiple channels (branches) that are separated by relatively stable, often vegetated islands (Nanson and Knighton, 1996; Makaske, 2001; Jansen and Nanson, 2004). Individual branches of an anabranching river may be straight, sinuous, or braided (Nanson and Knighton, 1996). Currently there is no theory to predict under what conditions a river will form multiple branches. Nevertheless, it has been argued that anabranching rivers can be an equilibrium form under certain combinations of flow strength, sediment transport, and vegetation (Nanson and Knighton, 1996; Jansen and Nanson, 2004). Stable distributary channels on deltas and alluvial fans are another example of branching river systems. While it is known that their occurrence is associated with environments of net deposition, the conditions that cause channels to become distributary are not well quantified. Current models for equilibrium channel morphology (Parker et al., 1998; Dade, 2000) cannot predict the occurrence of branching rivers because they do not consider dynamical processes such as avulsion, i.e., the rapid abandonment of a channel in favor of a new path at lower elevation.

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PROCESS SCALING ANALYSIS

We hypothesize that branching in depositional rivers is a manifestation of avulsion, and that the requisite condition for branching is that the lateral motion of channels via bank erosion is small relative to their vertical displacement above the surrounding flood plain via focused sediment deposition on the channel beds. This idea is formalized by a simple scaling analysis of the time scales associated with dominant processes. We define the lateral migration time scale, $T_C = B/v_C$, as the time, T_C, it would take a channel to migrate the distance equal to its total width, B, given a representative measure of bank erosion rate, v_C (e.g., Tal et al., 2004). A representative time scale for channel aggradation, T_A, is similarly defined as the time required for the river to aggrade one average channel depth, $\bar{h}$, above the distal flood plain. This time scale may be approximated as $T_A = \bar{h}/v_A$, where v_A is a representative aggradation rate. Because deposition rates on the distal flood plain are often very small relative to those measured in the vicinity of a channel (Heller and Paola, 1996, Törnqvist and Bridge, 2002), v_A is taken to equal a near-channel or in-channel rate of sediment accumulation. In an examination of ancient river deposits, Mohrig et al. (2000) found that avulsion was associated with aggradation of the river channel to a height above the surrounding flood plain (superelevation) equal to approximately one channel depth (Fig. 1). In this sense T_A is an avulsion time scale, or more properly, it is the average time between avulsions for a single channel. The avulsion frequency of the river system, f_A, may be directly estimated as:

$$f_A = \frac{v_A N}{\bar{h}}, \tag{1}$$

where N is the number of active channels. We define the mobility number, M, of a given river system as the ratio of avulsion and lateral-migration time scales,

$$M = \frac{T_A}{T_C} = \frac{\bar{h}}{B}\frac{v_C}{v_A}. \tag{2}$$

For rivers having $M >> 1$ we expect a system with a single channel that sweeps across its flood plain relatively rapidly, reworking the flood plain as it moves laterally. Avulsions are expected to be relatively rare (Fig. 1), while rapid combing would tend to cause coalescence rather than creation of channels. For cases of $M << 1$ individual channels aggrade rapidly compared to any lateral shifting in response to bank erosion (Fig. 1). Avulsions should be relatively frequent, causing several channels to be active at once (Makaske, 2001). Our hypothesis predicts that these rivers should be branched. If M is 0 (10°) (order one), transi-

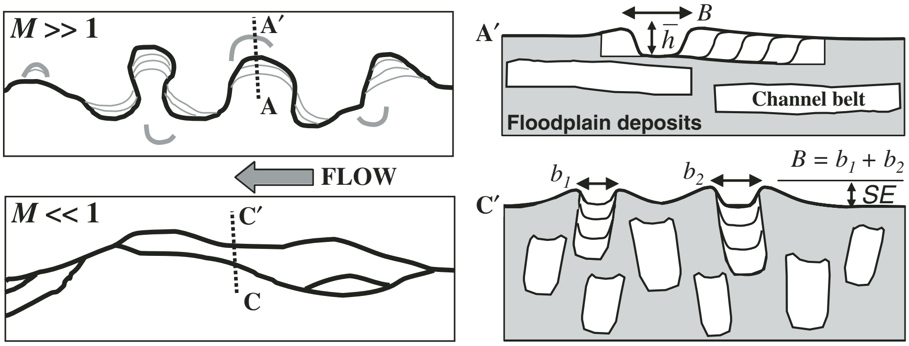

Figure 1. End-member channel types, deposits, and definitions. Top: Hypothetical single-channel meandering river in planform (left), and representative cross section through meander belt (right). Lateral channel movement is accomplished principally by bank erosion. Bottom: Anabranching river with multiple stable branches. Cross section at right shows that these channels are superelevated (SE), with relative superelevation $SE/\bar{h}$ = 1. River represents avulsion-driven morphology. Note that $B=\sum_i^N b_i$ is total wetted width of all active channels, where N is number of active channels and b_i is width of each channel. M is mobility number.

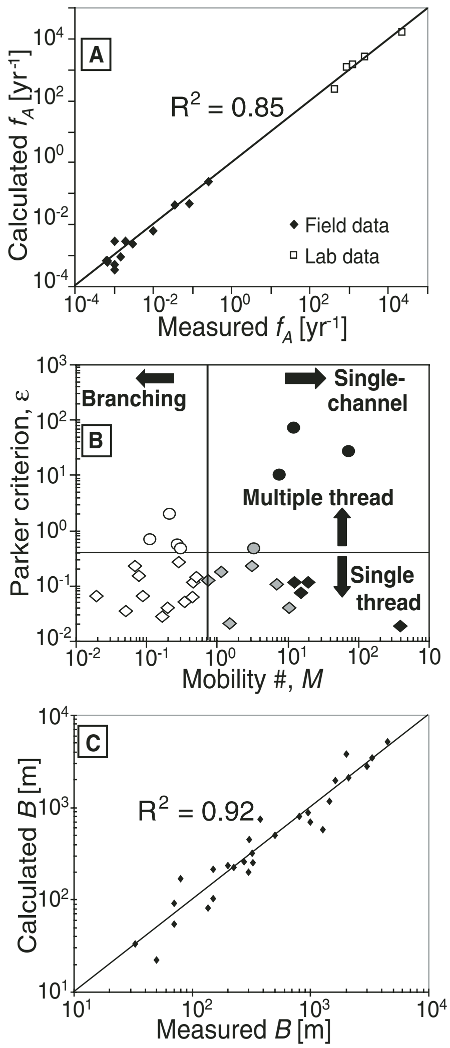

Figure 2. Measured and computed river characteristics (see text and footnote 1). A: Measured versus calculated avulsion frequency (1) for field and laboratory data. Line denotes perfect agreement. B: Phase space of mobility number (2) and Parker (1976) stability criterion. Lines delineate channel patterns observed from data. Diamonds and circles indicate sinuous (single thread) and braided rivers, respectively; white, black, and gray symbols are single-channel, branching, and transitional systems, respectively. C: Measured versus calculated total channel width for field data only. R-square values associated with the proposed relations for avulsion frequency and channel width are shown in A and C, respectively.

tion between single and multiple branches is expected if avulsion and lateral bank erosion are the only important processes.

Parker (1976) provided a theoretical stability criterion, ε, that can be used to assess whether a river should be braided (i.e., a single channel with multiple threads of high-velocity flow), or a single-thread channel with a sinuous to straight plan form (Fig. 2). This criterion may be written as $\varepsilon = S\sqrt{g\bar{h}B^4}/Q$, where S, g, and Q are water surface slope, gravitational acceleration, and formative water discharge, respectively. A single-thread channel is the dominant form at $\varepsilon \ll 1$, while a braided form is the common channel type for $\varepsilon \geq 1$ (Parker, 1976; Dade, 2000). We propose that the mobility number and the Parker stability criterion when taken together provide a complete qualitative picture of expected river planform pattern.

SCALING TEST

To test whether the derived mobility number is capable of discriminating between single-channel and branching systems, we have compiled data from 30 net-depositional systems reported in the literature (see GSA Data Repository[1]). These data include lowland rivers, deltas, and alluvial fans with perennial to ephemeral discharges, located in tropical to arid environments and transporting particles ranging from fine sand to cobbles. The reported systems also cover a wide range of scales, from the laboratory to the Amazon River. The size of the data set analyzed here is limited by the number of studies providing enough information to estimate v_C and v_A, which were computed using a variety of methods including dated cores in channel beds and banks, aerial photography, and channel surveys (see footnote 1). Note several caveats against overinterpretation of specific values reported for mobility number. Channel geometry was measured from modern rivers, so our analysis implicitly assumes that these values have not changed substantially over the Holocene. No quality checks were performed on reported rates, or on ages used to derive rates. Some researchers may object to reducing the large variability in any natural river to a single datum; in reality, a river system with varying channel geometry and rates of evolution could have a spatially varying mobility number. A comprehensive error analysis of the data is beyond the scope of this paper; however, it is not necessary for our purposes here. Validation of the scaling argument requires only that the predicted limits (branching for $M \ll 1$; single channel for $M \gg 1$) are consistent with the data.

Because avulsion is an inherently stochastic process, the computed avulsion time should be seen as an average value. In reality, avulsion may occur at superelevations >1 or <1, and one must integrate over many avulsions to recover the expected scaling behavior. To test the validity of our avulsion frequency relation (Equation 1), we compare computed values to average values measured in natural and laboratory systems. The agreement demonstrates (Fig. 2A) that long-term avulsion frequency may be estimated using the simple relation (Equation 1) proposed here. This result is of great significance because modeling efforts have shown that the morphology and depositional patterns of channelized landscapes are very sensitive to avulsion frequency (Heller and Paola, 1996; Sun et al., 2002), and there are competing descriptions of conditions necessary for avulsion (Bryant et al., 1995; Heller and Paola, 1996; Mohrig et al., 2000; Törnqvist and Bridge, 2002; Ashworth et al., 2004; Slingerland and Smith, 2004). Varying degrees of importance have also been assigned to the frequency of avulsion triggers such as floods, ice jams, and animal disturbance (Slingerland and Smith, 2004). Given that our data come from field and laboratory settings representing the broadest possible range of depositional environments, it appears that (1)

[1]GSA Data Repository item 2007108, river data and descriptions of how these data were derived, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

knowledge of the style of avulsion trigger is not necessary for modeling the long-term evolution of channel deposits, implying that occurrence of a triggering event is not a limiting factor in avulsion frequency; and (2) the condition for avulsion is well approximated by the time required to achieve a relative superelevation of one (Fig. 1). These results may be applied directly to morphodynamic models of channel and fan development (Sun et al., 2002, Swenson, 2005).

All reported river systems with a single active channel correspond to $M > 10^1$ (see footnote 1). All systems that clearly exhibit a branching pattern have M < 10°. Most river systems having $10^0 \leq M \leq 10^1$ are transitional, generally containing one dominant channel and a small number of secondary channels. Using measured river data (see footnote 1) we have constructed a phase space that relates channel pattern to M and ε. We find this method effectively segregates systems into four categories: single channels with multiple threads (simple braided channels), single channels with single threads (straight to sinuous channels), multiple channels with multiple threads (branching systems with braided channels), and multiple channels with single threads (simple branching systems) (Fig. 2B). Because of the variable data quality these values for M should be taken only as order of magnitude estimates. Nonetheless, analysis of these data clearly demonstrates the discriminating power of the mobility number.

CASE STUDIES

It is useful to focus on a few specific river systems to address the meaning of computed mobility numbers (see footnote 1). The Yellow River of China has an extremely large Holocene channel aggradation rate of v_A = 100 mm/yr (Fig. 3). Although this river avulsed on decadal time scales before human intervention, constructing a large delta, only one channel has been active at any one time due to the high degree of channel migration by bank erosion (Wu et al., 2005). Despite modern channel control structures, the mouth of the Yellow River exhibits very similar activity today (van Gelder et al., 1994). The values M = 16 and ε = 0.07 indicate that the Yellow River Delta should be a single-channel, sinuous river system (Fig. 2), in agreement with observation. Hence, this example serves to demonstrate that rapid aggradation alone is not sufficient to generate a branching system. An interesting counter example is the anabranching Cooper Creek (Gibling et al., 1998; Fagan and Nanson, 2004), in arid central Australia (Fig. 3). Although vertical aggradation is very small ($v_A \leq 0.1$ mm/yr), the exceedingly low channel migration rate, estimated as $v_C \leq 8$ mm/yr, results in a maximum value for M of 0.3, indicating multiple branches. Even if the lower (flood plain) estimate v_A = 0.04

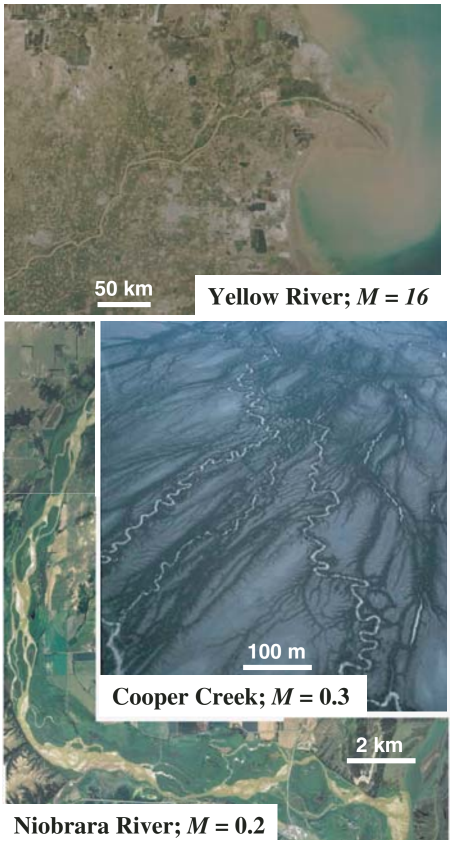

Figure 3. Example rivers and their mobility numbers (*M*). Yellow River image is from http://visibleearth.nasa.gov; Niobrara River image is from http://www.dnr.state.ne.us/databank/spat.html; and Cooper Creek image is courtesy of G. Nanson.

mm/yr is used, mobility number is still <1 (M = 0.7), and it is probably much less due to the (likely) overestimated value for v_C. Cooper Creek shows that very stable channel banks may induce an avulsion-driven morphology, even if channel aggradation rates and avulsion frequency are very low. It is relative rates, not absolute rates that are important. A final case is the lower Niobrara River, Nebraska (Fig. 3). The channel has undergone rapid bed aggradation throughout the past 50 yr in response to base-level rise from reservoir construction. This aggradation has driven multiple avulsions and the conversion of some reaches to narrower anabranches separated by stable, vegetated islands (Ethridge et al., 1999). Our calculations suggest that the present morphology of the lower Niobrara should be branching and braided (M = 0.2, ε = 2), in agreement with observations. We propose that the mobility number may be used to predict if a change in boundary conditions, whether tectonic, climatic, eustatic, or anthropogenic, will result in a conversion from single-channel to branching morphology. This is of critical importance for river management and habitat issues, and is equally important in the reconstruction of paleoenvironmental conditions via the analysis of ancient fluvial deposits.

EQUILIBRIUM CHANNELS AND BRANCHING

Assuming steady uniform flow and a Chezy flow-resistance relationship, channel width of a single-branch river may be cast as $B = c_f^{1/2} QS \big/ \sqrt{R^3 \theta^3 d_{50}^3 g}$ (Parker et al., 1998; Dade, 2000), where θ, d_{50}, and c_f are dimensionless bed (Shields) stress, median grain diameter, and Chezy friction factor, respectively, and $R = 1.65$ is the relative specific gravity for quartz. The measured values for total wetted width of rivers in our database are plotted against calculated values of single-channel width in Figure 2C. These data show that the sum of active channels in anabranching and distributary rivers behaves like a single channel of comparable size. More support for this idea may be found in the mean values for Shields stress of sandy and gravel-bedded branched rivers (1.1 and 0.07, respectively), which are very close to the constant observed values for single-channel systems (Parker et al., 1998). The mean channel depth, total wetted width, and dimensionless bed stress may all be estimated (Parker et al., 1998; Dade, 2000) without reference to the number of channels in a river system, indicating similar channel-forming processes for all types.

It appears that the pattern of branching has little to do with the mean transport of water and sediment, and therefore it is not likely an adjustment to optimize flow efficiency or transport capacity (e.g., Jansen and Nanson, 2004). Our analysis suggests that the cause of branching is independent from the causes of other river patterns such as braiding. Braiding results from bar deposition, a fundamental instability of coupled fluid and sediment transport within a channel (Parker, 1976). While bars may cause flow splitting at small to intermediate scales, we argue that branching (and anastomosis) in depositional rivers derives from an emergent instability at a larger scale , i.e., channel avulsion. The existence of multiple stable branches in the rivers examined here appears to be determined by boundary conditions conducive to net deposition of sediment, combined with some degree of channel-bank stability (usually from vegetation) such that the mobility number is 0 (10°) or less. This point addresses the question as to whether anabranching patterns can exist as a persistent channel-system form (Makaske, 2001; Jansen and Nanson, 2004). Anabranching need not be merely a transitional pattern; the requirement that M < 1, however, means that anabranching may only be maintained in environments undergoing bed aggradation rates that are rapid compared to lateral cutting rates.

CONCLUSIONS

By deriving the characteristic time scales of dynamical processes, we determined the conditions leading to the formation of branching patterns in depositional rivers. Anastomosed rivers and distributary delta channels may arise from the same processes, the principal difference being that the former are usually confined by valleys while the latter are generally unconfined. Using relatively few parameters, it is possible to predict if and how frequently a river will abandon its channel, and whether a change in boundary conditions will induce a transition in channel pattern. Conversely, the empirical ranges of channel pattern delineated by the mobility number may be used to place constraints on the relative rates of channel aggradation and bank erosion in ancient channel deposits. Such constraints are useful not only for terrestrial rivers, but for interpretation of deposits on other planets, such as Mars (e.g., Jerolmack et al., 2004), where availability of detailed stratigraphic data is limited.

A shortcoming of our analysis is neglecting to treat the process of channel filling after abandonment, which undoubtedly influences the number of channels that may be active at once. Erasure of channels by flood-plain sedimentation could potentially shift the mobility-number boundary between branching and single-channel rivers, but we expect the general trends to hold. Another open question is the time scale over which channels may adjust their planform pattern to a new mobility number regime. Many modern deltas may still be responding to early to mid-Holocene sea-level rise, and presumably the response time of a system scales with its size and the rates of deposition and erosion. Our analysis helps to shed light on dominant processes and, we hope, motivate further research in this area. A major remaining challenge is to develop predictive algorithms for channel aggradation and bank erosion rates that may be incorporated into current morphodynamic models (Sun et al., 2002; Murray and Paola, 2003; Swenson, 2005), providing a more complete description of river patterns at all scales.

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